ARCHITECTURE AND BUILT ENVIRONMENT DEPARTMENT

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ARCHITECTURE AND NEUROPSYCHOLOGY: INVESTIGATING CROSS-MODAL NEURAL ACTIVITY DURING IMPLICIT MOTOR IMAGERY WITH ARCHITECTURAL ELEMENTS

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Dedicated to my lovely Nisa

ABSTRACT

This thesis studies the 'agency' and 'implicit motor imagery' (in the context of cross-modal neural interaction). The agency refers to the action capacity of an organism/agent within a given environment. In this thesis, agency has been examined with its ecological and architectural contexts and with the emphasis on its two sub-components. These are the embodiment (or embodied perception) or embodied account in general and architectural affordance. The 'embodiment' refers to bodily activation and its potentials. The 'embodied perception' underlies the influence of the body on perceptual processes. The concept of 'affordance' has been formulated by James Gibson (1966) and can be defined as the potentials of an environment for embodied (inter-) actions of an agent/organism. The other theme of the thesis as 'implicit motor imagery' can be regarded as ongoing neurophysiological or cognitive processes in line with imagery of the action. Implicit motor imagery can emerge as a result of either inner or outer stimulation relevant to imagined action (e.g., observation, analogy) although there is no execution of the action. In the context of the thesis implicit motor imagery was examined within the context of cross-modal neural interactions between theregions of the brain relevant to visual and embodied perception (i.e., mental agency).

In this regard, this thesis tries to contribute three different conceptual background(s) which can be listed as 1) literature dealing with agency within architectural theory, 2) studies based on neuropsychological investigations on agency and 3) new forming research area dealing with application of tools of neuropsychology to the realm of architecture. In Agency within Architectural Theory area, this thesis achieves its originality via instrumentalizing the theories in order to test with tools of neuropsychology. In formed literature based on approaches of cognitive and neuropsychology to agency, this thesis provides its novelty via using architectural elements as doors differently from earlier experiments dealing affordances of hand-scale objects. In emerging research field grounded on implementing instruments of cognitive neuroscience to the realm of architecture, the thesis uses essential principles of experimental design in cognitive and neuropsychology to achieve scientific reliability.

This thesis provides aforementioned originalities in a series of experiments testing agency within architectural context in search of cross-modal interactions between visual and embodied perception. After literature review and a detailed chapter on neuroscientific methods, the thesis presents experiments using electroencephalography (EEG) - a method to record brain activity through electrodes placed on the scalp - and a behavioural experiment that assesses reaction times. For this purposes in both EEG and one of behavioural experiment we used images of doors with different handles including different degree of motor imagery. In the first EEG experiment and behavioural experiment we used only images of doors without cues for motor imagery and in the second experiment; we use images of doors including cues for motor imagery - hands and arms approaching and non-approaching to the handles. In the experiment without motor imagery cues where the attention of participants directed to just doors, we could find some evidence of the existence of motor content in the early phases of activity of visual cortex ~100 ms after stimulus presentation (P100 component of event-related potential). In the experiment with motor imagery cues, the ~10 Hz EEG rhythm recorded over the motor cortex during rest (mu rhythm) showed a decrease

(indicating motor cortex activation) in response to images of doors, and the decrease varied with door category. These findings can be assessed as the indicator of role of how experiencing parts of architectural environments shapes our understanding the way of their perception and provides comparisons of architectural elements designed differently with their perceptive/cognitive background both conscious or unconscious levels within the context of doors affording different potentials for action.

In addition to contributions of experiments, this thesis discusses some philosophical problematics, technical and practical limits to define the thesis position and its value. Additionally, problematics, close conceptual horizon and far conceptual horizon of the thesis were also discussed to emphasize the importance of studying architectural agency within inter-disciplinary and trans-disciplinary contexts by benefitting from such disciplines as evolutionary biology, human-computer interaction and other branches of cognitive science for considering potential studies.

Keywords: Affordance, Architectural Elements, Agency, Embodiment, Neuropsychology, EEG, Cross-Modality, Embodied Perception, Visual Perception, Doors

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THE CONTRIBUTION

This thesis shows the researcher's own study except for chapter 6, mentioning an experiment conducted in collaboration with Ms Camilla Woodrow-Hill, master conversion student in School of Psychology of University of Nottingham. For this chapter, the researcher Hasan Basri KARTAL developed the research question, designed the basic experiment, prepared stimulus images and PsychoPy script, and developed part of the MATLAB scripts for data analysis. Camilla Woodrow-Hill modified the experimental design, ran experiments to acquire EEG data, preprocessed data using MATLAB scripts, developed R scripts for statistical analysis and applied these scripts; and she also prepared graphs shown in this chapter.

Additionally, the experiment which was mentioned in the chapter 7 was conducted in clloboration with Mr. Kenneth Tong, a bachelor student in School of Psychology of University of Nottingham. For this chapter, the researcher Hasan Basri KARTAL developed research question, designed the basic experiment, prepared stimulus images and PsychoPy script. Additionally the research recruited first 14 participants for data acquisition. Kenneth Tong recruited 38 further participants for data acquisition, preprocessed data using R scripts for statistical analysis and applied these scripts and he also prepared graphs shown in this chapter.

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GLOSSARY

- **'go-no go' task:** This task refers to a pass/fail test (or check) principle using two boundary conditions or a binary classification (Gomez et al., 2007).
- **action potential:** An action potential is defined as a sudden, fast, transitory, and propagating change of the resting membrane potential. Only neurons and muscle cells can generate an action potential; that property is called excitability (Vasković, 2021).
- **active inference:** This is a first principle account of how autonomous agents operate in dynamic, nonstationary environments (Sajid et al., 2021).
- **affordance:** This term means what the environment offers the individual in terms of potentials for acting.
- **affordances for higher cognition:** The higher cognition activities may be applied at many different spatial and temporal scales, including at the scale of sociocultural practices. Imagination and long-term planning can be samples of this kind of affordances (Bruineberg et al., 2019).
- **agency:** The agency implies the ability to perceive and change the agent's environment (Emirbayer and Mische, 1998).
- **alien hand syndrome:** Alien hand syndrome is a phenomenon in which the mind does not control one hand. The person loses control of the hand, acting as if it has a mind of its own (Panikkath et al., 2014).
- **alpha oscillations suppressions:** This means a power reduction of posterior alpha oscillations and is thought to reflect visual activity, in addition to attentional reorienting and memory processes (Girges et al., 2014).
- **architectural agency:** agency within architectural context (e.g., inter-action of agent with architectural elements)
- **artefact rejection:** eliminating physiological or non-physiological artefacts contaminating acquired data via EEG
- **autoscopy:** This is the experience in which an individual perceives the surrounding environment from a different perspective, from a position outside their own body (Blanke and Mohr, 2005).
- **band-pass and band-stop filters:** A band-pass filter admits frequencies within a given band, rejecting frequencies below and above. A stop-band filter does the reverse, rejecting frequencies within the band and letting through frequencies outside it (Puckette, 2007).
- **bio-potential of stimulation:** The biopotential originated from the electrical brain activity is called an electroencephalogram. Biopotentials occur due to the electrochemical activity of the cells, where the electrical activity is caused by differences in ion concentrations within the body (Kim et al., 2016).
- **blind source separation:** Blind Source Separation (BSS) refers to a problem where both the sources and the mixing methodology are unknown; only mixture signals are available for further separation. Blind source separation (BSS) is a technique to estimate source signals in an observed mixture signal without knowing any prior information (Deville, 2016).
- **body schema:** It is a postural model of the body that actively adjusts "the impressions produced by incoming sensory impulses in such a way that the final sensation of body position, or of locality, rises into consciousness charged with a relation to something that has happened before" (Head, 1920).
- **brain oscillations:** They are rhythmic or repetitive patterns of neural activity in the central nervous system (Jee, 2020).
- **cognitive congeniality:** The measure of how cognitively hospitable an environment is its cognitive congeniality (Kirsh, 1996).
- **(cognitive) marking:** markings are the products of kinesthetic dynamics of a non-representational sort that allow humans to engage and discover the semiotic affordances of mark making opening up new possibilities of enactive material signification (Malafouris, 2021).

- **cognitive offloading:** Cognitive offloading refers to reducing the mental processing requirements of a task through physical actions like writing down information or storing information on a cell phone or computer (Morrison and Richmond, 2020).
- **cognitive scaffolding:** It refers consolidation and accumulation of learning processes through.to the interaction between the knowledge and skills of teacher and student (Flick, 1998) in addition to socio-cultural medium itself.
- **common-mode rejection:** The common-mode rejection ratio (CMRR) is a metric used to quantify the ability of the device to reject common-mode signals (Mancini, 2000).
- **contralateral organisation of the forebrain**: It is the property that the hemispheres of the cerebrum and the thalamus represent mainly the contralateral side of the body. Consequently, the left side of the forebrain primarily represents the right side of the body, and the right side of the brain primarily represents the left side of the body (Graziano and Botvinick, 2002).
- **cross-modality:** Crossmodal perception is the perception that involves interactions between two or more different sensory modalities (Shimojo and Shams, 2001).
- **discrete-time:** The discrete-time shows values of variables as occurring at distinct time (Shumway et al., 2000).
- **dorsal vs ventral:** Dorsal and ventral are paired anatomical terms used to describe opposite locations on a body in the anatomical position. On a human body, dorsal (i.e., posterior) refers to the back portion of the body, whereas ventral (i.e., anterior) refers to the front part of the body (Tiarks, n.d.).
- **ecological revolution:** rise of approaches taking into account of ecological context of cognition in cognitive science.
- **EEG:** It is a method to record an electrogram of the electrical activity on the scalp that has been shown to represent the macroscopic activity of the surface layer of the brain underneath (Teplan, 2002).
- **embedded cognition:** Embedded Cognition amounts to the idea that cognition is afforded and constrained by ongoing interactions between body and environment (Pouw et al., 2014).
- **embodied cognition:** Embodied cognition is an approach to cognition that has roots in motor behaviour. This approach emphasises that cognition typically involves acting with a physical body in an environment in which that body is immersed (Spencer et al., 2009).
- **embodied simulation theory**: Embodied simulation theory is, amongst other things, a theory of social cognition – a theory of how it is we understand others' actions, primary intentions, emotions and sensations (Gallese, 2014).
- **embodiment:** In the field of cognitive science, embodiment is associated with understanding the function of the body of agent/organism on its situated cognition which is used in the daily life of agent/organism (Gibbs, 2005).
- **emergent properties:** An emergent property is a property that a collection or complex system has but which the individual members do not have. An emergent behaviour or emergent property can appear when many simple entities (agents) operate in an environment (Sinjab, 2013).
- **enactive approach:** An enactive approach views cognition as a form of sense-making – it is not a matter of representing a pre-given world, but rather an active, embodied process creating meaning or significance. In other words, sense-making occurs when a person (or another autopoietic system) finds significance in its world (Stilwell and Harman, 2019).
- **enactive cognition:** Enactive cognition is a new version of recently developed embodied cognition approaches. It claims that explaining human cognitive processes across the board should not appeal to internal representational or computational states (Ye et al., 2019).
- **enactivism:** Enactivism argues that cognition arises through a dynamic interaction between an acting organism and its environment. The organism's environment is brought about or enacted by the active exercise of that organism's sensorimotor processes (Thompson, 2010).
- **epistemic space:** an assumption of an ontological entity (a space) including alternative scenarios in terms of possible epistemic constructions

- **EEG spectral dynamics:** changes in the (power) spectrum of EEG (Mazaheri and Picton, 2005).
- **ERSP (Event-Related Spectral Perturbation):** ERSP measures the average time course of relative changes in the spontaneous EEG amplitude spectrum induced by a set of similar experimental events (Jarmolowska et al., 2018). It means event-related changes in spectral power at each time during the epoch and at each frequency (Zhao and Zhang, 2007).
- **event-related potentials (ERP):** An event-related potential (ERP) is the measured brain response directly from a specific sensory, cognitive, or motor event (Luck, 2005).
- **event-Related Synchronisation and Desynchronisation:** Event-related desynchronisation (ERD) reflects a decrease of oscillatory activity related to internally or externally paced events. ERD is the short-lasting attenuation or blocking of rhythms within the alpha (beta) band. ERD is found during but also before visual stimulation. The increase of rhythmic activity is called event-related synchronisation (ERS). ERS describes a short-lasting amplitude enhancement (Pfurtscheller and Neuper, 2010).
- **evoked potential:** This is an electrical potential in a specific pattern recorded from a specific part of the nervous system, especially the brain of humans (VandenBos, 2015).
- **field of affordances:** The affordances that stand out as relevant for a particular individual in a particular situation, i.e., the multiplicity of affordances that solicit the individual. The field of affordances includes soliciting affordances understood as action possibilities relevant to a particular situation from the perspective of a particular person (Bruineberg and Rietveld, 2014).
- **FieldTrip:** This is a MATLAB software toolbox for electroencephalography (EEG) analysis.
- **free-energy minimisation:** Free energy minimisation is equivalent to maximising the mutual information between sensory and internal states that parameterise the variational density (Karl, 2012).
- **harmonic analysis:** Harmonic analysis is a branch of mathematics that represents functions or signals as the superposition of basic waves (Paul et al., 2014).
- **hemispheric laterality:** Hemispheric lateralisation is the idea that both hemispheres are functionally different and that specific mental processes and behaviours are mainly controlled by one hemisphere rather than the other (Guy-Evans, 2021).
- **ideomotor:** The ideomotor phenomenon is a psychological phenomenon wherein a subject makes motions unconsciously. It relates to an unconscious or involuntary bodily movement in response to a thought or idea rather than a sensory stimulus (Gauchou et al., 2012).
- **Imbrications (sociomaterial):** In socio-material realm, imbrications refers to ontological distinction of human and technological agencies and prioritization of human agencies on technological agency within socio-material realm (Introna, 2013).
- **Independent Component Analysis (ICA):** Independent component analysis (ICA) is a statistical and computational technique for revealing hidden factors that underlie sets of random variables, measurements, or signals. ICA defines a generative model for the observed multivariate data, typically given as an extensive database of samples (Junhong and Zhuobin, 2011).
- **intensionality:** Intensionality is a semantic property, marked by such features as the failure of truth preservation when one referring expression is replaced by another with the same reference (Sainsbury, 2018).
- **ipsilateral versus contralateral:** Ipsilateral: On the same side, as opposed to contralateral. Contralateral: The opposite of ipsilateral (the same side). For example, a stroke involving the right side of the brain may cause contralateral paralysis of the left leg.
- **isomorphic functionalism (or functional isomorphism):** In extended mind hypothesis, assumption of an isomorphy in terms of functional qualities between inner and outer processes relevant to extended cognition as a result of parity principle (Bernecker, 2014).
- **the lateralisation of brain function:** It is the tendency for some neural functions or cognitive processes to be specialised to one side of the brain or the other (Tucker, 1981).
- **low-pass and high-pass filter:** A low-pass filter is a filter that passes signals with a frequency lower than a selected cutoff frequency and attenuates signals with frequencies higher than the cutoff

frequency. A high-pass filter allows for easy passage of high-frequency signals from source to load and difficult passage of low-frequency signals. If a filter passes high frequencies and rejects low frequencies, it is a high-pass filter. It is a low-pass filter if it passes low frequencies and rejects high ones (Vaishya and Choubey, 2017).

- **mental agency:** Agency without execution of action, instead, agency with mental imagery of execution of action/agency.
- **mereological & axiological considerations:** Mereology shows the relations of part to whole and part within a whole (Varzi, 2019). Axiology means the philosophical study of goodness, or value, in the broadest sense of these terms (Britannica.com, 2015).
- **mirror neurons:** The brain cell reacts both when a particular action is performed and only observed (Acharya and Shukla, 2012).
- **mnemonic effects:** It is associated with choosing might arise because participants feel an increased sense of agency when they are allowed to make choices (Coverdale and Nairne, 2019).
- **motor empathy:** Motor empathy refers to unconsciously mirroring facial expressions, which is suggested to induce shared representations of perception and emotional contagion (Bons et al., 2010).
- **motor imagery:** This term can be defined as a dynamic state during which an individual mentally simulates a physical action. This phenomenal experience implies that the subject feels themselves acting (Decety and Ingvar, 1990).
- **mu rhythm:** The mu rhythms are synchronised patterns of electrical activity involving large numbers of neurons, probably of the pyramidal type, in the part of the brain that controls voluntary movement (Amzica and da Silva, 2010) Mu oscillation can also be defined as the activation of mu rhythm.
- **mu suppression:** Mu suppression has been proposed as a signature of the human mirror neuron system (MNS). A person suppresses mu rhythms when he or she performs a motor action or, with practice, when he or she visualises performing a motor action (Coll et al., 2017; Zheng, 2020).
- **neural oscillations:** Neural oscillations, or brainwaves, are rhythmic or repetitive patterns of neural activity in the central nervous system (Shah et al., 2017).
- **neurogenesis:** Neurogenesis is how new neurons are formed in the brain.
- **neuroplasticity:** Neuroplasticity, also known as neural plasticity, or brain plasticity, is the ability of neural networks in the brain to change through growth and reorganisation (Cherry, 2021a).
- **neuropsychology:** Neuropsychology is a branch of psychology. It is concerned with how cognition and behaviour are related to the brain and the rest of the nervous system (Cherry, 2021b).
- **neurotrophins:** Neurotrophins are a family of proteins that induce the survival, development, and function of neurons (Skaper, 2008).
- **noetic:** Noetics is concerned with the changes and potentials of consciousness (encyclopedia.com, 2021).
- **nomology:** It is the science of law and law-making. the branch of science concerned with the formulation of laws explaining natural phenomena (collinsdictionary.com, 2021).
- **non-Gaussianity (noise):** Feature of the noise which do not obey the Gaussian statistics where the noise's probability density function does not shoe Gaussian distribution.
- **normativity:** Normativity is the phenomenon in human societies of designating some actions or results as good or desirable or permissible and others as bad or unwanted (dbpedia.org, 2021).
- **ontogeny:** It is all the developmental events that occur during the existence of a living organism (Britannica.com, 2010).
- **P100 ERP Wave Component:** The 'event-related potential' (ERP) refers to the electrical reactions of the brain to a specific stimulus or cognitive process. P100 is sensitive to the perceptual features of stimuli such as brightness, size, and visual acuity (Miyakoshi et al., 2007).
- **Parahippocampal area (PPA):** It is a functional region of the brain that responds more strongly to images of scenes and places than other visual stimuli classes and is critical for scene and place recognition and navigation (Weiner et al., 2018).

- **phenotypic plasticity:** Phenotypic plasticity is the ability of an organism to change in response to stimuli or inputs from the environment (West-Eberhard, 2008).
- **philosophication:** The act of philosophising.
- **postsynaptic potentials:** Postsynaptic potentials are changes in the membrane potential of the postsynaptic terminal of a chemical synapse (Anderson, 1985).
- **present-at-hand, ready-to-hand:** These two terminology are Heideggerian and present-at-hand refers to theoretical comprehension of external environment and things within this environments and ready-to-hand mainly refers to practical (inter-)actions with these things and environment.
- **primary-secondary distinction:** The primary/secondary quality distinction is a conceptual distinction in epistemology and metaphysics concerning the nature of reality. It has come to express a position on the nature of sensory qualities – those which we attribute to physical objects due to the sensuous character of sensations they produce when perceived correctly by us (Smith, 1998).
- **Principal Component Analysis:** Principal component analysis (PCA) is a technique for reducing the dimensionality of such datasets, increasing interpretability while minimising information loss (Smith, 1998).
- **proprioceptive, hylonoetic and tectonic awareness:** Types of (self-) consciousnesses relevant to characteristics of body (proprioceptive), or relevant to materiality (with/ through matter) (hylonoetic), or relevant to contructing/designing things (tectonoetic).
- **realisticity:** The quality of being realistic.
- **repetition suppression:** Repetition suppression (RS) is commonly defined as a diminished neural activation that results from the repeated presentation of a stimulus. A reduction of neural response is often observed when stimuli are presented more than once (Epstein et al., 2008).
- **rubber hand illusion:** The Rubber Hand Illusion (RHI) is an illusion, where the feeling that a rubber hand belongs to one's body is brought about by stroking a visible rubber hand synchronously to the participant's own blocked hand (Rohde et al., 2011).
- **sense modality:** It is a particular way of sensing a stimulus.
- **sensorimotor theory of perception:** Sensorimotor theory offers a constitutive account of perceptual experience, an account of what experiencing is, aiming to bring together physical/biological and phenomenological descriptions of the character of perceptual consciousness (Degenaar and O'Regan, 2015).
- **sensory substitution:** Sensory substitution is a change of the features of one sensory modality into stimuli of another sensory modality.
- **signal-to-noise ratio:** Signal-to-noise ratio (SNR) is a measure to describe how much-desired signal is present within acquired data instead of unwanted signal (noise) (rode.com, 2021).
- **Simon Effect:** The Simon effect is the difference in accuracy or reaction time between trials in which stimulus and response are on the same side and trials in which they are on opposite sides, with responses being generally slower and less accurate when the stimulus and response are on opposite sides (Proctor and Lu, 1999).
- **Singularity (technological):** Refers to aspects of technological developments where technological assets gain characteristics relevant to individuality.
- **situated cognition:** Situated cognition is the theory that people's knowledge is embedded in the activity, context, and culture in which it was learned (Brown et al., n.d.).
- **skeuomorphism:** Skeuomorphism is where an object in software mimics its real-world complement.
- **skilled intentionality framework:** This is a new conceptual framework for embodied/enactive cognitive science. It means a philosophical approach to understanding the situated and affective embodied mind (Rietveld, 2016).
- **socio-material/constitutive entanglement:** This term may mean the constitutive entanglement of the social and the material in everyday organisational life. It examines the social and material aspects of

technology and organisation, the centrality of materials within the communicative constitution of organisations (Orlikowski, 2007).

- **stimulus-response compatibility:** Stimulus–response (S–R) compatibility is the level to which a person's perception of the world is matched with the required action.
- **tau theory:** General tau theory deals with the guidance of bodily movements. The theory is embedded in ecological thinking, paying attention to both organism and environment and drawing information from their forms of interaction (bionity.com, 2021).
- **time window**: A time window is an interval in time during which an activity can or must take place.
- **tool-being:** In object-oriented ontology, prioritization of justification of existence tools within themselves to cope with anthropomorphic tendeny of philosophication of being. Like the thing, tools are not primarily something to be seen, represented, conceptualized, produced, spatially located, made of physical parts, or related to anything else at all. And like the thing, tool-beings are absent from all detection by their environment, since such detection is always merely partial (Harman, 2009).
- **top-down / bottom-up order:** hieararchical orders among the mechanisms of system, information, or any relevant ontological entities such as domain(s) processes either from specific to general (bottom-up) or from general ro specific (top-down).
- **trigger code:** This code means one-time encrypted numeric interpretation sent to the application to perform any action.
- **truthmaking:** The truthmaker theory may say that truth depends on being. For example, a tree's perceptual experience may be true because there actually is a tree. However, if there were no trees there, it would be false. So, the experience by itself does not ensure its truth or untruth; it depends on something else (Cameron, 2011).
- **volumetricity:** The quality of having the volume.
- **windowing function:** The window function is a mathematical function that is zero-valued outside of some chosen interval, normally symmetric around the middle of the interval, usually near a maximum in the middle, in signal processing and statistics middle (Shehu et al., 2019).

CHAPTER 1: THE INTRODUCTION

This chapter will introduce keywords, scope, research questions and hypothesis, motivation, aim and objectives, value and originality, methodology, and thesis structure. The themes of the thesis are mainly based on two keywords as 1) agency, 2) implicit motor imagery. In terms of the scope of the thesis, the agency has been considered with its ecological/architectural context. Furthermore, this thesis concentrates on two sub-components of ecological/architectural agency as embodied perception (or in the broader sense, embodiment, embodied cognition) of agent and architectural affordance within the ecology of the agent. Second term, implicit motor imagery has been regarded within cross-modal neural context, especially cross-modality between visual and motor processes relevant to the interaction of agent(s) with architectural affordances within the ecology of agent(s). These theoretical considerations have been addressed to experiments via several research questions.These research questions are mainly based on investigations about 1) changing weights (i.e., amplitude) of neural activity (i.e., ERD of mu oscillation) /cognitive activity (i.e., response time) associated with implicit motor imagery in line with architectural affordances within the ecology of agent/participant and 2) lateralisation of this neural/cognitive activity. Moreover, cross-modality between visual and motor processes has also been investigated via the influence of motor-related characteristics on neural processes relevant to early phases of visual perception (i.e., P100 ERP Waveform Component) in one of the thesis experiments (i.e., Experiment 1).

The main motivation beyond conducting these experiments is to understand underlying neural processes relevant to interactions of agent/organism with its/their architectural surrounding as one of the most important issues within the realm of architecture for architects and for experts in different fields relevant to architecture (e.g., interior architects, industrial designers). In this context, this thesis is one of the early attempts to investigate these issues with the tools of neuropsychology. The aspect of the thesis makes the research original and offers valuable contributions to the new rising inter-disciplinary area in architectural neuroscience. Therefore, to examine neural activity, EEG was used as the primary method of the experiments. Additionally, response time analysis was performed to have insights into cognitive processes. By starting from these clarifications, structure and general aspects of issues relevant to the thesis (e.g., keywords, scope, research questions) will be explained briefly in the following parts of the introduction.

1.1 THE KEYWORDS AND DEFINITIONS

This thesis is based on mainly two themes: the architectural agency (in ecological context) and motor imagery (in the context of cross-modal neural interaction). The term ‘agency’ has been

investigated with its different dimensions or contexts within various disciplines in line with the research interest and themes of the disciplines. Some of these disciplines can be listed as; evolutionary biology, philosophy, cognitive neuroscience and psychology, sociology, anthropology, computer science and robotics, human factors and human-computer interaction. The agency is mainly conceptualised within the agent-environment framework with (inter-) action-oriented focus in these disciplines. The action-oriented conceptualisation of agency can be classified into two categories as; kinaesthetic dimension of action (e.g., control, coordination) and the contextual dimension of action (e.g., ecological context, socio-cultural context). In this thesis, the kinaesthetic properties of the agency have mainly been examined. These kinaesthetic properties have mainly been conceptualised within the context of bodily/embodied characteristics of agency and perceived environmental potentials offered for the actualisation of agency relevant to embodied characteristics. In this context, kinaesthetic properties relevant to the agency's ecological and architectural context will be discussed around two central themes: embodied perception (or in a broader sense, embodiment and embodied cognition) and affordance.

Bodily and embodied characteristics of relationships of agent(s) with its/their environment have begun to be considered thanks to the rise of approaches of post-cognitivism in neurophilosophy and action-oriented approaches in cognitive science (i.e. pragmatic turn). One of the main characteristics of approaches of post-cognitivism is based on rejecting the approaches that isolate the brain from its bodily and environmental/ ecological contexts and posit cognitive processes as mere representation or computation or emergent product of connections. By starting from these considerations, approaches of post cognitivism (e.g., situated mind, embodied cognition, extended mind thesis, distributed cognition, enactivism) mainly concentrate on the constitutive role of contextuality (e.g., body, ecology) of agency on cognitive processes. In this context, embodied cognition generally refers to the formative/ constitutive/influential role of bodily characteristics of agent on cognition. This conceptualisation can be implemented to other processes relevant to cognition such as perception (i.e., embodied perception), (inter-) action (i.e., embodiment) and different modalities of cognition. From the perspective of embodied account, body or embodied characteristics becomes the primary ontological ground and medium of (inter-)actions of agent(s) with its/their ecological context/given environment. Additionally, these embodied characteristics have a constitutive role on (background) cognitive processes relevant to these (inter-) actions.

In addition to philosophical considerations of post-cognitivism emphasising context (bodily, environmental), pragmatic turn in cognitive neuroscience put effort to explain all cognitive

processes as action-oriented and sensorimotor grounded. Pragmatic turn benefits from the ideas of pragmatism in philosophy, and all cognitive processes are considered as the forms of practice in changing weights. By starting from these considerations relevant to approaches of post-cognitivism and pragmatic turn, (inter-)actions of agent(s) with their ecology/given environment is based on embodied characteristics (i.e., post-cognitivism) and forms the cognitive processes (i.e. pragmatic turn). Therefore, the context (body, ecology) and action have become very important in the last decades in understanding/conceptualising the cognitive processes. In terms of this consideration, affordance -which was formulated by James Gibson-, as the perceived potentials for action within the given environment become an important term to understand contextuality and action-oriented aspects of cognition for neuropsychologists. Additionally, architects and practitioners of different design branches have had an ongoing interest in reciprocal influential relationships between design and user(s) since ancient times, and affordance offers new insights for creating new formulations to comprehend and manipulate these relationships through design. Thus, affordance has also become an essential term for architects and designers since its formulation. Thus, the revolutions within neurophilosophy and cognitive science (i.e., context and action revolutions) and formulation of affordance-relevant models to cope with dichotomies between organism and environment have significantly impacted the newly emerging discipline of architectural neuroscience. On account of these considerations, the ecological dimension of the agency is studied within these themes. Due to experimenting facilities, the embodied perception was chosen as one of the immediate revealing effects within embodied cognition account. Thus, affordance and embodied perception are chosen as the two central themes of this thesis in terms of the ecology of the agency.

Thanks to the rise of post-cognitivism in the philosophical domain and pragmatic turn in cognitive science in addition to technical advancements relevant to neurophysiology, new theories relevant to action and perception emerged in cognitive neuroscience. The theories expanded our understanding of the anatomical background and physiological characteristics and functional integration relevant to perception and action couplings during (inter-) acting within the given environment. Some conceptual expansions can be considered as 1) requisite of consciousness for perception and 2) criticism of visually-oriented conceptualisations of perception, 3) considerations of characteristics of perception-action relationships (e.g., domain specificity, inter-dependency, hierarchical and temporal order) and 4) modes of action (e.g., execution, imagery, observation, referential, verbalisation). By benefitting from perception-action theorisations within cognitive neuroscience, embodied affordance perception has been addressed to the thesis

experiments. Implicit motor imagery mode of action related neurophysiological and cognitive aspects was examined to avoid motor-related artefacts during action execution.

Implicit motor imagery can be considered as the existence of cognitive and neurophysiological aspects relevant to (inter-) action as a result of imagining the action, although there is no execution of the action. In the experiments of this thesis, implicit motor imagery was measured via examining the characteristics of mu rhythm (e.g., level of suppression, laterality, latency) as one of the brain rhythms emerging on the motor cortex during different modes of action. Cognitive aspects relevant to motor imagery were examined in the thesis's behavioural experiment through reaction times. In order to understand cross-modal interactions between visual and motor-related processes, motoric influences on neurophysiological aspects associated with visual feature detection (i.e., P100 ERP) and characteristics of laterality (contra-/ipsi-) between topographies relevant to visual and motor processing was examined. Cross-modality can be considered as one of the immediate effects of neuroplasticity and can provide functional unification of perception and action within phenomenological unity of experience. Embodied perception within the context of affordance has been addressed to the thesis experiments in the mode of implicit motor imagery to avoid motor-related artefacts during action execution. Implicit motor imagery mode of (inter-)actions within the context of embodied characteristics of affordance perception has widely been studied via neurophysiological indicators of motor cortex activity (i.e., ERD of mu oscillation).

1.2 RESEARCH BACKGROUND AND SCOPE

One of the main themes of this thesis, the agency, has widely been studied in various disciplines with different contextual emphasis. In this thesis, the agency is mainly issued with its ecological and architectural contexts, and neurophysiological investigations relevant to the contexts of the agency were examined via neuropsychology and cognitive neuroscience tools. In this contextual understanding agency includes three elements as agent(s), (inter-)action and environment (i.e., architectural). This agent-environment framework can be considered as ecology for the sciences and philosophical movements which emphasise kinaesthetic features of agency. In this regard, ecological context is mainly used by such sciences and disciplines as biological sciences, cognitive science, philosophy of mind, philosophy of biology, computer science and robotics, human-computer interactions. However, the context of agent-framework is considered with socio-cultural emphasis within such disciplines as sociology, anthropology, archaeology, economy and organisational studies, ethics, management science. The agency has been mainly considered in these disciplines with its conceptual features and mereological & axiological considerations. Furthermore, characteristics of each element of the agent-environment framework (i.e., agent,

(inter-)action and environment), contextual characteristics, and emergent characters within the chosen context have been diversified in line with the specific research interests of each discipline. This part will mainly examine conceptualisations of disciplines that pay attention to the kinaesthetic aspects of the agency.

For instance, agent as the first element of the agent-environment framework has widely been considered with phenomenological conceptualisations in the philosophy of mind and neurophilosophy (also neurophenomenology), emphasising the inner mental and experiential processes of agent/organism. In these contextual discussions, some of the central concepts defining the horizon of the discussions can be listed as; intentionality, body schema, body image, the experience of agency, free will, embodied cognition. In terms of philosophy of biology, biology, cognitive science, characteristics of bio-cognitive structural unity and its elements (e.g., dynamism, continuity, orders) are mainly issued. In this regard, some remarkable concepts can be listed as; autonomy, self-organisation, singularity, plasticity (e.g., neuroplasticity, cognitive plasticity, phenotypic plasticity), autopoiesis, emergence, order (e.g., hierarchical order such as top-down, bottom-up), asymmetry (e.g., behavioural asymmetry such as handedness, hemispheric asymmetry), trade-offs (e.g., evolutionary, cognitive). Some of the discussions on these concepts relevant to the agency have also been addressed to computer science, robotics and human-computer interaction disciplines, either their practical area (implementing) or philosophical discussions within these disciplines.

The second concept of the agent-environment framework is (inter-) action. However, (inter-)action can be considered with different modes such as action execution, imagery, observation, their referential versions and in different modalities (e.g., verbalisation, reading, hearing). Additionally, intervention and mediations between agent and environment can also be thought independently from the action. Discussions on mediations or intervention between agent and environment mainly concentrate on characteristics of the action itself (e.g., ontology, dynamisms, elements, order, system), characteristics of inter-action/ mediation or intervention and its emergent properties, contextual considerations on inter-action/ mediation or intervention. In terms of philosophy of mind and cognitive science, some of the remarkable concepts can be listed as; enaction, constitutive relatedness, sense-making, (dis-) embodiment, parity and complementary (e.g., isomorphic functionalism), varieties of reflexive consciousness (e.g., proprioceptive, hylonoetic and tectonic awareness). These concepts are mainly used by enactive, embodied and extended accounts within post-cognitivism to expand conceptual horizon by extending inter-action, intervention and mediation by emphasising anti-representational, contextual (body, environment) and sensorimotor grounded considerations. In addition to

ecological account (kinaesthetic domain), in terms of socio-cultural account (contextual domain), some of the concepts which are used in social sciences and philosophies such as sociology, anthropology, archaeology, political philosophy can be listed as entanglement, imbrication, engagement, constitutive intertwining, mediation, assemblage, context-sensitivity and pertinence. These concepts expand the horizon of discussions on the socio-material context of interactions between things, agent(s) and environment and information flows.

The third element of the agent-environment framework is the environment; however, the environment should be thought of as a given and perceived environment. Additionally, things, objects, tools, architectural and designed elements, and natural elements within the given and perceived environment should also be considered. Discussions on a given perceived environment and its elements mainly concentrate on conceptualisations relevant to emergent characteristics relevant to the perception of the environment, perception of environment-related characteristics, the function of environment for the agency in terms of cognitive processes. Environmental enrichment, cognitive congeniality, cognitive offloading, free-energy minimisation, cognitive scaffolding, cognitive marking, material anchor for cognition can be considered some of the concepts relevant to the function of the environment for the agency from a cognitive perspective. Affordance (e.g., ontology, normativity), sense of presence, metaphysics of presence, pre-reflectivity, distributed cognition, embedded cognition can be thought some terms relevant to emergent characteristics relevant to the perception of the environment. Regarding the perception of environment-related characteristics, some of the concepts of theoretical horizons can be listed as; present-at-hand, ready-to-hand, tool-being, skeuomorphism, (bio-/material-) semiotic properties. However, these concepts and relevant discussions will not be explained within the context of the thesis.

In addition to defining conceptual horizon relevant to elements of the agent-environment framework and emergent characters within this framework to some degree, how agency obtained different contexts within different disciplines will be helpful to examine. In this regard, in philosophy, the agency is mainly issued with such theoretical discussions as; content of action, the constitutive role of agency and ontology of becoming agent, ontological and axiological problematics relevant to exercise of agency and epistemological problematics of sense of agency, agency in terms of causation and determinism. In cognitive science and psychology, the agency has been examined in terms of sense and sensation of agency, characteristics of cognitive and neurophysiological mechanisms beyond the exercise of agency and its components in different modes, in different modalities, in different forms (e.g., imagery, observation, control, and ownership), the ontogeny of the agency. In sociology, the agency has been issued in terms of

characteristics and types/forms of the sociality of agent and social agency, characteristics of the constitutive and influential role of agents on social structure (e.g., hierarchical order, asymmetry of reciprocal relationships, in-/inter-/dependency of domains). The agency obtained a similar contextual understanding of anthropology and archaeology with its sociological considerations. Additionally, the agency has mainly been issued in anthropology and archaeology in terms of characteristics of cultural agency, symbolic and semiotic relevance of agency, characteristics of culture-agent interactions, (cognitive, symbolic, behavioural) traces of agency within archaeological material. In linguistics, sensorimotor accounts relevant to linguistics, especially within cognitive linguistics (e.g., syntax, semantics, grammar, image schemas), pay attention to the exercise of agency and its constitutive role on language/linguistic formation.

In human factors, human-computer interaction and design science disciplines, agency has mainly been issued in terms of characteristics and mechanisms of execution of agency and their potential designerly ways of implementation. In computer science (especially artificial intelligence studies) and robotics, the agency has been examined in terms of characteristics, dynamics and mechanisms of execution of agency, autonomy, singularity and self-organisation of agent to generate computational models, which has also been used for robotic implementations (for singularity). In biology, the agency has been issued with various dimensions such as within eco-system or ecological context, with its evolutionary dimension, characteristics and functions of bio-dynamics of execution of agency (e.g., survival benefits, organisational closure). Although the significant value of agency in different disciplines is clear, details of considerations on agency within each mentioned discipline will not be examined within the context of this thesis. In this thesis, the agency will be issued in cognitive and neurophysiological aspects and within architectural and ecological contexts.

Neurophysiological and cognitive aspects of the agency have been examined through four experiments. In these experiments, the agency has been examined in terms of embodied account and mental/motor imagery within the context of cross-modal interactions between visual and motor relevant domains. Due to immediate measurement of participants' neurophysiological and cognitive processes, embodied perception relevant to the architectural agency of participants and due to technical limits of experimental setup, mental/motor imagery mode of execution of agency was measured. In order to understand the visual and motor dynamics of mental execution of agency, cross-modal functional interactions between these two domains have been investigated through both neurophysiological and behavioural experiments. In this context, embodied perception can be considered reflection/ influence of bodily and embodied characteristics (e.g., body image, body schema, ownership of body and self-localisation, self-

assessments relevant to control of the body or namely sense of agency, proprioceptive and kinaesthetic sensations relevant to agency) on perceptual processes. Additionally, motor imagery or mental agency can also be considered the emergence of neurophysiological and cognitive features relevant to the agency due to just imagining the agency without direct motor execution of the agency. In order to understand neurophysiological and cognitive mechanisms relevant to the effects of visually perceived architectural affordances on embodied perception within the context of mental agency/motor imagery, cross-modality between visual and motor perception should be understood.

Cross-modality can be thought of as one of the immediate emerging aspects of neuroplasticity which can facilitate multi-sensory integration of two or more sensory modalities within phenomenal unity of experience through some shared or substituting functional mechanisms. Aspects of neuroplasticity such as cross-modality are beneficial to cope with the complexity of architectural affordance and environment. Neuroplasticity can be categorised in various ways in line with different parameters such as temporal order (e.g., developmental/ontogenetic, evolutionary/phylogenetic, instant/immediate), anatomy vs physiology (i.e., structural and functional), scale (e.g., cellular, organ-level) and so on. However, mainly anatomy-physiology distinction based categorisation is used. In this regard, functional neuroplasticity refers to the plasticity of neurons' physiological adaptations, which serves functional modulation, regulation, maintenance, and organisation within the phenomenal unity of experience in different temporal scales. Moreover, structural neuroplasticity is associated with the plasticity of anatomical adaptation, especially connectivity between/among which serves adaptation, maintenance, regulation and organisation to fulfil the function or cope with lesions. The structural formations that contribute to the neural plasticity can be listed as the ‘neurogenesis’, ‘neuroglia genesis’, ‘neurotrophins’, ‘modification of neural circuits and structural connectivity’, ‘structural changes in dendritic and axonal anatomy’, ‘increase in white and grey matter integrity’, ‘changes in brain blood flow (neurovascular coupling)’, ‘activations and inhibitions of bio-chemical materials like hormones and some other protein structures’, ‘changes in membrane excitability and non-synaptic plasticity’. The functional activations that provide neural plasticity are the multisensory integrations, frequency couplings and functional connectivity, the activations and inhibitions in electrophysiological activities. In this regard, cross-modality between visual and embodied perception can be regarded as the immediate product of functional neuroplasticity.

1.3 RESEARCH AIMS & OBJECTIVES, QUESTIONS & HYPOTHESES, VALUE & ORIGINALITY

There are three motivation points beyond this thesis. The first one is to understand how architectural design features influence neurophysiological and cognitive aspects of visual

perception of human(s). The second one is to understand how perceived architectural affordances influence neurophysiological and cognitive aspects of embodied perception and action relevant characteristics (especially implicit motor imagery mode of action/mental agency). The third motivation is to understand whether there is cross-modal interaction between visual perception and embodied perception during the perception of architectural affordances. In this context, this thesis aims to draw attention to the significant value of understanding agency in the architectural realm comprehensively (especially within cross-modality between visual and embodied perception context) through the tools of neurophysiological and cognitive measurements. By starting from motivations and aim of the thesis, cross-modal interactions between embodied perception during implicit motor imagery/mental agency and visual perception of architectural affordances have been examined through neurophysiological (i.e., ERD of mu oscillation, P100 ERP) and one cognitive marker (i.e., response times). In these investigations within each experiment, research questions are mainly based on two types of considerations (i.e., 1) laterality, 2) amplitude and latency). The first one is characteristics of lateralisation (i.e., contra-laterality vs ipsi-laterality) of cognitive or neurophysiological activity interest of the designed experiment with laterality features of presented stimuli (i.e., location of handle or required hand operation to use) within the same experiment. The second consideration is diversification of amplitude of neurophysiological activity of interest (i.e., ERD of mu oscillation, P100 ERP Waveform Component) or latency of cognitive aspects of interest (i.e., response time) in line with handle type categories of presented stimuli. Accordingly, with these considerations, research questions, hypotheses and predictions have been formed for each experiment.

In this regard, in the first experiment, the influence of visual perception of images of doors with different types of right or left handles on embodied perception during implicit motor imagery/mental agency was examined in terms of characteristics of laterality and amplitude of neurophysiological activity of interests (i.e., ERD of mu oscillation). Furthermore, motoric influences on early phases of visual processing relevant to features of perceived stimuli were also examined in terms of the same considerations (i.e., characteristics of laterality and amplitude). In the second experiment, the effects of observation of action state relevant to perceived architectural affordance in the images of doors with similar aspects on embodied perception during implicit motor imagery/mental agency were examined in the same considerations. In addition to architectural affordance, in the third experiment (pilot experiment), cross-modality between the effects of visual perception of affordance relevant to images of cups/mugs with different handles (e.g., typical, atypical, left, right) on embodied perception was examined in

terms of same characteristics. The fourth experiment, differently from previous three neurophysiological experiments, revealed effects of cross-modality in the form of cognitive aspects relevant to architectural affordance was examined through participants' reaction times in terms of characteristics of laterality and latency. In this experiment, the same stimuli of the first experiment as images of doors with different types of right or left handles were used to understand cross-modality between visual and embodied/motor domains.

In this context, this thesis makes three different original contributions to three different literature as 1) architectural neuroscience literature, 2) architectural theory literature relevant to the agency within the ecological context, and 3) neuropsychology literature relevant to the agency within an ecological context. In terms of architectural neuroscience, limited research satisfies experiment design standards (e.g., control conditions, counterbalancing, statistical comparison concern). This thesis also considers satisfying scientific rigorosity in terms of experiment design standards within neuropsychology. Thus, this thesis provides some suggestions for forming literature regarding scientific concern and reliability. In terms of agency in architectural theory, this thesis is one of the early attempts to examine the agency (or similar formulated concepts and relevant conceptual discussions) within ecological and architectural context through neurophysiological and cognitive aspects. These aspects were examined in terms of the cross-modal interaction between visual and embodied perception relevant to architectural affordances. This aspect was also one of the first attempts in the current literature. In terms of literature on the neurophysiological and cognitive aspects of agency, this thesis also investigates architectural agency differently from previous literature dealing with agency relevant to hand-scale daily objects instead of agency relevant to body-scale architectural elements. In addition to original contributions to listed three established works of literature through its experiments, this thesis also provides vigorous theoretical discussions on the architectural agency (especially with the emphasis on embodied account, pragmatic turn within post-cognitivism and affordance in ecological psychology). Theoretical discussions and experimental work also seek the potential for further trans-disciplinary studies based on evolutionary, cognitive and computational perspectives about the issue. These experiments and discussions on potentials relevant to further trans-disciplinary studies can deepen and diversify our comprehension about reciprocal relationships and influence between architectural design and perception-action relationships relevant to the architectural agency.

1.4 RESEARCH METHODOLOGY

In the experiments of this thesis, EEG and task-based performance measurement were used to investigate neurophysiological and cognitive aspects of cross-modal interactions between

embodied perception during implicit motor imagery/mental agency and visual perception of (architectural) affordances. EEG is one of the neurophysiological measurement techniques which are applied without invasion. In the experiments of this thesis, 64-channel extended 10-20 system EEG was used to measure the neurophysiological activity of interest of the experiments (i.e., ERD of mu oscillation, P100 ERP Waveform Component). Additionally, six external electrodes were used to record Electrooculography (EOG). In neurophysiological analysis, after data acquisition through EEG, acquired data was segmented into trials and was filtered from some frequency band ranges in line with defined bandpass limits. Additionally, acquired data by each channel were re-referenced to the average amplitude of acquired data by all-channel in each time point and corrected to the control signal of which time window was defined within the pre-stimuli period. After pre-processing, data were cleaned from artefacts (i.e., physiological artefacts, non-physiological artefacts) through visual inspection scripts of FieldTrip routines (Oostenveld et al., 2011) and independent component analysis. After completing data pre-processing and cleaning, two types of data analysis were performed for examining neurophysiological activity at the individual level (participant-specific). All group-level analyses were performed through IBM SPSS Statistical Software.

In Experiment 1, both Time-Lock/Time Domain Analysis for P100 ERP Waveform Component and Time-Frequency Analysis for ERD of mu oscillation were performed. In Time-Lock Analysis, the average amplitude of time-locked ERPs was computed for posterior P100 ERP Waveform, which emerges around 90 to 120 ms after stimuli onset. Additionally, in Time-Frequency Analysis, the average amplitude of non-phase locked (not a necessity) for central mu oscillations relative to chosen baseline were computed. Thanks to the good temporal resolution of EEG, Time-Lock/Time-Domain Analysis for P100 ERP Waveform and Time-Frequency Analysis for ERD of mu oscillation were appropriately performed. In other experiments investigating neurophysiological activity, as in Experiment 2 and Experiment 3, only Time-Frequency Analysis for ERD of mu oscillation was performed. In order to understand cross-modal interactions between visual and embodied perception (in the context of implicit motor imagery/mental agency), hemispheric cross-laterality between the topographic definition of posterior (parieto-occipital) alpha oscillation and central mu oscillation was inspected through topographic maps. Additionally, changing amplitudes in line with the door category (according to handle type and laterality) for P100 ERP amplitude was also inspected to understand motoric influences on early phases of visual feature processing which can be considered as evidence for cross-modality between visual and embodied perception.

As well as neurophysiological investigations, in the behavioural experiment, influences of embodied perception (implicit motor imagery/mental agency context) relevant to visually perceived architectural affordances on task decisions influencing performance were examined statistically in terms of latency of the reaction times. In a behavioural experiment, the reflection of spatial account of stimulus-response compatibility effect (e.g., Simon Effect) vs motor program-related object-based correspondent effect (e.g., Affordance Effect) on the latency of response time can be considered with the context of cross-modality. Repeated measures design was used in all experiments, and oddball task paradigm and event-based experiment design were preferred. In all of the experiments of the thesis, tests within-subjects design and only in a behavioural experiment an additional test between-subjects design was used.

1.5 THESIS STRUCTURE AND ORGANISATION

This thesis includes eight chapters in addition to the abstract of the thesis. These are; 1) Introduction, 2) Literature Review, 3) Methodology, 4-7) Four Experiment Chapters (Experiment 1, Experiment 2, Experiment 3, Experiment 4) and the last one is 8) General Discussion. Literature Review can be considered the combination of three different pieces of literature as; 1) agency in architectural theory and design (with the emphasis on embodied account and affordance), 2) architectural neuroscience as the new emerging inter-disciplinary area, and 3) agency in neuropsychology literature (with the emphasis on embodied account and affordance). These literature reviews formed in line with original contributions of the literature, which combine agency (with emphasis on architectural agency), architectural theory and neurophysiology pair by pair. In these literature reviews, theoretical discussions and conceptualisations in architectural theory and artistic creations (e.g., installations) relevant to the architectural agency (with the emphasis on architectural affordance and embodied account of post-cognitivism) were examined. Additionally, discussions on potentials and possible contributions of architectural neuroscience, experiments relevant to immediate neurophysiological effects of architectural design process and creativity were also reviewed. Furthermore, experiments relevant to immediate neurophysiological effects of architectural characteristics, theoretical insights of long term effects of architectural neuroscience to improve the performance of architectural design were also revised. Moreover, theoretical discussions relevant to the agency within post-cognitivism (with the emphasis on embodied account and affordance), experiments on agency in neuropsychology, perception-action theories (unifying, dissociating, and ecological), and experiments on affordance in neuropsychology were also examined.

In the methodology chapter, a brief explanation of cellular level biophysics of the human central nervous system (e.g., action potentials, post-synaptic potentials), EEG physics (mechanisms

relevant to analog data acquisition through electrodes, data amplification and digitisation) were given. Data pre-processing steps (i.e., segmenting, filtering, re-referencing, correction to baseline) were introduced and Harmonic Analysis Methods (e.g., Fourier Transform, Wavelet Transform) for de-composing acquired signal into its frequency components were briefly explained. Additionally, some of the methods and problems relevant to signal de-composition processing for Time-Frequency Analysis (e.g., Windowing, Multi-tapering, spectral leak) were presented. Characteristics of EEG artefacts, artefact rejection methods, blind source separation techniques, Independent Component Analysis were briefly explained. Furthermore, Time-Lock/Time-Domain Analysis and Time-Frequency Analysis were introduced and ERP Waveform Components and Brain Rhythms were shortly presented. In the end, statistical methods used for group-level analysis were presented in a nutshell.

In the experiment chapters, literature review of experiments which discuss problematics of experimenting architectural affordance in general and in thesis-specific levels and aspects of each experiment (e.g., design features of each experiment, predictions) were briefly introduced. Additionally, the methodology of each experiment (e.g., task, procedure, and preparation) and data acquisition were presented, and off-line signal processing steps and data cleaning processes were introduced. And then, each experiment's individual-level data analysis processes are relevant to Time-Lock/Time-Domain Analysis (for only Experiment 1), relevant to Time-Frequency Analysis (Experiment 1, Experiment 2 and Experiment 3), relevant to response time analysis (Experiment 4) were briefly explained. After all, the completed group-level analysis results were presented, and the results were discussed in each experiment's discussion parts.

The general discussion chapter emphasised the value of trans-disciplinary research for better architectural design. Moreover, far and close conceptual horizons relevant to the thesis, philosophical problematics, technical and practical limits, strengths and weaknesses and distinguishing characteristics of the thesis were defined briefly. Furthermore, the results of each experiment were discussed, and alternative ways of improving the results of experiments and their potential future implementations were mentioned.

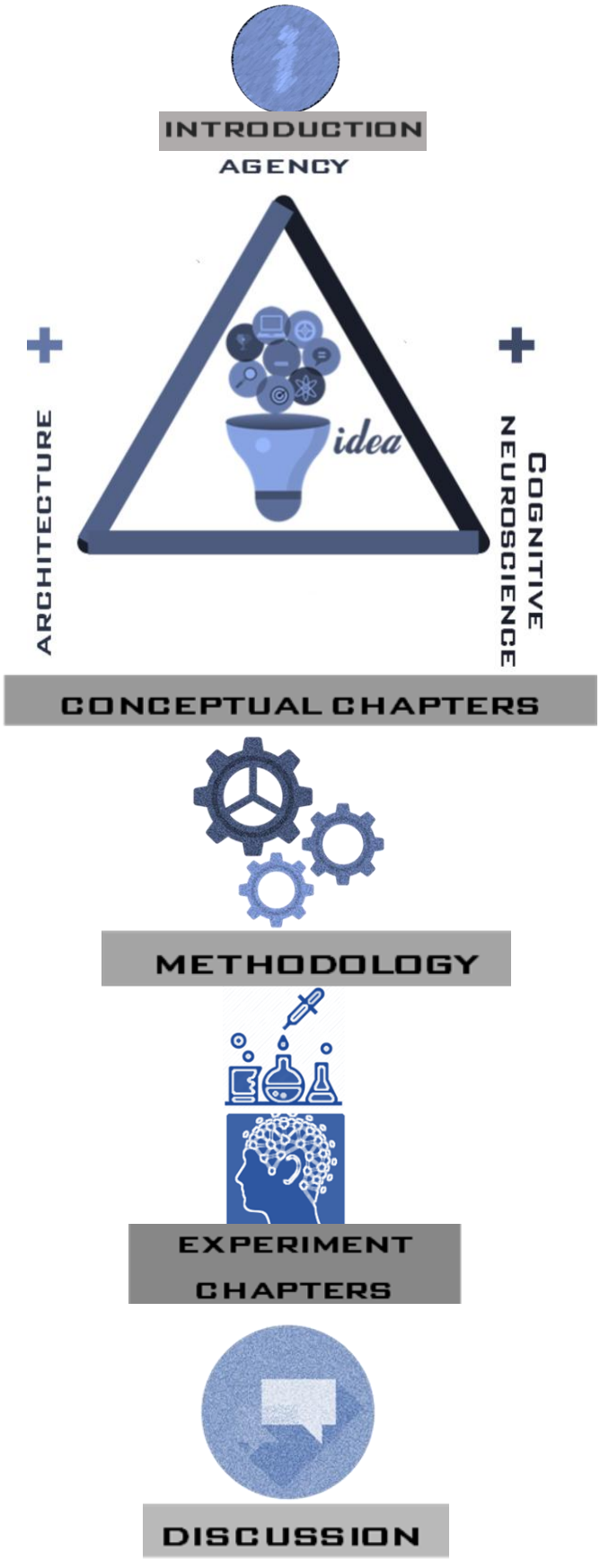

Figure-1.1: The thesis structure

CHAPTER 2: THE LITERATURE REVIEW

2.1 THE AGENCY IN ARCHITECTURAL THEORY AND DESIGN

Brain activity is the primary o search for the relation between the world and the body. The biological body is the base of cognitive processing, however, except the biological structure of the body (bio-external factors), which may function the same work as parts of the brain's activities. Embodied cognition is shaped in a process-based, both physical and cultural systems. The environment's stimuli, the reaction of the body, and the interactions in the brain occur in the entities of the uncertainty: the body, environmental situation and perception (Clark, 2010; Clark, 2015).

The architectural 'agency' has been discussed in the literature with its ecological and metaphysical dimension and ideological, moral and political context. Here, the 'agency' was addressed by focussing on the theme of embodiment/embodied cognition and affordance. We could say the agency has been approached in two ways. One kind of study looked at the agency on a big scale. They problematized the responsibilities of the architects in terms of identity construction, ideological positioning, and the aestheticization of the urban environment. The second group of studies paid attention to the closer perspective of the individual scale. They examined the agency's ecological dimensions based on the agent, organism and environment framework. This group problematized the relationships between these three elements of agency.

How buildings influence their users has been an exciting topic for architects since the ancient ages. Scientific examinations in the modern sense have been achieved since the late 19th century thanks to the foundation of experimental psychology. The advancements in technology have improved the understanding of the built environment and design relationship (Doucet and Cupers, 2014). Thanks to architectural phenomenology, existentialism, hermeneutics, and ecological psychology, user experience became an interesting issue among architects, especially after the 1960s (Awan et al., 2011). The 1960s' user-centeredness -due to the ideas of post-modernity within architectural theory- provides the basis for architectural liberalism instead of modernist elitism. In the 1980s and 1990s, the movements paved the way for manipulating cognitive and computer science limits and our interaction modes within architecture. In the 2000s and 2010s, the effects of computer and cognitive sciences profoundly influenced the architecture's realm (Paterson, 2011). Especially, Dourish's 'embodied interaction' topic is crucial as it focussed on the experience between humans and computation. For this approach, computer interaction is guiding us. The computational capacities can present the augmented versions of the physical objects; this point is critical. The model supports that our experiences as embodied

actors may contact the world through augmented realities (Dourish, 2001). We see the architects have new opportunities to design new user interfaces by benefiting from the embodiment, embodied cognition and embodied perception. The human-computer interaction, human factors, robotics and industrial design expand the horizons of generating different agency-based models. So, the agency was examined by different approaches to problematize the embodiment and affordance based on human creativity.

The agency within architectural context was examined mainly by benefitting from the theories of post-cognitivism. Post-cognitivism pays attention to external elements such as body, action, tools or objects within the environment. Another notion that provides architects with a theoretical ground to discuss the 'agency' is the 'affordance'. This term was coined by one of the pioneers of ecological psychology, James Gibson (Gibson, 1977). Gibson formed the term 'affordance' by benefitting from the ideas of the 'Pragmatism's activation of the agent as the perceiver of the environment', 'Behaviourism's discussions about the influential roles of elements of environment on the emergence of behaviour', 'Gestaltists' formulizations of the mechanisms of perception' and 'M. Ponty's philosophical investigations about bodily perception' (Gibson, 1966; 1977). The 'affordances' provide us with the action abilities in the environment (Bruineberg and Rietveld, 2014).

Although affordance has been formulated several decades ago and has been studied through several experiments within the context of affordance of daily hand-scale objects, architectural affordance has not widely been understood. In this context, there are some of the experiments examining architectural affordance without so much concern about investigating 'architecture-specific' characteristics where door handles were used. Early investigations on architectural affordance began through behavioural experiments. In this regard, Tipper et al. (2006), examined effects of attention to properties of the door handles (i.e., shape/form and colour) and also action state (i.e., active vs. passive object) on affordance effect. They found attention to form/shape related qualities and observing active action state qualities have facilitating effects on affordance effect (Tipper et al., 2006). Loach et al. (2008) extended the research of Tipper et al. (2006) by questioning the effect of congruency of orientation of pair of door handles (within a sequence) in line with motor program (i.e., grasping the affordance) in addition to previous investigations. They found facilitating effect of congruency on affordance effect (Loach et al., 2008) (for further discussions, see Chapter 4.1.1).

Cho and Proctor (2011) extended the research of Tipper et al. (2006) by questioning the effect of laterality of presentation of door handles (base-centred vs. handle-centred) to dissociate

affordance effect from spatial account of stimulus-response compatibility effect. They found facilitating effect of lateralization of door handles on affordance effect due to ready-to-hand condition of presented door handles (Cho and Proctor, 2011). Cho and Proctor (2013) extended previous research by additional parameters as properties of the object (i.e., shape/form, colour, orientation) and action state (i.e., active vs. passive object). They found spatial account of stimulus-response compatibility effect (e.g., Simon Effect) is influenced by visual features, visual stimulation and passive action state of the object. Conversely, affordance effect is influenced by form, orientation and active action state of the object (Cho and Proctor, 2013). Lien et al. (2014) replicated Cho and Proctor (2011)'s experiment design with two parameters as laterality of presentation (handle vs. base-centred) and action state of the object (i.e., active vs. passive) and measured neurophysiological activity (i.e. P1 and N1 ERP) in addition to behavioural measurements. Although they could not find any significant effect in ERP studies, they found similar results (e.g., facilitating effect of active action on affordance effect, facilitating effect of colour judgement task on Simon effect) in their behavioural experiments (Lien et al., 2014) (for further discussions, see Chapter 4.1.1).

One exciting approach in manipulating the architectural agency was made by Rietveld Architecture-Art-Affordances Foundation (RAAAF) in collaboration with visual artist Barbara Visser in 2014. In the project entitled 'The End of Sitting', they manipulated the act of sitting via the design of 'sitting furniture' such as the chair, armchair, sofa (Withagen and Caljouw, 2016). In the paper of 2016, Rietveld mentioned the possibilities and stimulations of the affordances in the working environment, while the participants were in the standing position. Through the help of some material structure, the work focussed on the standing affordances (Rietveld, 2016). The project allowed users to explore different boundaries between standing and sitting positions to seek different potentials of working environments. The 'landscape of affordances' concept which was formulated by Eric Rietveld and Julian Kiversteins was also essential to understand the term 'affordance'. Their idea mentions the role of bodily emplacement in the environment experiencing capacity. This concept reveals the significant role of action potential in architectural space—the importance of the pragmatic action-oriented encounters with our environment (Rietveld and Kiverstein, 2014). The ecological-enactive side of the 'affordance' was also discussed (Rietveld et al., 2018). The concepts that frame the body schema establish an individual's actions with the surrounding objects and others.

By the way, some studies focused on examining architectural agency via tools of cognitive neuroscience. For instance, in 2016, Andrea Jelić and her colleagues examined the notion of affordance related to the perceived action-potential of designed artefacts inviting users'

behaviours. The studies stressed the reciprocal interaction between architecture and humans following the impacts of their reciprocal embodiments. The 'affordance' needs to become a significant issue in understanding the relationships between architectural space's tectonic characteristics and human embodiment. The affordance has rich potentialities of interaction that emerge in the agent's perception (Jelić et al., 2016).

The neurophysiological effects of three-dimensional interior forms and architectural features on the users' brain activity were examined in the study of Banaei et al. in 2017. The study's method was based on mobile brain/body imaging (MoBI) and electroencephalogram (EEG). The EEG of the participants was recorded while they walked through different interior architectural spaces in virtual reality (VR). The findings showed a substantial effect of interior architectural spaces' curvature shapes on brain activity (Banaei et al., 2017).

In 2015, Mark Johnson published a book chapter entitled *'The Embodied Meaning of Architecture'* published in the book entitled '*Mind in Architecture: Neuroscience, Embodiment, and the Future of Design'* edited by Sarah Robinson and Juhani Pallasmaa dealing with reciprocal relationships between architectural space and human embodiment. Johnson asserted that architectural places are created by bodily performances, interests, and goals essential for survival. He defined the 'affordance' as the way of creating the 'meaning'. The embodiment of the users affords the reciprocal interaction between the brain and architectural space. So, we can generate the meaning according to the different cognitive activities such as perceptions, emotions, thoughts, and actions. The meaning emerges from the embodied transactions with the physical surrounding, interpersonal relations, and cultural practices. He claimed that the meaning of objects or spaces is related to the action potential. So, it includes social functions and cultural values and practices surrounding them (Johnson, 2015). In Johnson's concept, 'affordance' also relates to exploring mirror neurons, neural and cognitive interaction with objects/spaces. The mirror neurons let the affordance be shaped by our body schemas and affected by the embodiment of other peoples. According to this approach, meaning is not just abstract mental symbols but also a dynamic, constructive, and embodied cognitive process. The affordance involves neural stimulation of sensory, motor, and affective processes that we associate with things or events. Johnson's concept says the architectural agency provides us with material and cultural affordances meaningful for our survival (Johnson, 2015).

In the 2016 ANFA Conference, the architect Joshua Broadway and his colleagues published a paper entitled '*The Real Meaning of Architecture: or How to Make Architecture Mean Something*' dealing with the meaning in architecture in terms of neuroscience. The study focussed on the concepts of atmospheric sense, embodiment and affordance. IT investigated the relationships

between neural mechanisms. The study discussed the empathy and embodied simulation connecting people, objects or spatial entities. It also mentioned the brain waves are active in different cognitive activities and delta waves have the lowest frequency in perception related to bodily projection as a type of empathy. The study stressed that the architectural affordance is meaningful with the context. It is extended to the cultural and social functions via embodied simulations. The architectural affordances include personal and individualistic past experiential elements (Broadway et al., 2016).

In 2017, Michael F. Bonner and Russell A. Epstein done a study entitled 'Coding of navigational affordances in the human visual system'. The study method was based on fMRI. The aim was to identify representations of navigational affordances in the human visual system via two experiments. The regions of interest were the Occipital Place Area (OPA), Parahippocampal Place Area (PPA), Retro-Splenial Complex (RSC) and Early Visual Cortex (EVC). The data analysis was based on the Pearson Distance (one minus the correlation co-efficient), Spearman Correlations and Representational Dissimilarity Matrices, Whole-Brain Searchlight Analysis. In experiment 1, the stimuli were artificially rendered 270 pieces 3D models of a variety of surface textures, and the number of the visible exits were varied eight stimulus conditions, some of the stimuli have got paintings at the location of exits. The participant profile was twelve subjects (8 females, 24.3 y, SD = 2.9). The Siemens 3.0 T Trio scanner and 32-channel head coil were used in the exp 1. In terms of the brain scanning session, the images appeared on the screen for 2 s, 1-s inter-stimulus interval was made, and a colour-detection task was performed. In exp 1, the first finding was that coding navigational affordances activated OPA more than other ROIs, null activation in RSC. OPA was the only ROI to exhibit significant effects for the coding of navigational affordances across all manipulations of textures and paintings and no reliable evidence for navigational-affordance coding in the PPA (Bonner and Epstein, 2017).

In their second experiment, the stimuli have 50 colour photographs depicting indoor environments viewed at eye level with clear navigational paths passing through the bottom of the image. The participant profile was sixteen subjects (8 female, mean age 29.4 y, SD = 4.8). For the data acquisition, Siemens 3.0 T Prisma scanner and 64-channel head coil were used. In terms of the brain scanning session, the images appeared on the screen for 1,5 s, 2,5-s inter-stimulus interval was made, and a category-detection task was performed. In exp 2, a substantial effect was found for the coding of navigational affordances in the OPA compared with other ROIs and a weaker but significant effect in the PPA, null activation in RSC. The findings of exp 1 and 2 say OPA extracts spatial features from visual scenes that can be used to identify the navigational affordances of the local space and that these representations could be used to map out potential

paths in local space. PPA was sensitive to the conjunction of textural and structural scene features (PPA may perform a combinatorial analysis of the multiple scenes features that identify a place or landmark). The overall result says OPA has a causal role in perceiving spatial relationships between objects and environmental boundaries, but not between objects and other objects. Moreover, the navigational affordances are encoded automatically even when they are not directly task-relevant. We learnt from this study that spatial navigation is associated with perceived affordance qualities of the local environment. The navigational affordances automatically are encoded by sensorimotor mechanisms of mobile organisms via scene perception. There is a link between architectural affordance and spatial navigation. The study claimed that the human visual system routinely extracts visuospatial information (Bonner and Epstein, 2017).

Djebbara's study analysed the neural dynamics through the spatial perception of the architectural settings in 2019. The method was based on the electroencephalogram (EEG) with combining a Mobile Brain/Body Imaging (MoBI) approach. The result said the spatial affordances of the architectural places have an impact on positive Motor Related Cortical Potentials' activity in prefrontal and parietal areas (Djebbara et al., 2019). Djebbara et al. (2021) also examined neurophysiological dynamics between architectural affordances and human behaviour. The bilateral parahippocampal areas and the sensorimotor dynamics are effectively processed for transition behaviour based architectural affordances while interacting with the architectural environments (door apertures) (Djebbara et al., 2021). The link between architectural affordances and emotional activity was analysed in a paper dated 2020. The participants were required to see a video in an AR (Augmented Reality) environment; during their experiences, an electroencephalogram (EEG) recorded their brain activity. The study revealed the augmented reality would be helpful to analyse the visual affordances in the built environment and their effects on emotions (Florescu and Nistor, 2020) (for further discussions, see Chapter 4.1.1).

The better design of everyday objects and improving the architectural elements' usability are related to the users' needs. So, the codes and insights of cognitive sciences are vital to approach agency-based design problems (Norman, 2002). The cognitive information would generate solutions on how the users experience the environment. We see the 'affordance' and 'embodiment/embodied cognition' provided us with a prolific basis in order to theorize 'how humans cope with architectural environments' and 'how mechanisms can be manipulated via design in the age of posthumanism and trans-architecture by benefitting from different disciplines of cognitive, evolutionary and computational sciences'. It can be easily seen that there are very few publications dealing with architectural affordance in terms of neuroscience. These

publications are based on theoretical debates. In these articles, affordance is related to the theme of 'body schema', 'embodiment', 'embodied simulation theory', 'embodied meaning', 'enactive approach', 'sensorimotor theory of perception', 'embodied metaphors', 'empathy', and 'sense of place'. We understand that the term 'affordance' is mainly related to our embodied interactions. The crucial role of the body-based meaning structures is related to the constructed environments. The architectural agency is based on the image schemas generated from experiencing the world.

Term	Issues
Affordance	• links between architectural affordance and human embodiment • sensorimotor theory of perception • enactive approach as a framework for understanding links between architectural affordance and embodiment • objective and living body, body image and schema, body-action potentials and affordance • action-perception cycles and affordance • sense of self through embodiment and architectural affordance, behaviours and affordance • embodied simulation theory and empathy, embodied mechanism in aesthetical experience and affordance • objects and affordances, readiness to hand and manipulability • sense of presence in virtual environments and affordance • built environments as a tool for survival and as a tool for meaning-making (affordance shapes these aspects) • architectural space as affording embodiment of their users • embodied transactions with physical environments, interpersonal relations, and cultural institutions and practices as the source of creating meaning • cognitive linguistics and relational, experiential and enactive characteristics of language • embodied simulation theory and language processing and affordance • affordance as the source of creating meaning and conceptualization process • forms of embodiment, mirror neurons and affordance • holistic experiential and affordance based embodied characteristics of architectural meaning • patterns of image schemas and affordance • neural mechanism beyond face recognition and recognition of building facades • architectural settings and objects as the source of empathy and embodied simulation thesis • atmospheric sense/poetic dimension and embodied metaphors embedded in architectural environments • potential role of neuroscience on researches on architectural affordance • architectural affordance and context and meaning

Table-2.1 The contents of the theoretical publications dealing with the theme of architectural agency, the 'affordance', in Neuroscience and Architecture

2.2 NEUROSCIENCE AND ARCHITECTURE: RISING NEW INTERDISCIPLINARY STUDIES

2.2.1 The Introduction

Even examining the influence of architectural settings on their users can be dated back to ancient times by architects; this issue had not even become a scientific subject before the 19th century. Some scientific studies were based on biology and physiology. They investigated the brain mechanisms beyond psychological manners or philosophical debates, mental processes, somatic and sympathetic nerves, speech, and hierarchical relationships among brain functions and so on (Andreas, 1972). Wilhelm Wundt founded experimental psychology in the 19th century.

After the foundation of experimental psychology by Wundt, different approaches emerged in this area in the 19th century. Behaviourism made one of the main contributions investigating the role of architectural settings on human psychology. Unlike functionalism based on pragmatism and evolution theory assessing the human mind as the latest evolved version of previous animal minds in the Anglo-Saxon World, Behaviourism escaped metaphysical manipulations. Their notions attacked Structuralisms' introspection approach due to its subjectivity and abstract terms such as mind, cognition, intelligence, mentality and assessed behaviours as the manifestation of mental activity. So, the approach tried to generate new empirical methods (McBurney, 1990). Founder of Behaviourism, John B. Watson, claimed psychological issues could be examined without the abstract and subjective methods. He emphasised the importance of observations and experiments. Watson defined the psychology's aim to analyse phenomenological aspects such as behaviours (Watson, 2015). However, Behaviourism was examining the behaviours in a very objective way. The approach was highly analytical. Gestalt Psychologists criticised this idea. They claimed the holistic structure of reality could not analyse the particles (Ash, 2007). One of the main contributions related to architecture against objective and analytical aspects of behaviourism was made by Kurt Koffka and Kurt Lewin from Gestalt psychology. Kurt Koffka defined the environment as the physical and behavioural environment. He claimed behavioural environment occurs differently owing to changing attributions of perception from person to person (Koffka, 2013). Kurt Lewin applied the holistic approaches of Gestalt psychology to social psychology, put forward a new theory called 'field theory'. This theory examined social behaviours with their psychological environment in a holistic perspective (Lewin, 1976).

The physiology or biology-based studies were generally based on lesions on the brain. The primary purpose of these studies was to examine the role of these areas on specific functions by benefitting from these lesions. In the late 19th century, animals or dead humans were generally used in experiments to detect the mechanisms beyond human mental and behavioural abilities

(Mandler, 2007). This approach, called 'neuropsychology', has been different from the other brain-imagining techniques such as fMRI or EEG, examining the areas of the brain while the subject is active (Berlucchi, 2017). The primary neuropsychology method observed the patients' mental or behavioural activities (Gazzaniga, 1979). Then, the environment and behaviour relations began to be examined seriously. New psychology areas such as 'Environmental Psychology' and new interdisciplinary areas such as 'Environment-Behaviour Studies' emerged dramatically in the second half of the 20th century.

2.2.2 Architecture as the Container of the Behaviour and the rise of Environmental Behaviour Studies

Since the beginning of the 20th century, some works have begun to examine the role of the environment on mental and behavioural activity (Kardas, 2014). In the article entitled 'Environmental Psychology Overview', published in 2013, Raymond de Young explained the history of the field and its integration into architecture. He examined the effects of urban environments and elements such as crowd, traffic, hurry, and overstimulation on human psychology. He criticised the approaches of Behaviourists based on examining behaviours in artificial laboratory conditions and stressed the significance of examining human behaviours in extreme environmental conditions. In the first half of the 20th century, some research was based on examining the effects of the city and its elements on children, the young and other citizens. These studies generated new terms such as personal world, personal time, personal space, etc. Also, some sociologists, especially neo-Kantians, examined immigrants' psychological and sociological manners to the city and their adaptation process and settlement problems. New terms such as human ecology, city ecology was coined by them. The cities began to be defined as ecosystems. Thanks to the contributions, after the Second World War, the new movements focused on the environment, such as ecological movements and phenomenology environmental psychology literature. So, the terms were diversified, and new terms such as 'psychological ecology', 'ecological psychology', 'and ecological theory of perception 'or' environmental perception' become to be used by psychologists commonly. The research about the links between cognition instead of behaviour and environment began to be made. Moreover, cognitive maps became one of the best experimental methods for this research (Young, 2013).

After the mid-1950s, the methods were begun to be used by architects to investigate. By the 1980s, the field was described as 'Architectural Psychology' (Pol, 1993). Many meetings, conferences and symposiums were organised in the same decades. In those years, some issues related to architecture such as the body orientation and perceived environment, spatial identity, symbolic values of architectural settings, spatial encoding via cognitive mapping, the relationships

between physical and experimental spaces in architecture were examined. The hospitals and their effects on mental illnesses, proxemics and personal space, spatial configuration and 'space syntax', built organisation, and users' effects were also investigated. The other topics discussed were sense and architectural perception, language and environmental perception, visual perception, and children's perception of distance, position and orientation of objects in space. The decision making and spatial preference, place attachment, spatial memory, the links between cultural dimensions, territoriality, socio-cultural aspects on constructions of environmental perception and design were debated too. The 1970s were the years of consolidation of theories of the 1960s. In the 1980s, social and ecological perspectives strongly influenced the field, and terminology and theories had been formed. In that decade, environmental psychology spread to Asian Countries, and some international institutes were founded. In this decade, some theoretical shifts on the definitions and limits of the field were made. So, the studies of the 1970s were developed and diversified.

2.2.3 First Attempts to Integrate Neuroscience to Architecture and Foundation of ANFA

Although environmental psychology and environmental behaviour studies were examined the relationships between the user and architectural settings -based on observations and some psychological methods and tests-, these studies ignored the psychological mechanisms beyond the architectural design process. In design-based research, it was examined architectural design under the shadow of user experience. However, after the 1960s, thanks to the increase of complexity in design fields and the advances in computer technology, designers, artists and scientists, generated new models. They benefitted from the elements of the design process and design activity. The focus was to increase design efficiency and their explanations about the cognitive mechanism beyond the design process.

The earliest attempts to integrate new brain imagining techniques emerged after the 1970s in 'neuroscience' (Longstaff, 2011). The aim was to understand the neural mechanism beyond the architectural design process. They examined the multi-sensory neural processing beyond architectural experience and the influence of architectural settings on the psychological and neural manners of the users. The Academy Neuroscience for Architects (ANFA) was founded in 2003 by the San Diego Chapter of the American Institute of Architects (Alison, 2013). The first president became architect John P. Eberhard, and there have been many scientists from neuroscience, genetics, biological studies, medicine, computational neurobiology, neuropharmacology in the institution's advisory board. Some researchers published papers about the influence of architectural settings on the psychological manners of users. In 2003, '*How the Brain Experiences Architecture*' was published in the Journal of American Institute of Architects. In

this collection, John P. Eberhard expressed his ideas about the significance of examining neural mechanisms beyond architectural design /user experience. It was emphasised the significant role of the institution and mission of ANFA. The work was also stressed that the institution promotes advanced knowledge that links neuroscience research to a growing understanding of human responses to the built environment (Eberhard, 2003a). The team started to deal with issues of the possible integration of neuroscience into the realm of architecture. From 2003 to 2005, the foundation process of ANFA continued. In those times, the members of ANFA were giving lectures to architecture students and organising interdisciplinary workshops. Since then, new activities such as seminars, college-level courses, conferences have begun to be arranged so far to increase the awareness of the significant role of neuroscience in architecture. In the works of the ANFA team, the neuroscientists and architects collaborated to benefit from the methods of neuroscience for examining human experience in the architectural context.

2.2.4 The Publications about Neuroscience and Architecture and Potentials of New Interdisciplinary Area

Thanks to ANFA's drawing attention to the potentials of the application of Neuroscience, many interdisciplinary publications based on neuroscience and architecture has been published since 2003. These publications can be classified into two categories as theoretical and experimental. The theoretical publications deal with the 'potentials of applications of neuroscience to architecture', 'value of measuring environmental features or cognitive processes of users while experiencing different architectural settings', 'possible benefits of the application of neuroscience to architectural design practice', 'role of neuroscientific findings for healthcare-based design in a theoretical way'. In experiment-based publications, researchers studied brain imagining techniques such as fMRI and EEG. They dealt with the effects of 'architectural buildings and environmental attributions on human cognitive activity', 'neural mechanisms beyond spatial cognition and sense of presence (especially Virtual Environments)', 'neural mechanisms beyond architectural design process', and 'experimental designed setups for neuromorphic/brain-friendly adaptive architecture'.

ANFA published electronic newsletters including some events, organisations, publications about neuroscience and architecture from 2003 to 2006. In the first electronic newsletter of summer 2003, the topics such as how healthcare-based designing can be achievable for Alzheimer's disease through the application of neuroscience to architecture' was discussed. Then, '*Beyond Intuition*' was released by Paul Eberhard's effort; the work gives information about the publications and plans of ANFA and some details of neuroscientific experiments (Eberhard, 2003b). In 2003, Ann Jarmusch published an article entitled '*Mind-set: Research project will study*

architecture's impact on the brain', underlining the effects of architectural settings on our behavioural patterns. The article discusses the influence of our behaviours on brain mechanisms such as affect memory, spatial perception, emotional responses from pleasure to pain, familiarity and novelty in the architectural environment (Jarmusch, 2003).

In the same year, Tracy Certo published '*Neuroscience and Architecture: From Alzheimer's Care to Neonatal Units, the Design Environment is Critical*', investigating the significant role of applying neuroscience to architecture, especially for mentally ill people and neonatal units for prematurely born babies (Certo, 2003). John Zeisel and his colleagues published the article '*Environmental Correlates to Behavioural Health Outcomes in Alzheimer's Special Care Units*' examined some special care units of people having Alzheimer's disease in terms of aggression, agitation, social withdrawal, depression, and psychotic problems (Zeisel et al., 2003). In 2004, John P. Eberhard and Brenda Patoine published '*Architecture with the Brain in Mind*', examining user experiences in the architectural contexts of sacred spaces, learning environments, nursing special care units and hospitals. The study also discusses the potentials for examining user experience through neuroscientific methods instead of intuitive findings (Eberhard and Patoine, 2004).

In 2006, Rabiya S. Tuma published '*Architecture, Neuroscience Intersect',* examining neurogenesis and the influence of architectural environments (Tuma, 2006). In the same year, John Zeisel published a book entitled '*Inquiry by Design: Environment/Behaviour/ Neuroscience in Architecture, Interiors, Landscape and Planning*', dealing with the application of neuroscience to design studies. In the book, new potentials for improving decision-making mechanisms of design are given. It is mentioned that the neuroscience-based approach would present significant chances to environment behaviour studies. In terms of understanding such concepts as place, territory, personalisation, navigation, and spatial orientation, examining the brain's anatomy, structure, and function would be helpful (Zeisel, 2006). In 2007, Kayt Sukel and Russell Epstein published '*Building for Shattered Mind*', examining the ways of designing better nursing homes and other facilities for ageing. They examined changes in mental activities such as memory, sensory perception, cognitive mapping, physical abilities, and brain physiology. They suggested some solutions in architectural settings to activate the brain, primarily semantic memory, as much as possible (Sukel and Epstein, 2007).

In the same year, Eberhard published one of the earliest introductory books investigating neuroscience and architecture relationships, entitled '*Architecture and the Brain: A New Knowledge Base from Neuroscience*'. He benefited from Rita Carter's book on neuroscience entitled '*Mapping the Mind*', published in 1998. He discussed the evolution of the brain/mind and anatomy, structure and functions of the brain, the anatomy and functions of sensory systems, the

links between emotions and behaviours and architectural settings, the perception and recognition of architectural settings, the neural mechanisms beyond aesthetical appraisal and neural mechanisms beyond memory. The book also presents some ideas about the future potentials of applying neuroscience to architecture (Eberhard, 2007). In 2008, Eberhard edited another book investigating the potentials of new interdisciplinary studies, entitled '*Brain Landscape: The Coexistence of Neuroscience and Architecture*'. In this book, the authors examined the assessments of integrating two areas (Neuroscience + Architecture). The neural plasticity, and the neural mechanisms beyond cognitive activities such as attention, awareness, learning, visual perception, memory, emotions, especially in architecture, were debated. The 'potential benefits of neuroscience to design the classrooms, working and sacred environments' and 'neural effects of fundamental design principles such as symmetry, proportion, lightning degree and harmony' were discussed too. The book also discussed the healthcare-based design principles for older people having Alzheimer's disease and ageing problems in the brain anatomy and functions (Eberhard, 2008). In 2009, new neuroscientific experiments were begun thanks to the advances in virtual reality technology and brain imagining techniques such as fMRI and EEG.

In the same year, Architectural theoretician Harry Francis Mallgrave published a book entitled '*The Architect's Brain: Neuroscience, Creativity and Architecture*', investigating potentials of the newly emerging interdisciplinary field, Neuroscience, under the perspective of architectural theory. In the book, the influence of architectural environments on users' psychological manners was given from neuroscientific debates (Mallgrave, 2009). In 2009, Emily Anthes published an essay entitled '*How Room Designs Affect Your Work and Mood-Brain research can help us craft spaces that relax, inspire, awaken, comfort and heal*' examining the role of architectural settings on mental activity and comparison of restorative effects of natural and built environments (Anthes, 2009). In the same year, John P. Eberhard published an article entitled '*Applying Neuroscience to Architecture*', examining the 'parahippocampal' brain areas and its effects on cognitive mapping and assessments on some architectural design examples under the perspective of neuroscience (Eberhard, 2009).

In 2010, sociologist John Zeisel published a book entitled '*I'm Still Here: Creating a better life for a loved one living with Alzheimer's',* dealing with Alzheimer's disease and architectural environments (Zeisel, 2010). In 2011, a book edited by Stamatina Th Rassia and Panos M. Pardalos, entitled '*Sustainable Environmental Design in Architecture: Impacts on Health*', examining the healing spaces, user satisfaction and chronic diseases related to the use of a designed space (Rassia and Pardalos, 2011). In 2012, ANFA organised its first international conference in SALK Institute for Biological Sciences. Before the panel sessions, three workshops

were organised based on neural mechanisms, design, and neuro-architecture. In the panel sessions, researchers dealt with the environmental influence on mental activity (such as visual perception, contemplative thinking, memory), the application of neuroscience to design, design thinking and mental spatial transformations, and the issues related to empathy and embodied simulation (ANFA conferences,2012).

In the following year, Betsey Olenick Dougherty and Michael A. Arbib published an article entitled '*The evolution of neuroscience for architecture: introducing the special issue*', including formal and functional aspects of architectural settings on emotion by benefitting from neuroscience and behavioural data (Dougherty and Arbib, 2013). In 2013, architectural theoretician Harry Francis Mallgrave published a book entitled '*Architecture and Embodiment: The Implications of the New Sciences and Humanities for Design*' investigating the points of 'influence of architectural settings on human cognition', 'cultural influence on brain activity and evolution', 'mirror neurons and radical embodiment in architecture' and 'aesthetical appraisal and its contribution to the human cognitive evolution, aesthetical appraisal and origins of art' (Mallgrave, 2013a).

In the same year, a symposium was organised in Helsinki about Neuroscience and Architecture. After this symposium, a book about the symposium, including three essays, was published. These three essays were the architect and architectural theorist Juhani Pallasmaa's '*Towards a Neuroscience of Architecture*', architectural theorist Harry Francis Mallgrave's '*Should Architects Care about Neuroscience?*', and neuroscientist Michael Arbib's '*(Why) Should Architects Care about Neuroscience?*'. Pallasmaa, in his essay, dealt with the 'complexity and impureness of architectural experience, measurable and non-measurable dimensions of it', 'relationships between architecture and mental activity such as empathy, aesthetical appraisal and imagination' to understand the relationships between neuroscience and architecture (Pallasmaa, 2013). Mallgrave, in his essay, stressed the embodied nature of architectural environments, mirror neuron systems, empathy in architectural design (Mallgrave, 2013b). In his essay, Michael Arbib mentioned the 'perceptual and motor schemas of visual scenes and architectural settings', 'effects of different memory types such as working, procedural and episodic memory', 'tool use and construction behaviour among animals and humans and niche construction' and 'group creativity and mirror neurons' (Arbib, 2013).

In the following year, in 2014, Ann Sussman and Justin B. Hollander published a book entitled '*Cognitive Architecture: Designing for How We Respond to the Built Environment*' examining four key concepts, in the theme 'pattern matters' referring to the visually-oriented nature of humans and in the theme '*shapes carry weight*' referring to origins of aesthetical appraisal of humans based on bilateral symmetry (Sussman and Hollander, 2014).

In 2015, Sarah Robinson and Juhani Pallasmaa edited a book entitled '*Mind in Architecture: Neuroscience, Embodiment, and the Future of Design',* including critical essays on neuroscience and architecture (Robinson and Pallasmaa, 2015) (see Table b in appendix). In the same year, in 2015, architectural theoreticians Juhani Pallasmaa, Harry Francis Mallgrave, psychologist Sarah Robinson, and Vittorio Gallese published a booklet including their essays examining relationships between empathy and architecture entitled '*Architecture and Empathy'* (Pallasmaa et al.,2015). In this work, the 'form, experience and poetic aspects of architecture' (Pallasmaa, 2015b), the 'relationships between mind, culture and architecture' and 'social brain hypothesis and human enculturation' (Mallgrave, 2015a), the 'sensation, emotions and ecological dimension of empathy' and 'haptic sense, materiality, thinking through skin and primary role of touch' (Robinson, 2015a), and the 'mirror neurons and embodied simulations', 'nature, anatomy and functions of brain areas' and 'sensorimotor processing in the brain' (Gallese, 2015) have been discussed (see Table a in appendix).

In 2016, Coyne published a book, *'Mood and mobility: navigating the emotional spaces of digital social networks'* and discussed the changeable moods through communicating, entertaining ourselves by technological tools and channels. Here, he stated that the potentials to disseminate our moods are related to empathy and contact with other people's situations. He approached the 'mirror neurons' as the carriers to make us feel a similar action just by observing and seeing the action. Without doing the action, we learnt that the motor system could provide the ability to give the same reply in neural activities (Coyne, 2016).

In 2017, architect, author, and critic Sarah Williams Goldhagen published a book entitled '*Welcome to Your World: How the Built Environment Shapes Our Lives*', dealing with influences of architectural environments in the city. She gives information on our cognitive processes such as emotions, memories, feelings in the architectural environments of the cities. She benefitted from some research in cognitive neuroscience investigating the effects of architectural environments on health, social structure, and personal manners. She stresses the societies should examine how they benefit from the biological and cognitive sciences to create more suitable environments. Goldhagen debated the effects of architectural environments on shaping memories and experiences (Goldhagen, 2017).

Our understanding of how we understand the world via the brain-body-environment component has been extended. The psychology-based studies before the foundation of ANFA mostly debated generating healing spaces to improve mental health, learning and working capacity. The ANFA has paid attention to the usefulness of the combination of Neuroscience to Architecture. Then, the studies started to focus on the influence of architectural settings on our brain/mind activity. The

outputs have been crucial to produce a new body of knowledge on perception, attention, memory, emotions, creativity, sensation, decision-making, and aesthetical appraisal. The neuroscientific approach has made outstanding contributions to the psychological sides of architectural design and architectural environments. It has also paved new ways for creating the neuromorphic architectural setting for the future. The studies examining the relationships among brain-body-architectural environments based on brain imagining techniques have been helpful to further discussion for neuroscience and architecture.

	CATEGORY	SUB-CATEGORY	KEY TERMS	PUBLICATIONS
NEUROSCIENCE+ARCHITECTURE LITERATURE (THEORETICAL PUBLICATIONS)	Potentials and Applications	Potentials	• potentials of new interdisciplinary area • potentials of ANFA • methods and models for further research	(Eberhard,2008) (Mallgrave,2013b)
		Applications	• applications of neuroscience to the realm of architecture • application of theory to research • application of neuroscience to the education of architects • application of neuroscience to environment-behaviour studies	(Eberhard,2008) (Zeisel,2006)
	Mental/ Cognitive Activities- Brain and Human Biology	Visual Perception	• effects of light on the brain in built environments • visual perception and aesthetics • perceptual and motor schemas of built environments	(Eberhard,2008) (Mallgrave,2013a) (Arbib, 2013) (Albright,2015)
		Attention	• neural mechanisms beyond attention and awareness	(Eberhard,2008)
		Empathy	• mirror neurons and empathy • empathy and emotions • empathy and embodied simulation	(Mallgrave,2009) (Mallgrave,2015b)
		Creativity	• neural mechanisms beyond creativity • effects of tools on creativity • mirror neurons and group creativity • creativity and empathy	(Zeisel,2006) (Arbib, 2013) (Farling,2015)
		Sensations	• haptic sensation and materiality, texture and primary role of touch • auditory sensation and memory	(Robinson, 2015a) (ANFA conference, 2012)
		Decision-Making	• improving decision-making mechanisms via examining the research process for designing • problem-solving activity in the design process	(Zeisel,2006) (Eberhard,2009)
		Aesthetical Appraisal	• links between aesthetical appraisal and basic design principles • natural selection and beauty (survival) • neuroaesthetics and architecture • the sensation of awe in the sacred environment • aesthetics and hedonic circuit in the brain • aesthetics and arts and brain/cognitive evolution	(Eberhard,2008) (Mallgrave,2013a) (Gallese and Gattara,2015)
		Memory	• cognitive maps • semantic, working and procedural memory and architecture • ways of increasing memorability degree of architectural settings • neural mechanisms beyond memory storage • ageing and memory and distributed memory systems • effects of the parahippocampal area on	(Eberhard,2008) (Eberhard,2009) (Arbib, 2013)

			cognitive mapping	
		Learning	• neural mechanisms beyond learning • different forms of learning • links between skills and learning	(EberhardandPatoine,2004) (Eberhard,2008) (Eberhard,2009)
		Embodiment and Embodied Cognition and Body	• mirror neurons and radical embodiment in architecture • embodied nature of emotions in architecture • bodily basis of human cognition • body schema and architectural space • bodily ownership and space	(Mallgrave,2013b) (Robinson, 2015c) (Gallese and Gattara,2015)
		Behaviour	• links between emotions and behaviours • movement in architectural settings • tool use and construction behaviour among animals and humans	(Eberhard,2007) (Eberhard,2009) (Arbib, 2013)
		Meaning	• metaphors and mirror neuron systems • place-making and meaning • embodied dimension of architectural meaning	(SussmanandHollander, 2014) (Gallese,2015) (Johnson,2015) (Pérez-Gómez, 2015)
		Spatial Cognition and Perception	• navigation and way-finding • encoding space and orientation • memory and navigation/ orientation	(Zeisel,2006) (Arbib, 2013)
		Consciousness	• (un)conscious folds in arch. experience • primary, core and extended consciousness,	(Eberhard,2008) (Pérez-Gómez, 2015)
		Contemplative Thinking	• contemplative thinking in sacred architecture and built environments	(Eberhard,2008)
		Emotion and Intuition	• emotional responses from pleasure to pain • emotions and architectural design • neuroscientific relationships between form, function and emotion • neural mechanisms beyond intuition • imagination in architectural design • intuition in architectural experience	(Jarmusch, 2003) (Eberhard,2008) (Pallasmaa, 2013) (Farling,2015)

Table-2.2 The structure of the theoretical-based publications in Neuroscience and Architecture (I)

	CATEGORY	SUB-CATEGORY	KEY TERMS	PUBLICATIONS
NEUROSCIENCE+ARCHITECTURE LITERATURE (THEORETICAL PUBLICATIONS) (II)	Mental/Cognitive Activities- Brain and Human Biology	Brain and Human Biology	• anatomy, nature and functions of the brain • brain areas strongly related to architecture • effects of architectural settings on neurogenesis • ageing and changes in the brain and brain physiology • evolution of brain/mind and DNA and brain development • action potentials of the brain • mental categorisation and neural plasticity • effects of architectural environments on the immune system • cultural influence on brain activity • social brain hypothesis • role of human biology on architecture	(Tuma,2006) (Eberhard,2007) (Sukel and Epstein,2007) (Eberhard,2008) (Zeisel,2006) (Sternberg,2009) (Mallgrave,2013a) (Albright,2015) (Eberhard,2015) (Mallgrave,2015a)
	Environmental Attributions	Proportions	• effects of golden ratio on mental activity	(Eberhard,2015)
		Lightning and Colours	• designing principles of lighting in buildings • wavelengths of used light in special environments	(Eberhard,2008) (Anthes,2009)
		Familiarity and Novelty	• effects of familiarity and novelty of architectural environments on mental activity	(Jarmusch,2003) (Albright,2015)
		Interior Design and Furniture	• functions of interior design on brain activity • links between furniture choices and layouts and effects on relaxation • effects of ceiling height on feeling freedom	(Sukel and Epstein, 2007) (Anthes,2009)
		Natural Environments	• restorative effects of natural environments	(Anthes,2009)
		Contours	• effects of curvilinearity and rectilinearity on mental activity • thigmotaxis	(SussmanandHollander, 2014)
	Design-Based Research	Neuromorphic Design	• kinetic architecture and enriched spaces	(ANFA conference, 2012)
		Design and Design Research	• elements of the design process • ways of increasing quality of design and design research • organising design as research • evidence-based design • design thinking	(Zeisel,2006) (ANFA conference, 2012)
		Chronobioengineering	• application of circadian rhythms to the field of design and engineering	(ANFA conference, 2012)
		Learning Environments	• ways of increasing efficiency of learning	(Eberhard,2008)
		Working Environments	• ways of increasing efficiency and productivity	(Eberhard,2008)

			• learning and memory use in working places • working conditions of laboratories, campuses and institutions	
	Healthcare and Design	Neonatal Units	• design criteria for neonatal units	(Certo,2003) (Eberhard andPatoine,2004)
		Hospitals and Healthcare Environments	• healing effects of architectural settings on mental activities • ways of designing a place of healing	(Sternberg,2009)
		Special Care Units and Nursing Homes	• ways of creating well-built environments • enhancing stimuli by clues	(Zeisel,2010) (Eberhard,2008)
		Sustainability	• designing buildings both energy efficient/ sustainable and healing	(RassiaandPardalos,2011)

Table-2.3 The structure of the theoretical-based publications in Neuroscience and Architecture

(II)

2.2.5 Recent experiments examining the relationships between Neuroscience and Architecture based on the Brain-Imagining Techniques

Thanks to the foundation of ANFA, several experiments based on brain-imagining techniques began to be conducted. This situation revealed that ANFA had been a locomotive power to analyse the relationships between Neuroscience and Architecture, especially after 2010. We see the early attempts of neuroscience and architecture-based experiments that investigated the neural mechanisms beyond aesthetical appreciation of architectural settings and the architectural design process. The latest examples were about 'neurourbanism', in which we could see the urban areas from the perspectives of cognitive neuroscience and cognitive psychology. In this part, we focused on the experiments in chronological order from 2008 to today. They showed us that brain imagining techniques have been helpful to investigate the relationships between neuroscience and architecture.

In 2008, Associate Professor Ulrich Kirk from the Department of Psychology of the University of Copenhagen and his team conducted the experiment investigating the relationships between levels of expertise and perceptual processing, memory and reward processing by comparing architectural facades and faces as control stimuli (Kirk et al., 2008) (see Table c in appendix). Senior Lecturer Katerina Alexiou from the Faculty of Science, Technology, Engineering and Mathematics of The Open University and her colleagues conducted another experiment in 2009 investigating the relationships between neural mechanisms beyond architectural design process as ill-defined problem-solving activity and well-defined problem-solving activity as the control condition. A criterion to decide the task's termination is given in the problem-solving task, and a definition of legal moves. Although a problem-solving task may require creative thinking and hypothesis formation or inductive reasoning, the problem itself is well-defined, the legal moves are known, and the solution is unique. In the design task, there is no predetermined final state or criterion for deciding the termination of the task (the task is open-ended). The task requires defining the problem as well as the solution space: it requires the creation and interpretation of a set of moves, as well as the creation of a function (criteria) for evaluating the solution (Alexiou et al., 2009) (see Table d in appendix).

In 2012, ANFA organised a conference, and several architects and neuroscientists submitted papers based on neuroscience and architecture. The papers generally adopted similar attitudes with environment behaviour studies, but they referred to future directions as integrating their finding to brain imagining techniques such as fMRI or EEG. For example, senior lecturer Diogo Teixeira from the University of Saint Joseph and his colleagues submitted a paper entitled '*Weak Architecture: How to Enhance Neural Efficiency Using Public Space*', examining how weak design

strategies (i.e., based on experiential events) in the public space can affect human behaviour regarding memory, consciousness, and emotions. The paper evaluated whether these effects can be determined at the neuro-physiological level to investigate the process associated with perception. The work also discussed the emotional attachment to the use of public places (Teixeira et al., 2012) (see Table e in appendix).

Isabella Pasqualini and Olaf Blanke from École Polytechnique Fédérale de Lausanne and their colleagues published a poster paper entitled '*The 'I' of architectonic perception Own body perception and bodily feelings in architectonic space*' investigating the body experience, perception, and architectonic expression of spaces. They discussed the tectonic elements such as the walls or modulation of the architectonic interiors. The result found that the perceived geometries of the interiors depend on the position of the visual stimulus in the extra- or peri-personal space of the observer (Pasqualini et al., 2012). Vedran Dzebic from the University of Waterloo and his colleagues published a paper entitled '*The Influence of Visual Perception on Responses towards a Real-world Environment and Application towards Design*', investigating how the visual perception of the place's physical features influences human behaviour and experience. They answered how such information could design more successful buildings (Dzebic et al., 2012).

Despoina Linaraki from the University of Crete and her colleague submitted a poster paper entitled '*The Interaction of Space with the Human Nervous System and Its Impact on Human Psychology'* to investigate how the built environments affect human psychological disorders. They debated how the built environments help people improve their psychological health (Linaraki and Voradaki, 2012). Eve A. Edelstein from the University of California and his colleague published a paper entitled '*The Neuroscience of Extraordinary Places: Examining Machu Picchu and the Great Wall of China*', examining how brain processes may influence our reactions. They used photographic imagery of two architectural 'Wonders of the World' revealing the value of light, depth, and form to convey the interaction between people, architecture and nature. They examined the influence of colour and light intensity on heart rate reactivity, the cardiac and autonomic nervous system's response to environmental stressors and conditions, biophilic desire for natural settings, and movement's influence on spatial cognition (Edelstein and Torrey, 2012).

Prof. Michael J. Ostwald from the University of New Castle and his team prepared a conference poster for the 2012 ANFA organisation entitled '*Pareidolia Analysis of Architecture: Reading the Emotional Expression of a Building Façade'* examining the 'facial pareidolia' by using a database of images of human faces. The paper discussed face-like forms and expressions in the facades (Ostwald et al., 2012). Stephan K. Chalup from the University of New Castle in Australia and his colleagues presented a paper entitled '*Simulating Mechanisms of Emotion Associated with Visual*

Perception of Urban Space: an Artificial Agent's Perspective', discussing how the visual characteristics of urban space have an impact on human emotions. The team used software tuned machine learning and abstract facial expression patterns to understand how humans (emotionally) experience architectural products (Chalup et al., 2012).

Architect Joe Manganelli from Clemson University and his team prepared a conference poster entitled '*Patterns in Architecture, Cognition, Systems, and Software: Representing and Analysing Cognition during the Design Process*', proposing a human-based software to be used by human factors engineers, software developers, and neuroscientists (Manganelli et al., 2012). Bruce A. Wheatcroft from The Abbey for the Arts, in the Lancaster/Alexandria area of Eastern Ontario, presented a paper entitled '*Past, Present and Future Memory Informed by Reverberation Characteristics of Worship and Performance Spaces*', focussing on the reverberation characteristics of worship and performance spaces and their influence on the experience of worship. They benefitted from some interviews to measure the reverberation effects of these two areas (Wheatcroft, 2012). Associate Professor Julio Bermudez from The Catholic University of America and his team submitted a paper entitled '*fMRI Study of Architecturally-Induced Contemplative States*', reporting the results of testing how the perception of environments - designed for contemplation- elicits brain activations (Bermudez et al., 2014) (see Table f in appendix).

Joel Martínez-Soto from the Institute of Neurobiology in the National Autonomous University of Mexico and his team represented a paper entitled '*Exploration of Neural Correlates of Restorative Environment Exposure through Functional Magnetic Resonance Imagining*', explores the neural correlates of the environmental exposure with functional magnetic resonance imaging (Martínez-Soto et al., 2012) (see Table g in appendix). Upali Nanda from RED Centre at American Art Resources and her colleagues presented a paper entitled '*Lessons from Neuroscience: Building Blocks for Charting New Frontiers',* investigating the critical role of the amygdala in emotional processing. They discussed some visual properties, including objective properties like contours, spatial frequency and contextual association and personal properties like valence, arousal and dominance (Nanda and Pati, 2012). Anders Nereim from the School of the Art Institute of Chicago presented a paper entitled '*Loose Neural Nets in Architecture',* analysing loose networks of analogue integrated circuits. They investigated the potentials of the neural nets through building components (Nereim, 2012).

Daniel Michler from the University of Bremen and his team prepared a paper entitled 'Analyses of Mental Spatial Transformations during Early Design Conception', reporting experiments based on EEG based brain-computer interface. They investigated the role of object-based mental spatial

transformations with the primitive operations of object rotation, translation, scaling, and perspective shift during a spatial design task through focussing on design conception and refinement performed during early sketching and desk-crit sessions. The team found patterns from the motor cortex characterise body parts' real and imagined motion. They claimed that the results might guide the considerations for such systems, where natural interaction capabilities for design manipulation and exploration are critical (Michler et al., 2012).

After the first conference of ANFA, the members of ANFA organised another conference in which some of the papers included some experiments based on EEG, fMRI and eye-tracking methods. Karen Dobkins from University California, San Diego and her colleagues presented a paper entitled *'Using Neuroscience to Tailor Visual Environments for Infants and Children',* examining the effects of the environment on physical and mental health, especially on infants and children. They mainly focussed on infants and found that young infants respond to specific patterns that include high contrast dark/light stimuli and highly saturated colours (Dobkins and Heyman, 2013). Eugenia Victoria Ellis and her colleagues presented a paper entitled '*Chronobioengineering Indoor Lighting to Enhance Facilities for Ageing and Alzheimer's Disorder*', dealing with the evolution of 'circadian rhythm' systems. They focussed on light cycles to synchronise circadian rhythms and potential ways of enhancing healthcare in the ageing population, especially those with dementia (Ellis et al., 2013).

In 2014, Mirjana Prpa from Simon Fraser University and her colleagues presented a paper at the ANFA Conference entitled '*Towards User Personalized Environments: An Artistic Exploration Using an EEG-Based Brain-Computer Interface*' dealing with virtual-reality-based artistic installation in Unity3D incorporating with an EEG headset. They evaluated the potential of BCI (brain-computer interfaces) devices, as well as the users' perception of the virtual environments (Prpa et al., 2014) (see Table h in appendix). Vasiliki P. Kondyli from the Department of Architecture of the University of Patras and her colleagues submitted a paper entitled '*The Design of an Urban Park in the City of Patras, Greece: Towards the Development of an Enriched Environment*' dealing with the multi-sensory experience, cognitive stimulation of the urban environments (Kondyli et al., 2014). Turkish architect and Technology Director of UCLA Department of Architecture and Urban Design, Guvenc Ozel, prepared a paper entitled '*Case for an Architectural Singularity Through Robotically Actuated Motion and Neuro-Sensensory User Interaction',* introducing his team's project called 'Cerebral Hut', which they focus on the configuration of the space physically through EEG Device activations. The paper discussed the neuro-sensing technology and adaptive architecture (Ozel, 2014).

Dr Giovanni Vecchiato from the Department of Physiology and Pharmacology of Sapienza University and his colleagues presented a paper entitled '*Electroencephalographic Signatures of Interior Design Appreciation in a CAVE System: A Pilot Study',* seeking the possible ways of correlating neuro-physiological parameters with the appreciation of interior designs (Vecchiato et al., 2014) (see Table i in appendix). Dr Debajyoti Pati from the Department of Design of Texas Tech University and his colleagues presented a paper entitled '*An fMRI-Based Exploration of Neural Correlates of the 'Formal' Environmental Attributes of Healthcare Settings*', exploring neural activation in adult brains in response to visual stimulus focussing on the emotional impact of visual stimuli (Pati et al., 2014) (see Table j in appendix). In 2015, Giovanni Vecchiato from the Department of Physiology and Pharmacology of Sapienza University of Rome and his colleagues Gaetano Tieri, Andrea Jelić Federico De Matteis, Anton G. Maglione Fabio Babiloni published an article entitled '*Electroencephalographic Correlates of Sensorimotor Integration and Embodiment during the Appreciation of Virtual Architectural Environments*' dealing with the neuro-physiological correlates of architectural perception by using the virtual architectural environments (Vecchiato et al., 2015) (see Table k in appendix).

Parastou Naghibi Rad from Neural Engineering Research Laboratory of Institute for Research in Fundamental Science in Tehran and her colleagues presented a paper entitled '*Facades of building significantly modulate EEG signals of brain cortical lobes*' dealing with the building facades' effects on the behavioural reactions. They focussed on brain lobes and waves using EEG signals (Rad et al., 2016) (see Table l in appendix). Richard Georges Aoun, Architect and Urban Designer consultant at SOLIDERE International, prepared a paper entitled '*Emotional Design in Architecture*', dealing with the influences of architectural environments on our emotions in terms of healing and getting pleasure (Aoun, 2016) (see Table m in appendix). PhD Candidate Xin Shan from Nanyang Technological University in Singapore and his colleague submitted a paper entitled '*EEG Pattern Recognition and Classification for Thermal Comfort*' examining the electroencephalography (EEG) techniques to see the thermal comfort's effects on emotions (Shan and Yang, 2016) (see Table n in appendix). Young-Ah Rho from the Department of Bio and Brain Engineering of Korea Advanced Institute of Science and Technology in Seoul and her colleagues submitted a paper entitled '*The impact of positional configuration of a desk in a room on attention and creativity measured by behavioural and neuro-physiological recordings*' dealing with the effects of architectural features such as window, ceiling, floor, or wall on behaviour and neuro-physiological states of individuals (Rho et al., 2016) (see Table o in appendix).

Cherif Amor from the Department of Interior Design of Virginia Commonwealth University in Qatar and his colleagues presented a paper entitled '*Neuroscience Informing Design: Impact of*

Fluorescent CCT on Neurodiverse Populations', reporting the findings of experiment dealing with relationships between colour warmness and emotions (Amor et al., 2016) (see Table p in appendix). Shareh Ghanbari Azarneir from the School of Architecture and Environmental Design of Iran University of Science and Technology and his colleagues prepared a paper entitled '*The perception of symmetry in architecture: an eye movement study*' dealing with the issue of symmetry in terms of creating a visual order and reducing the time needed to perceive the space visually (Azarneir et al., 2016) (see Table r in appendix). Vasiliki Kondyli and Mehul Bhatt from the DesignSpace Group of Human-Centred Cognitive Assistive Lab from the University of Bremen submitted a paper entitled '*Transparency as an environmental factor that influences cognitive visuo-locomotive experience in large-scale buildings*', examining the relationships between the visual-locomotive experience and the spatial memory (Kondyli and Bhatt, 2016) (see Table s in appendix).

Hasti Mirkia from the Design Studies Department and Interior Architecture Program of the University of Wisconsin and her colleagues submitted a paper entitled '*The Impact of Biomorphic Design on the Memorability of Interior Environments-A Preliminary Study*', addressing the relationships between memory, emotions, empathy and neuroaesthetics in the built environment (Mirkia et al., 2016) (see Table t in appendix). K. Rhett Nichols from the Massachusetts Institute of Technology and her colleagues prepared a paper entitled '*Eye Tracking Architecture: A Pilot Study of Buildings in Boston*', explaining an eye-tracking study to understand better how people see their world, especially for using these findings as architect's toolkit (Nichols et al., 2016) (see Table u in appendix). In 2017, Heeyoung Choo from Beckman Institute for Advanced Science and Technology of University of Illinois and her colleagues Jack L. Nasar, Bardia Nikrahei, Dirk B. Walther published an article in Scientific Reports entitled '*Neural Codes of Seeing Architectural Styles*' investigating the comparisons of architectural styles in terms of visual perceptions (Choo et al., 2017) (see Table v in appendix).

One of the latest studies made by Neale et al. was about *'neurourbanism',* which is a perspective that we could analyse the urban areas by the perspectives of cognitive neuroscience and cognitive psychology. The study focussed on the effects of urban areas on the brain activity of people who were 65 years old. It aimed to discuss the correlation between mental well-being and urban features. The method was based on urban walking in two different urban settings (six walking activities have been conducted). The participants experienced the defined urban environments through walking. For data acquisition, mobile electroencephalography (EEG) was used to record brain activity. The study analysed the differences between the participants' alpha (associated with relaxation) and beta (associated with attention) waves while they walked in the

field areas. The findings showed that the neural data differed according to the urban environments' qualities such as busy, quiet, and green. The alpha activity was recorded considerably different in the busy and green parts of the urban area. They increased in the busy areas while they decreased in the green places. The study revealed that the urban areas' notifications generate different perceptions and experiences in the brain activities of older people (Neale et al., 2020). This paper was essential to show the impacts of diverse-qualified urban contexts on people's neural action, cognition, and perception.

The relationship between neuroscience and architecture has been examined theoretically and experimentally. Many researchers have conducted experiments dealing with various topics related to architectural experience and the designing process. Many dealt with neural mechanisms. Some pioneer works are based on the neural mechanisms beyond the architectural design process, neural mechanisms beyond visual perception in terms of brain activity, neural mechanisms beyond an aesthetical appraisal of architectural settings, neural mechanisms in physical and virtual environments. A few studies worked on the neural effects of built environments on cognitive activities such as emotions, memory, empathy, consciousness and behaviours. The relationships between loose neural networks in architectural environments and the users' behavioural patterns were discussed. Limited studies revealed different cognitive processes during architectural experiences, such as visual perception and cognitive aspects of architectural environments on the design process. Some of them focused on regulating human biological systems for generating new design principles. Many studied the effects of visual features (colour/nature) of architectural environments on stress levels, colour warmness on emotions, architectural contours and building facades (geometries, materials and proportions) on cognitive activity. The effects of biomorphic and minimalist architectural design on memorability and relationships between the visuo-locomotive experience, movement and spatial memory have been issued too. Except for very few theoretical debates, we could say that there is no previous research investigating the relationship between affordance and architecture based on a neuroscientific approach. This research asserts that investigating the origins of architectural experience by focusing on affordance has been significant in architecture and neuroscience.

2.3 THE 'AGENCY' IN COGNITIVE NEUROSCIENCE AND PSYCHOLOGY

Agent and Agency within Ecological Context

The 'agent' can be defined as a goal-oriented entity that perceives the environment in a psychological context. The agent fulfils the planned performance through efficient heuristic or algorithmic actions to achieve the intended goal. The 'agency' can be thought of as the organisms' capacity to perceive the environment to conduct goal-oriented performances. In this regard, agency contains the ability to perceive the environment in terms of action potentials relevant to either environment or living (other organisms) or non-living entities (objects, tools, other things) locating in these environments. In a broader sense, organismal qualities relevant to the agency (e.g., cognition, perception or action, and anatomical and other physiological traits) are fundamental for survival. From an ecological perspective, these qualities have a significant role in other cognitive processes such as action planning, predictions about actions of other agents, empathic processes (e.g., theory of mind). These qualities are essential for the organism in terms of autonomy through actions and cognitive/perceptual features, which provides 'singularity' to the organism in the given environment.

Ecologcial Agency in the context of Agent + (ınter-) Action + Environment System

In the context of ecological psychology, the agency is mainly conceptualized with its three elements of agency. These elements are (1) **organism** (especially, with their psychological context), (2) (inter) **action** (with its different modalities such as imagery, execution, observation or domain of the action-either direct interaction or interaction via a tool, namely tool-use) and (3) **environment/object** (with its features which serves the performance of the agency and contextuality). Operationalizations based on these conceptualizations are used to form models, providing practical frameworks for design studies. New definitions and theoretical discussions around these conceptualizations have been addressed to neuro-psychological research with two focal points as 1) representational qualities of actions (more conventional, based on subject-object dichotomy) and 2) ecological context of interactions of perception-action loops of the organism (Gibsonian, based on sensory substitution) with/without developmental or evolutionary context. In this chapter, the agency will be examined in three dimensions. First one is conceptual dimension (history and theory, conceptions). Second one is experimental dimension (with tripartite conceptualizations given above (i.e., agent+(inter-)action+environment) with two intersections (i.e., agent+action and action+environment within these three categories). And third dimension is generative (models, frameworks for design and production) dimension with the emphasis on two concepts as affordance and embodiment underlining the ecological context of the agency.

2.3.1 The Conceptual Background of the term 'Agency'

Rise of Contextual Revolution: Thinking Cognition with its Ecology

Experimental psychology research dealt with the agency in the light of the philosophy of mind (e.g. mind-body dualism). In the studies of behaviourism and cognitivism, the agency has been issued with a strong emphasis on cognitive or behavioural mechanisms. The studies worked beyond the representation of information content of agency without considering its ecological context. The representation of information is based on such dichotomies as agent-environment, subject-object within the context of dualism (see Michaels and Carello, 1981; Shobris, 1994; Chiesa, 1998; Kim, 2005; Uttal, 2004). The contextual revolution -as consideration of the role of other elements such as body, action or tools within the given environment on cognitive processes as contexts in addition to brain or mind -, emerged as a result of the integration of theoretical attitudes and conceptualizations of different schools . These schools contribute the criticization of current schools of the first half of the 20th century in terms of underestimation of the role of context on cognitive processes (Lobo et al., 2018; Järvilehto, 2009).

Formulating Agency within Ecological Context and Considering the Content

Despite conventional approaches to agency, ecological revolution (see, Glossarry) pioneered by James. J. Gibson and Eleanor J. Gibson, post-cognitivism approaches tried to cope with dichotomy-oriented conceptualizations of conventional attitudes (especially between action-perception, mind-body). One of the pioneers of Ecological Psychology, James Gibson, benefitted from *radical empiricism* (dynamism of experiential processes) and *neutral monism* (rejection of dichotomies between matter and mind) (see Heft, 2001), *behaviourism* (manipulanda-features of environment/objects that support activity formed by manipulations of agent) (Tolman, 1932 as cited in Lobo et al. 2018), *Gestalt Psychology* (laws of perceptual organization and isomorphy between stimuli and mental states of agent) (see Jenkins, 2008) and *Phenomenology* (especially *Embodied Phenomenology*) (body schema and bodily context of meaningful perception formed via interactions of agent with environment) (see Merleau-Ponty, 2012 [1945]). He examined the ecological context of perception (Lobo et al., 2018). Moreover, he formulated his term affordance as an action possibility formed by the relationships between an agent and its environment (Gibson, 1977). In his conceptualisation, experiential and information content of agency obtain ecological dimension and have become organism-agent interaction-based dynamic products. Gibson conceptualized environmental information as a survival-related symbol given to an organism by the environment. Gibsonian ecology defined the information within its relational, functional context (the teleosemantic notion of agential information).

Coping with the Content: Enactivism as Radicalism for Anti-Representationalism

Some of the radical attitudes within post-cognitivism, such as radical enactivism (see, Glossary), have gone one step further in the issue of content. They have radicalized the idea that information cannot carry content. They tried to refute the role of cognitive systems as maintenance of transmission of the content of agential information (anti representationalism) (Dijk et al., 2015). The general tendency within mainstream attitudes of post-cognitivism is to transcendent dichotomy oriented conventional conceptualizations. They situate within the philosophy of mind, psychology or cognitive neuroscience in the concepts relevant to the cognition (perceptual, motor or cognitive processes) such as embodied, situated, enactive or embedded cognition (see, Glossary). They have issued the agency within the interactions of cognitive processes of agent (e.g. sensory substitutions, perception-action loops) or agent-environment interactions (e.g. enactivism, active inference). So, they give the agent a more active role in forming agency information content (see Heras-Escribano, 2019; Segundo-Ortin et al., 2019; McGann et al., 2020).

Epistemic Space of Theoretical Discussions on Agency within Ecological Context

James Gibson's investigations on the ecological context of perception, the interdependency of perception and action, agent-environment interactions around affordance paved the way for new theoretical insights. Thanks to his contributions, several theoretical discussions have been made and these discussions have formed the epistemic space. In this regard, some of the discussed themes wthin the epistemic space can be listed as;

- the matters of 'habituality and ontogenetic features' (relevant to development; habits and enculturation) (Magri, 2019; Withagen and van der Kamp, 2010; Zoghi et al., 2016; Ramstead et al., 2016),
- 'temporality' (time axis of affordance, changes in variation and degree of solicitations of affordances over time) (Kiverstein et al., 2019a),
- influential roles of 'dependent variables of agent-environment system' (e.g. body scale and representation (Irvine et al., 2019), 'action capabilities' (Konczak et al., 1992; Choi and Mark, 2004), 'expectations/demand of agent or namely demand characteristics' (Withagen et al., 2012), or 'socio-cultural elements' (Pyysiäinen, 2021) (e.g. behaviour settings) (Bélanger and Coolen, 2014; Heft et al., 2014) and 'changes within given environment' (Withagen et al., 2017),
- 'role of learning' in affordance perception (Franchak et al., 2010; Ferretti, 2021), 'action estimation/calibration' (Franchak, 2019), 'updates within the learning mechanisms' (Ugur and

Piater, 2014), 'process of convergence of agential information for affordance from non-specific invariants toward more specific invariants' (Lobo et al., 2018),

- 'ecological and semantic context or namely contextuality and agency' (control and maintenance capacity of affordance oriented coupling with environment which provides individuality, normativity and interactional asymmetry and spatio-temporality to agent) (Dijk et al., 2015; Withagen et al., 2017; Barandiaran et al., 2009),
- 'nature of affordance-action/behaviour system' e.g., spontaneity (Weichold, 2018; Hutto and Myin, 2013), 'pre-reflectivity' (Dohn, 2009; Dings, 2018), 'degree of normativity' (Lo Presti, 2016; Heras-Escribano and de Pinedo, 2016), 'selectivity' (Bærentsen and Trettvik, 2002; Withagen et al., 2012; Withagen et al., 2017), 'degree of specificity/precision' (attentional and fine grained characteristics of bio-mechanical properties of action, skill use) (Bruineberg and Rietveld, 2014; Rietveld and Brouwers, 2017) and 'utilization/activation of affordance' (Ruppel, 2015; Borghi and Riggio, 2015)

have been studied in different areas from architecture (Maier et al., 2009a; Maier et al., 2009b; Daneshgarmoghaddam and Eslampour, 2013; Rietveld and Brouwers, 2017; Salingaros, 2017) to robotics and artificial intelligence (Zech et al., 2017; Yamanobe et al., 2017; Şahin et al., 2007; Jamone et al., 2018; Sun et al., 2010; Nye and Silverman, 2012) from developmental psychology (Zoghi et al., 2016; Withagen and van der Kamp, 2010; Franchak, 2019) to sports (Craig and Watson, 2011; Weast et al., 2014; Seifert et al., 2018).

Perception within Ecological Agency Context

In the ecological program, perceptual system -which is conventionally conceptualized as a process of neural system of organisms-, is associated with a sense modality (see, Glossary) facilitating detection of ecological information. It is realized via a behavioural medium where agent-environment interaction emerges. The perception is defined as active constructions of the perception-action loop where organism and environment are entangled within these dynamics (Lobo et al., 2018; Turvey, 2019; Gibson, 1979). The 'entanglement' between agent/organism and environment has ecological context instead of purely physical. It shapes perceptive capabilities of agent/organism. Moreover, perceptible characteristics of socio-material environment for action possibilities provide specificity to entanglement (Dijk and Rietveld, 2017). The 'specificity' is based on a nexus between the perceived ecological information and environmental properties (Lobo et al., 2018). It refers to the directionality of entanglement and sufficiency of the information content of agency (Kim and Lee et al., 2018), which is formulated as *'tau index'* (see, Glossary) elaborated in *'tau theory'* in visual kinesthetics (Lee, 2009). The perception system has redundant, polysemic characteristics and it includes non-specific variables (e.g., intersensory redundancy

hypothesis) (Bahrick and Lickliter, 2002). The ecological context of the agent-environment unit serves stabilization of perception, which causes specification.

Ecology of Information: Information between Agent and Environment

The specification or unique correspondence among environment, the information content of agency and affordances facilitate the direct perception of affordance provide '*transitivity*' (Turvey et al., 1981). Transitivity influences '*effectivities'* of agency execution, which depends on the behavioural capacity of the organism/agent and relevant properties of the environment (Lobo et al., 2018). In organisms, behavioural/motor capacity is dependent on anatomical, physiological and biomechanical features of organisms (Osiurak et al., 2017) and their fruitful coordination dynamics. Dynamics of coordination emerge from an ensemble of interdependent elements forming the unity of the system over time. They cause autonomous control and self-organization (Chemero and Turvey, 2007; Latash and Zatsiorsky, 2016). The '*autonomy*' and emergence of '*self-organization'* providing effectivity of execution are based on interdependence and degree of freedom of the dynamic and complex system elements. They provide control of the execution of agency as the capacity to modulate the coupling strength with affordances within a given environment (Moreno and Etxeberria, 2005; Richardson and Chemero, 2014: Barandiaran, 2017). Regarding the ecological account, perception of affordances can limit environmental actions and depend on organisms' learning capacity and sensorimotor plasticity (Osiurak et al., 2017). Affordances exist independently from the act of perception. The perception serves to guide the action instead of being a mere representation of information content of agency (Michaels, 2003; Ortmann and Kuhn, 2010). Gibson rejected indirect perception theories, which asserts ontological ground of information is dependent on both environment and agent. The agent fulfilled the function of enriching the content of agential information via the perception of environmental stimuli. In contrast to indirect perception theories, the ontological ground of information content of agency exists in the environment for direct perception theories. They are out of agent, and the perception process is associated with the extraction of specifying information that resides in the ambient array where specifying patterns are used for perceiving for acting (Withagen and van der Kamp, 2010; Gibson, 2002).

Chemero's Ecological Theory of Information

According to Chemero's ecological theory of information (2006), non-specifying variables (such as variables that correlate with environmental properties) can also carry information. The perception is conceptualized as a continuous column of disturbance between environment and agent. In contrast to the Gibsonian direct perception account -which defines perception as the detection of specifying information for the agency, there are no direct one-to-one relationships in

Chemero's conceptualization (Chemero, 2006). The link can be equivocality between specifying or non-specifying (such as correlating variables) optical variables of perception and environmental properties which means the same environmental property can be perceived via different variables or vice versa (Chemero, 2006; Withagen, 2004; Withagen and van der Kamp, 2010). Content of the perception or namely agential information becomes a kind of relationship instead of substance (as in conventional theories of information), and the perceptual process of agential information, which is influenced by ontogenetic/developmental, socio-cultural and phylogenetic/evolutionary processes (see Oyama, 2000; Flament-Fultot et al., 2016). The influential processes cause continuous epistemic contact of agents with the environment. As a result of this continuous epistemic contact, cultural conditioning, perceptual experience and inter- or intra-agential variability can cause susceptibility to visual illusions based on incorrect perceptual inference (as in indirect perception theories) or detection of a non-specifying optical variable. This variable correlates with perceived property/ property of interest but is not specific to it, instead of inadequacy or invariability of information (as in Gibsonian theory of direct perception) (de Wit et al., 2015).

Extension of Agency within Ecological Context towards the Realm of Culture

The ecological context of the agential experience of humans (affordance, perception, action, agential information and cognition) is shaped by sociocultural scaffoldings, and the concept of affordance can be extended towards the realm of culture. The affordance can be divided into the '*natural affordance'* and '*cultural affordance'*. The '*natural affordance'* refers to biological (agential capabilities) and material/environmental ground (environmental properties) of perceivable action possibilities within the given environment. The '*cultural affordance'* or '*conventional affordance'* refers to socio-cultural background (such as sociocultural practices, shared intentionality, joint or collaborative actions, expectations, norms and so forth) of affordance which shape behaviours (Ramstead et al., 2016; see also, Turner and Turner, 2002; Oshlyansky et al., 2004; Turner, 2005). The behaviour settings constraint the actions or potentials for action via cultural contextuality, normativity and culture sphere. They manifold the set of behavioural possibilities and modulate specific ways of acting. Readiness for bodily certain way of acting is modulated by invitation of affordances, but some of the affordances do not invite behaviour (Withagen et al., 2017, Norman, 1999).

Agency within Cultural Context and the Problem of Meaning

The 'engagement' of cultural affordance is dependent on embodied, cognitive and affective substrates of action, capabilities of agent and the sociocultural scaffoldings of embodied experience. It facilitates inferences about the cultural sphere or cultural world as ecological

context or equipment of being. In this regard, the cultural world can be conceptualized as meaningful for perceiving, thinking, and acting for agents/organisms and cultural knowledge. They facilitate the realization of agential capacity within a socio-cultural context (Ramstead et al., 2016; Turner, 2005; Riemer and Johnston, 2017). The semantic content of agential experience becomes intensional and serves the interpretations of other agents within a symbolically and linguistically mediated culture sphere. Theoreticians of enactivism have rejected the 'intensionality' of the semantic content of agential experience. The semantic content is conceptualized as an emergent property of action-perception cycles. The agent's embodied engagements with its environment are formed by the dynamic constitution of adaptive cognitive systems of the agent (Caiani, 2018; Ramstead et al., 2016).

Ladscape and Field of Affordances

The cognitive agents experience the agency via embodied engagements mediated by perceived afforded actions within the environment or culture sphere. The entire set of perceived affordances within the environment or culture sphere for a given environment is called the 'landscape of affordance', which corresponds to the term '*niche*' within evolutionary and anthropology literature. In this regard, a niche is defined as an ecosystem affording the survival of an agent/organism or population. The available affordances within the niche (either individual-specific or group/population-level) have a variety of dynamic relationships (in terms of action potentials), providing polyvalent characteristics for existing niche and facilitating the constitution of new ecosystems (Heras-Escribano and De Pinedo-García, 2018; Rietveld and Kiverstein, 2014; Heras-Escribano, 2020). The 'salient affordances' mediate the field of actualization or potentials of actualization of embodied engagements. As a result of autonomy and intelligent adaptivity, active and dynamic interactions cope with the given environment or culture sphere as a function of the agent's interests, concerns, and states at a given time and place. This situation results in the '*field of affordance*' formed by relevant affordances for each agent. It results from the dynamic copings and automatic agential assessments of the agent within the landscape of affordances. It refers to solicitation of affordance of the agent through specific forms of perceptual-emotional appraisal and readiness to act (Ramstead et al., 2016; Rietveld et al., 2018).

Landscape of Affordances and the Normativity/Selectivity of Affordances on Action

Relationships between affordance and embodied engagements within the 'landscape of affordance' are both '*descriptive*' (because of formative role on actualization of action) and '*prescriptive*' (because of selectivity/normativity for an appropriate mode of action). It is guided by shared expectations, cultural information, content-involving representations letting the agent makes a correct inference about some aspects of intentional systems (e.g., intentions of other

agents) and other symbolic systems (e.g., cultural symbols) (Norman, 1988; Ramstead et al., 2016; see also, Lo Presti, 2016; Heras-Escribano and de Pinedo, 2016). In the cultural context, the affordance of cultural artefacts has polyvalent characteristics due to the dynamical and multi-dimensional nature of the cultural context. The prescriptive aspects of agential interaction and material domain of these interactions serve stabilization and direction for novel possibilities for embodied engagements with cultural affordances (Terrone and Tagliafico, 2014). The ecological conceptualization of content involving representations of agential inferences within cultural context is rejected by theoreticians of enactivism. It has been asserted that embodied engagements of agents through perceptual and cognitive processes do not have content. It emerges due to adequate context-sensitive adaptive couplings between agent and culture sphere (Thompson, 2007; Hutto and Myin, 2013).

Bodily/Embodied Characteristics as the Primary Source and Ontological Ground of Affordance

Embodied engagements with cultural affordances have a constitutive role in the agency's perception of affordance and execution. In the light of enactivism, 'embodied modes of agency' or 'embodiment' can be conceptualized as the 'first experiential medium of encountering the socio-material realities' and 'primary/primordial site of performing the umwelt and culture sphere'. In this regard, the body becomes the primary source and ontological ground of affordance where embodiment functions. The intermediate zone of (re-)organizations between the socio-material realm and innovative technoscientific or artefactual domain occurs in the ecological context (Spatz, 2017; see also, Hirose and Ziemke, 2002). Engaging (Malafouris, 2018), entangling (Gherardi, 2017), or imbrication (Leonardi, 2011) with the socio-material world through embodied agential experience or embodiment give a chance to experience different modes of skilled practices. They are tinkering, tuning or tracking on complex and specific material processes through epistemic engagements. Tinkering is associated with material composition oriented embodied engagement; tuning is conceptualized as a mutual resonance between embodiment and socio-material realm through entanglement, and tracking is defined as directionality of goal-oriented imbrication or constitutive entanglement (Spatz, 2017). In these processes, bodily manifestations become the ground of landscape of affordances and agential actualization as externalization and socio-materialization of implicit multi-dimensional and dynamic relationships within embodied agency/embodiment. Bodily agential actualization has complex and multidimensional spatiality, which provides the diversity of bodily experience to encounter the emergent diversity and polyvalence of the socio-material realm (Hirose and Ziemke, 2002).

Ecological Agency within Tool Use Context: Different Forms of Affordances

The 'embodiment' or 'embodied agential actualization' can be manipulated via tool use. In embodiment or embodied agential actualization within tool-corporation context, the tools function as the mediator of encountering the socio-material realm. The tool-object interfaces externalize the body representation (especially by hand-tool interface) in the cognitive system. They also provide additional contextuality and perceptibility of affordances (see Osiurak and Badets, 2016; Osiurak et al., 2017). Discussions on externalization/assimilation processes within the tool-body incorporation framework emerge new contextual relationships (see Iriki and Taoka, 2012). The ways of perceptions provide the emergence of new definitions for parameters, contextual relationships, components, sub-domains of environment/object-tool-embodied agent system and various '*hybrid affordances'* within this system (see Hornecker, 2012). In terms of conceptual/perceptive, contextual components of mechanics of action, there are several types of affordances in different classifications. Some of them are;

- '*physical vs learned affordance*' (emphasizing on contextual vs mechanistic dimensions of affordance) (Norman, 2002),
- '*affordance vs functional affordance'* (underlining semantic context vs physical/mechanistic dimensions of affordance) (Young, 2006),
- '*micro- or pure physical affordances'* (stressing set of parameters of the biomechanical dimension of affordance) (Ellis and Tucker, 2000),
- '*affordance and paired object affordance'* (Humphreys, 2001),
- '*affordance'* (Buxbaum and Kalenine, 2010) (accentuating difference of conceptual and contextual (cultural) dimension from the mechanic dimension of affordance),
- '*variable vs stable affordance*' (Borghi and Riggio, 2015) (stressing short-term temporal axis and long-term cultural contextuality of affordance) are classified as the types of affordances.

Contextual and Biomechanical Dimension of Agency within Tool-Use Context

In the tool use mode of agential experience, embodied actualization/execution of agency is based on affordance perception. The execution system's biomechanical requirements and contextual relationships occur within the field of affordance and motor control. The neural counterpart of these cognitive processes is associated with the 'dorsal' (execution and control), 'ventral' (immediate perception) or 'ventro-dorsal' (contextual understanding) system within the cerebral system (Ferretti et al., 2021; Osiurak et al., 2017). As a result of dynamic, synergetic, synchronous or asynchronous feedbacks and couplings among these neural counterparts and transformation of visual information to action-related information, visually guided motor control and agency execution within the different frame of references are achieved (see Fajen, 2009). In terms of the

'ideomotor' account, intentional directionality of actions towards the field of affordances within given environments is mainly coded through the perceptual effects (see Shin et al., 2010). During mental simulation of tool use oriented agency, perceptual effects and appropriate agential actualization is guided by mechanical and abstract knowledge about semantic and functional context and reasoning about physical properties of the tool (Osiurak and Badets, 2016; Osiurak et al., 2017). The contextual relationships are learned and created either actively or passively within the cultural sphere. Humans are unique in accumulating transmission of contextual information, saving the cultural artefacts (and tools) for the future, and making innovations. Simple tools extend motor capacity; however, more complicated tools can extend humans' sensory and cognitive capacity. They facilitate qualitative changes in the mechanical content of action execution and transform behaviours (Iriki and Taoka, 2012; Pellicano et al., 2011; Turner, 2005, Osiurak et al., 2010).

Early Representationalist Investigations on Neuro-Dynamics of Agency

Neuro-dynamics of agential actualization in different modes (either tool-use or non-tool use, in different modes such as motor execution, imagery, marking or observation) has been widely investigated by cognitive neuroscientists and neuropsychologists (Hardwick et al., 2017; Hardwick et al., 2018; Maksimenko, 2018; Bhattacharjee et al., 2021; Eaves et al., 2016, see also, Mulder, 2007). In terms of neural approaches, early investigations about agential actualization were mainly representation oriented. They were based on investigations of one-to-one representational neural counterparts of modes, and they created parameters of agential actualization (de Wit et al., 2017). In standard representationalism accounts, such as FARS (Fagg-Arbib-Rizzolatti-Sakata Model), agent and environment are conceptualized as separate with no mention of mutuality between them (Fagg and Arbib, 1998). Also, the affordance effect in Tucker and Ellis' work posits the action and perception as separate with no mention of mutuality between them (Tucker and Ellis, 1998). The affordance competition account of Cisek (2007) also rejects action neutrality of environment. It conceptualizes agential actualization within the normative limits of adaptivity as the functional product of evolution. The work asserts parallelism and separateness between cognition, action, and perception instead of mutuality (Cisek, 2007).

Transcending Dichotomies: towards more Dynamic Neural Investigations on Agency

Thanks to the rise of sensory substitution oriented dynamic approaches, mechanisms of perception-action couplings of the agent-environment system and direct perception theory in Gibsonian ecological program can be investigated without dichotomy oriented thinking (such dichotomies as perception-action, object-subject, agent-environment, physical-perceived environment) (Hurley, 2001; Sønderstrup-Andersen et al., 2001; Richardson et al., 2008). Some of

these dynamic approaches can be listed as, cross- or supra-modal neuroplasticity (Calvert, 2001; Bushara et al., 2003; Senkowski et., 2008; Marinkovic et al., 2003; Eger et al., 2003; Spunt and Lieberman, 2012), neural reuse (Anderson, 2010, 2014), neuronal recycling (Dehaene and Cohen, 2007; Menary, 2014)), neuro-degeneration or neural lesion researches (Randerath et al., 2021; Sevos et al., 2016; de Vega et al., 2019). Some of technological advances in neuroimaging research (such as functional fingerprinting in fMRI) could also allow dynamical investigations which facilitate transcending dichotomies (Finn et al., 2015; Demeter et al., 2020). The resonance between neural dynamics of agential actualization is not based on one-to-one relationships between brain anatomy/structure and physiology. Instead, there are continuous polyvalent mappings (one-to-multiple, multiple-to-one, multiple-to-multiple, one-to-one) between brain anatomy and physiology. This matter is implied by using and reusing neural regions and achieved by their functional and structural connectivity (Pessoa, 2014). Structural and functional top-down and bottom-up polyvalent interactions and couplings (from single-neuron level to brain region scale) cause multidimensionality in perception and utilization of affordances. It also brings about complementary within the agent-environment system (de Wit et al., 2017).

Cognitive Benefits of Neurodynamics of Perception-Action Couplings within the Context of Agency

Neurodynamics of polyvalent neural mappings and perception-action couplings providing complementary within agent-environment system ensure minimisation of computational free-energy of the brain (Friston et al., 2006; Friston, 2009, 2010). The socio-materiality of the cultural landscape of affordances (Dijk and Rietveld, 2017; Rietveld et al., 2018) can provide cognitive congeniality (de Leon, 2006) and *'offloading'* (Risko and Gilbert, 2016). For the sake of continuity of self-organisation, resisting 'entropic dissipation' to be far from 'thermodynamic equilibrium', organisms maintain their existence in their phenotypical steady state via minimising the information-theoretic quantity 'variational free-energy' (Ramstead et al., 2016). In this context, for minimising the computational energy, the brain -as a complex dynamical system- uses a generative model for inferring and predicting and extracting function and encoding information dynamically. The distal environment sets probability distributions in the most contextually appropriate way (Friston, 2010; Clark, 2013; Williams, 2020). The reduction of prediction errors can be achieved by optimizations of actions (active inference), perception and learning (selecting the best reasonable hypothesis for an error minimising) within the prediction hierarchy in the light of context-sensitivity (Friston, 2012; van Es, 2020). The prediction hierarchy can be achieved through precision weighting and selective sampling among weighted precisions and modulated by attention gating mechanisms as the primary driver of action-perception (Feldman and Friston, 2010; Kanai et al., 2015). The attention gating mechanisms balance top-down prediction signals of

the generative models and bottom-up error signals in attention to increasing the signal-to-noise ratio (Clark, 2013; Gordon et al., 2019).

Cognitive and Cultural Benefits of Execution of Agency within the Context of Enactivism

Radical approaches within post-cognitivism, such as enactivism, rejected the semantic dimension of conceptualization of the brain as error reducing generative model for avoiding or at least minimising the implicit representational content understanding. They excluded semantic content from the cognitive system of an agent towards some forms of cultural context (Hutto et al., 2020; see also Hutchins, 2014). In this context, agential actualization through embodied engagements with the field of affordances within a given environment minimizes prediction error and computational free energy through skilled intentionality, selecting the best fitting engagement mode. The solicitations of affordance function manipulate the organism-environment dynamics towards the direction of the most efficient way of energy minimisation (Bruineberg and Rietveld, 2014; Bruineberg et al., 2018; Kiverstein et al., 2019b). Set of shared expectations and emerging patterns can also facilitate and modulate the minimisation of computational energy of the brain in enculturation and ontogenetic and learning processes. They manifest the shared expectations through joint actions and behaviour settings in the socio-material realm (Ramstead et al., 2016). In terms of the 'enactivist' account, the domain-specific patterns form cultural normativity and contextuality within the socio-material realm. These patterns are good sources of cultural meaning. Moreover, the bio-mechanical dynamics of the agent-environment system is sufficient where agents derive or infer the meaning correctly and minimise the computational free energy thanks to contextuality (Hutto et al., 2020; see Gallagher and Allen, 2018; de Jesus, 2018).

2.3.2 The experimental research on the 'Agency' in Cognitive Neuroscience and Psychology

Experimenting Agency: Clusters of Different Studies

We see the 'agency' has widely been examined via neuro- and cognitive psychology experiments. The studies mainly concentrate on four different aspects relevant to agency. These can be listed as 1) short term/immediate effects of agency, 2) long term effects of agency, 3) kineaesthetics or contextuality of agency system (i.e., perception-action coordination or contextuality) or 4) other cognitive mechanisms underlying agential experience. In this regard some of the studies in these categories can be listed as;

- impact of short-term/immediate manipulations (such as action inhibition (Vainio et al., 2011; Vainio et al., 2013; see also Xu et al., 2015), affordance motivation/competition (see Summer and Ahmed, 2006; Cisek, 2007; Calderon et al., 2018))
- long term processes (e.g., development (Müller et al., 2017: Valadi et al., 2018), skill acquisition and learning (Franchak et al., 2010; Pezzulo et al., 2010; Zhu and Bingham, 2010;

Seifert et al., 2013; Ossmy and Mukamel, 2016), sport training (Hristovski et al., 2006; Fajen et al., 2008; Riley et al., 2009; Kimmel and Rogler, 2018; Araújo et al., 2019) or evolution (primarily cultural) (Stout and Chaminade, 2007; Cutting et al., 2011; Neldner et al., 2017)

- kineaesthetics or contextuality of different elements of agent-environment system (agent-(inter-)action-environment/objects or tools+ objects) (see Osiurak et al., 2017) or the system's contextuality (e.g. sociality, culture) (see Oshlyansky et al., 2004; Turner, 2005) , or mechanisms of perception-action couplings (or perception of agency) (see Smets et al., 1994; Stoffregen, 2000; Creem-Regehr and Kunz, 2010; Weichold, 2018)
- other cognitive mechanisms underlying agential experience such as action decision (see Yoon et al., 2010; Osiurak et al., 2013; Comalli et al., 2017), estimation and calibration (Bastin et al., 2010; Day et al., 2015; Baker and Cinelli, 2017; Lamb et al., 2017; Hajnal et al., 2018), aesthetic appraisal (Heft, 2010; Xenakis and Arnellos, 2013), memory (Mecklinger et al., 2004; Bailey et al., 2008; Pecher et al., 2013) to understand the agency profoundly.

In addition to the examination of agential experience within agent-environment framework, there is also some research dealing with modelling the agency (Joo et al., 2013; Thill et al., 2013; Zech et al., 2017) or designing agency (Norman, 1999; Maier and Fadel, 2003; Maier et al., 2009a; Maier et al., 2009b). However, these studies will not be detailly mentioned within this section.

Experimenting Agency System (Agent + (ınter-) Action + Environment): Manipulating the Agent

The agent is the first element in the agent-environment framework (agent, (inter-)action, object/environment/tool and object). There can be a cluster of studies dealing with agent manipulations about its/his/her agency. The first cluster of studies mainly focuses on perceptive or motor manipulation (mainly perceptive or motor deficit-oriented research) of pre-reflective self-awareness of agent's ownership/potency-control/capacity (either partially or whole agency) to understand the impact of reflexive consciousness of agent. In the medical realm, especially neurology, some research investigating the neural and cognitive mechanisms beyond '*alien hand syndrome'* can be classified within this category (Biran and Chatterjee, 2004). The disparity between the patients' (agents) intentions and the executed actions results in the 'alien hand syndrome'. The researches mainly concentrated on the origination domain of the disparity (see Biran et al., 2006, Sarva et al., 2014; Hassan and Josephs, 2016) as either neural (e.g., neurodegeneration or lesions) (Assal et al., 2007; Gellman and Ng, 2018) or cognitive (e.g., affordance perception initiating uncontrollable actions) (McBride et al., 2013) or muscle (e.g., lack of capability of controlling actions due to anatomical or physiological deficits) (Bartolo et al., 2011; Park et al., 2012). The questions of motor control in different domains such as execution,

imagery tested demanding and avoiding the tasks (e.g., grasping task, *'go-no go'* task, affordance compatibility task) (Brainin et al., 2008; Cheyne et al., 2009; McBride et al., 2013).

Experimenting Agency System: Manipulating the Agent's Self-Location & Spatiality

In psychiatry, neurology, and neuro-, or cognitive psychology, research on '*autoscopy*' or '*autoscopic phenomena',* the patients or manipulated healthy subjects experience extracorporeal self-location due to the illusions (healthy subjects) or perception deficits such as hallucinations (patients). They can be classified in the same cluster (see Brugger et al., 1997; Blanke et al., 2004; Zamboni et al., 2005; Arias et al., 2007; Anzellotti et al., 2011). In healthy subjects, one of the examples of partial autoscopic manipulation is '*rubber hand illusion'.* The sense of agency/ownership of the subject's hand is manipulated via stimulation of the subject's hand. It applies a similar stimulation process to a rubber hand synchronously without any time lag (Tsakiris and Haggard, 2005; Costantini and Haggard, 2007; Rohde et al., 2011). In different modes of '*autoscopy* as *autoscopy'* (self-location is anchored the physical body but existence of hallucination/perception deficit about second own body outside the physical body), '*heautoscopy'* (perceived self-location at both the physical and the illusory body), '*out-of-body illusion'* (a sense of disembodiment with the physical body and hallucination/perception deficit as the attribution of self-location to another body) (Blanke and Arzy, 2005; Blanke and Mohr, 2005; Blanke and Castillo, 2007; Metzinger, 2009) or partial autoscopy like, '*rubber-hand illusion'*, similarly *'alien hand syndrome'*. The research investigates the origination-domain or underlying mechanisms and processes (behavioural, cognitive, or physiological). Its effects are on agential capacity and experience via suitable motor tasks and psychometric tests (see Blanke et al., 2004; Jerath et al., 2016).

Between Agent and (Inter-) Action: Perception and Preperation of (Self-) Agency

There are cognitive pre-processes of agency execution in terms of agent-environment framework, between agent and action or in the intersection of agent and action. From the action-perception couplings framework, the processes can be listed as the;

- 'perception of agency' (action observation/observation of execution of agency and judgements/observation of self-agency) (Hohwy, 2007; Balconi, 2010; Nahab et al., 2011; Friston, 2012; Timm et al., 2014; Timm et al., 2016; Montemayor and Phillips, 2017)
- 'sub-domains of preparation of execution of agency' (e.g., action estimation/calibration, action decision, action selection) (Haggard, 2005; Cisek, 2007, Sato, 2009; Costantini et al., 2010; Smith and Pepping, 2010; Obhi and Hall, 2011; Cisek and Pastor-Bernier, 2014; Chambon et al., 2014).

The perception of agency can be defined as the 'perceiving agency of another agent(s)' or 'self-agency during the execution of agency in the modes of actions without objects' (intransitive action); '(inter-) actions with the objects/environmental elements' (such as grasping, grabbing an object, opening a door) (transitive action) and 'actions where a tool is a mediator for interacting with another object' (tool-use actions) (Gallese, 2000; Vingerhoets et al., 2010; Wadsworth and Kana, 2011; Bonivento et al., 2014; Wamain et al., 2014; Bartoli et al., 2014; Natraj et al., 2015; Handjaras et al., 2015; Triberti and Riva, 2016).

Between Agent and (Inter-) Action: Experiment Clusters on Perception of (Self-) Agency System

In the experiments of perception of agency, some of the clusters of the experiments can be listed as;

- the elements/content or context (background of perceiver or agent, -e.g., development, skill acquisition, learning, habits, enculturation, health status, behavioural or neural asymmetry (such as handedness and hemispheric laterality) (Oshlyansky et al., 2004; Turner, 2005; Franchak et al., 2010; Pezzulo et al., 2010; Zhu and Bingham, 2010; Randerath et al., 2011; Kelly and Wheaton, 2013; Seifert et al., 2013; Lameira et al., 2015; Ossmy and Mukamel, 2016; Müller et al., 2017: Valadi et al., 2018; Thomas et al., 2019);
- the agent-action-environment system, -e.g., frame of reference, spatiality and temporality, mechanical or action relationships, function, semantic (Yoon et al., 2010; Ortmann et al., 2014; Dijk and Withagen, 2016; Lanamäki et al., 2016; Osiurak et al., 2017; Feven-Parsons and Goslin, 2018; Gastelum, 2020; Qi et al., 2020);
- manipulating either perceiver or perceived system by omission of elements (content) (e.g. comparing behavioural/neural changes with vs. without agent, object, tool or more than one element) (Barbieri et al., 2007; Randerath et al., 2011; Ujlayan, 2018)
- congruency of interactions/compatibility of the elements (context) (e.g., comparison of compatible vs. incompatible pair of interactions among agent, action, object, tool) (Humphreys et al., 2010; Kourtis and Vingerhoets, 2015; Guerard et al., 2015; Wokke et al., 2016; Hailperin-Lausch, 2017)
- mode/modality comparison (context) (e.g., comparison of different mode of actions, different kind of objects or tools, different sensory modality of agency) (Edwards et al., 2003; Worgan and Moore, 2010; Bach et al., 2011) were studied.

Experimenting Agency System: Manipulating the Agent's Temporality and Sense of (Self-) Agency

In addition to the manipulations on the spatiality of the body's 'autoscopy' experiments, the experiments are based on the manipulations on the agency's temporal order (or causal order/causality). The 'temporal delay' or 'distortions of directionality in the causality' between

the ‘execution of agency’ and ‘perception’ or ‘sensation of consequences of the executed action’ (e.g., illusions, unexpected consequences) and ‘perceptual adaptation to temporal delay/distortions of causality’ are investigated. The aim is to understand the effects of perception of time and causality (correlation between judgements on temporal order and sensation of agency) on the execution of agency and the sense of agency (Nahab et al., 2011; Timm et al., 2014; Timm et al., 2016).

Experimenting Agency System: Agent’s Sense of (Self-) Agency and Motor Simulation

In the ‘perception of agency’ and ‘preparation of agency’ (action decision, calibration, selection and so on), the motor simulation plays a significant role in understanding/awareness of (self-/other/collaborative-interactional) agency. In the simulations of agency executions or motor simulations, the accuracy of the execution of action judgements about capabilities of the body, inferences about calibration of action, prediction of action and error detection, properties and context of the object for action involve the fulfilment agency (Jeannerod, 2001; Avenanti et al., 2007; Witt and Proffitt, 2008; Witt et al., 2010; see also, O’Shea and Moran; 2017; Panasiti et al., 2017). The motor simulation process is mainly associated with suppressions of neural oscillations in the motor-related areas (especially ‘Rolandic mu oscillation’ and its frequency components in alpha and beta band ranges) in EEG (Pfurtscheller and Lopes da Silva, 1999; Panasiti et al., 2016; Rayson et al., 2016; Pomiechowska and Csibra, 2017) and ECoG (Toro et al., 1994; Crone et al., 1998; Pfurtscheller et al., 2003; Miller et al., 2007) and MEG experiments (Salmelin and Hari, 1994; Gaetz and Cheyne, 2006; Hasegawa et al., 2016) and BOLD imaging (blood-oxygen-level-dependent imaging) of fMRI-based experiments (Calvo-Merino et al., 2006; Bach et al., 2010; Arnstein et al., 2011).

Neurophysiology of Motor Simulation: Topographic Distibution and Levels of Suppression

The ‘topographical distribution’ (e.g., somatotopic distribution within different cortical areas such as premotor and motor cortex, regional distribution on the cortex such as regions of the occipital, frontal and temporal cortex and mappings of subcortical areas and cerebellum, lateral distribution across hemispheres) and ‘levels of suppression of neural oscillations’ (e.g., alpha, beta, mu and gamma) can vary following the simulated mode of action. The motor imagery, execution, observation, verbalisation (also hearing, reading an action sentence), imagery and observation of inferential action and marking in a different frame of references such as first- and third-person perspective occur under the simulated mode of action (see Lorey et al., 2013; Gatti et al., 2013; Lorey et al., 2014; Hardwick et al., 2017). The several mechanisms drive the variations in spatial distribution and levels of suppressions in brain oscillations. The variations of the content, context and elements of the action vary due to the stimulation mechanisms of the

action. With the frame of reference (ego- vs allocentric) and mode of the action, neural representations of sensory modality characteristics of mode of action (e.g., hearing, reading, seeing the action) occur. Moreover, the neural representations of emergent properties of the action, hemispheric lateralization (contra- and ipsi-laterality) accordingly with the frame of reference of representation of action and behavioural asymmetry within the action, additional cognitive demands/cost of the action or agent or object happen by the stimulation mechanisms of the action (Buccino et al., 2001; Calvo-Merino et al., 2005; Vignemont and Haggard, 2008; Vogt et al., 2013).

In terms of spatial distribution, the central regions of the brain taking an active role during motor simulation. They can be listed as; the primary motor cortex and somatosensory cortex, the premotor cortex (especially dorsal and ventral areas), the supplementary motor region, the inferior frontal cortex, posterior parietal regions such as the inferior and the superior parietal lobe, the basal ganglia, the cerebellum, as well as the occipitotemporal cortex (see Filimon et al., 2007; Filimon et al., 2015; Babiloni et al., 2016; Debnath et al., 2019). The activity of these mentioned areas can change in terms of hemispheric laterality (mainly contra-lateral but also ipsilateral) accordingly demand of the action in terms of behavioural asymmetry (e.g., handedness) (Proverbio et al., 2013; Kourtis and Vingerhoets, 2015; Donoff et al., 2018). Also, they can change following the cognitive processes additionally to the action itself. Some brain areas are required for understanding semantic/ functional context or logical reasoning/inference (see Osiurak et al., 2010; Osiurak et al., 2017), planning and designing the content of the action (Behmer and Fournier, 2014). In terms of the spatial distribution of different modes of action (e.g., execution, imagery, observation, referential action, verbalisation), the spatial distribution of neural representation is mainly similar with changing suppression levels of neural oscillations as an indicator of functional equivalence (see Lorey et al., 2013; Gatti et al., 2013; Lorey et al., 2014).

From Motor Simulation to Motor Empathy: Towards Phenomenal Unity of Experience of Agent(s)

The electroencephalography (EEG) scalp recordings (Pfurtscheller and Lopes da Silva, 1999; Panasiti et al., 2016; Rayson et al., 2016; Pomiechowska and Csibra, 2017), magnetoencephalography (MEG) recordings (Salmelin and Hari, 1994; Gaetz and Cheyne, 2006; Hasegawa et al., 2016) and electrocorticography (ECoG) recordings on epilepsy patients (Crone et al., 1998; Pfurtscheller et al., 2003; Miller et al., 2007) reveal evidence to understand more complicated mechanisms such as motor empathy. The mechanisms of motor empathy can be defined as the human capacity to combine motor and visual information processing with the intentions and emotions of other(s) about the actions. Motor empathy can emerge as a result of frequency couplings and synchronizations (gamma rhythm) and de-synchronizations according to

Pineda's model (see Pineda, 2005). The monkey brain studies showed that during different modes of action (in both execution and observation), some neural populations in inferior frontal and parietal areas are activated, called the 'mirror neurons'. The equivalent neurons in the human brain play a key role in learning and the capability of motor empathy within embodied first-person perspective (Pellegrino et al., 1992; Gallese et al., 1996; Rizzolatti et al., 1996; Gallese and Sinigaglia, 2011).

Neurophysiology of Motor Simulation & Empathy: Topography and Components of Mu Oscillation

The advancements of neuroimaging and electrophysiological technics are based on combining different techniques. They together improved the temporal and spatial representation of neural activity recordings (e.g., combining fMRI with EEG). So, the mirror neuron firing mechanisms, spatial and temporal resolution, sub-components of mu rhythm in different frequency band ranges, and spatial, temporal characteristics of de-synchronization began to be understood profoundly (Arnstein et al., 2011). The spatial distribution of neural representations of different frequency ranges of 'mu rhythm' -such as alpha frequency range components (i.e. 8–13 Hz) on primary motor cortex and beta frequency range components (i.e. 14–24 Hz) on anterior areas as on somatosensory cortex and parietal areas- (Salmelin and Hari, 1994) is the evidence of the composite nature of the integration of sensory and motor components during the experiencing different modes of agency (e.g., motor execution, imagery, observation) (Cochin et al., 1998, Babiloni et al., 2002; Martineau and Cochin, 2003; Perry and Bentin, 2009). The findings of EEG and MEG showed that suppressions/de-synchronization of frequency components of 'mu rhythm' in alpha band range is relevant to the somato-motor information processing as the ground of motor empathy (Pineda, 2005). Some functions as calibration, estimation, attention of action (e.g., precise grip vs flat hand movement) (Muthukumaraswamy et al., 2004) and beta frequency range correspondent are associated with kinematic properties such as haptic, tactile or motional characteristics of the action (Avanzini et al., 2012; Babiloni et al., 2016).

Phenomenal Unity of Experience/Execution of Agency: Integration of Perception and Action

In addition to correlations between different modes of action or functions of preparations of action execution and mechanisms of neural oscillations, it is important to examine how different cognitive modalities (e.g., perception, memory, consciousness) play a role in the fulfilment of agency. In the context of the thesis, multisensory and sensorimotor integration (especially between perception and action) during agency will mainly be examined in the transitive action modality of agency (except tool use modality). The fulfilment of agency is mainly dependent on integrating perception and action in daily life (Lalanne and Lorenceau, 2004; Warren, 2006; Schenk, 2010; Gegenfurtner et al., 2011; Hutchison and Gallivan, 2018). However, there are

vigorous debates (i.e., various theoretical positioning and experimental research) on how these two cognitive processes integrate each other during the process of execution of agency and their (inter-/in-/-) dependency characteristics (Ward, 2002; Lalanne and Lorenceau, 2004; Creem-Regehr and Kunz, 2010; Ridderinkhof, 2014).

Theories Emphasizing Shared Representational Mechanisms between Perception and Action

In this regard, some of the theoretical positions assume that the shared or integrating mechanisms (such as neural mechanisms or motor imagery/simulation) between action and perception (e.g., *common coding theory* (Prinz, 1997), *event coding theory* (Hommel et al., 2001), *motor/embodied simulation theory* (Gallese and Goldman, 1998; Jeannerod, 2001)) to elucidate the coordination between them during the execution of the agency. By starting from the assumption as the significant overlap between neuro-anatomical areas of perception and action (Grezes and Decety, 2001), these theories mainly assume the existence of *'(embodied) motor imagery'* which provides the functional equivalence and integration through motor simulations (Parsons, 1994; Gallese and Goldman, 1998) or shared representations (Prinz, 1997; Gegenfurtner et al., 2011).

Unification Theories: Phenomenal Unity and Functional Integrity of Perception-Action Couplings

These unifying/integrative approaches have been supported by the discovery of mirror neurons on area F5 in the macaque brain (di Pellegrino et al., 1992) and experimentations (Buccino et al., 2001; 2004; Kohler et al., 2002; Decety and Jackson, 2004; Gangitano et al., 2004; Oberman et al., 2007) in terms of (embodied) motor imagery/simulation assumption (Decety and Grèzes, 2006; Gallese and Sinigaglia, 2011; O'Shea and Moran; 2017; Savaki and Raos, 2019). Moreover, experiments manipulating embodied perception such as body illusion experiments (e.g., rubber hand illusion, autoscopy) support integrative approaches (Botvinick and Cohen, 1998; Tsakiris and Haggard, 2005; Kammers et al., 2009; Anzellotti et al., 2011). Additionally, experiments manipulating body schema such as tool use experiments (Iriki et al., 1996; Obayashi et al., 2001; Maravita and Iriki, 2004) where spatial (perception/judgement) is needed for action execution (e.g., reaching in peri-/extra-personal space) (Holmes et al., 2004a; 2004b; Witt et al., 2005; Holmes, 2012; Canzoneri et al., 2013; Morgado et al., 2013) show also significant evidence for unification theories of perception and action within the context of embodied cognition (Holmes and Spence, 2006; Proffitt, 2006; Cañal-Bruland and Van Der Kamp, 2015). However, integration characteristics of these cognitive modalities (e.g., direction and weight of effect, inter-/in-/dependency) still needs clarification (Stock and Stock, 2004; Beets et al., 2010; Shin et al., 2010; Witt et al., 2016).

Considering Integration and Unification Mechanisms between Perception and Action

Differently from traditional information processing approaches, which separate action totally from perception, various contemporary theoretical approaches consider acting as a form of perception, component of perception, or just influencing perception (Creem-Regehr and Kunz, 2010). Tremendous theoretical approaches assert (dominance of) perception effects on action for more than one century (Hecht et al., 2001; Shin et al., 2010; Hommel, 2013). However, examining effects of the action on perception needs clarification of characteristics of action (e.g., frame of reference, spatiality/field, type, mode, transitivity/ecology) and characteristics of relationship (e.g., interaction, integration, influence, inclusion) and characteristics of its dynamism (e.g., under different circumstances and time during life span, temporal and hierarchical order) (Blake, and Logothetis, 2002; Warren, 2006; Creem-Regehr and Kunz, 2010; Shin et al., 2010). Additionally, the complexity of defining what the perception is (e.g., the inclusion of consciousness or not, vision-oriented or not) (Leopold and Logothetis, 1999) and the complexity of defining the limits between action and perception (e.g., characteristics and (temporal or hierarchical) order of transitions within feedback mechanisms) (Giorello and Sinigaglia, 2007) creates additional difficulties to define the relationship between them, precisely. Also, divergent results of other experimental research on perception-action relationships and technical difficulties of experimenting with these relationships' dynamism and multi-dimensional characteristics contribute to the continuity of the ongoing debates (Gegenfurtner et al., 2011).

Dissociation Theories: Anatomical Distinction & Functional Differentiation of Perception & Action

Although some theories (e.g., common coding, motor simulation) emphasize the shared representation (neural) mechanisms between perception and action to explain the unified nature of experience within the context of (embodied) phenomenology, some of the other ones emphasize functional and neuro-anatomical dissociations between the mechanisms of perception and action (Goodale and Milner, 1992; Milner and Goodale, 2010). In this regard, one of the most known theories is *two visual pathways/systems theory* (Goodale and Milner, 1992) which underlines two different (neuro-anatomical and functional) visual systems serving recognition and control during visuomotor coordination (Bridgeman et al., 2000). Researches on patients with optic ataxia and visual agnosia contribute to the emergence of theories separating two processes functionally and neuro-anatomically (i.e., action and perception) (Culham et al., 2003; James et al., 2003; Karnath and Perenin, 2005). Additionally, on healthy subjects, visuomotor coordination experiments under illusionary visual stimuli (e.g., Ebbinghaus illusion, Müller-Lyer illusion, Ponzo illusion) provide diversification of ideas and these theories (Aglioti et al., 1995; Franz, 2001; Glover, 2002; Glover, 2004; Briscoe, 2008). Another contribution comes from the performance

experiments manipulating visuomotor coordination such as grasping, reaching and action calibration experiments (Andre and Rogers, 2006; Hesse and Franz, 2010; Klatzky et al., 2010; Blangero et al., 2011; Whitwell et al., 2011).

Ecologcial Theories: Considering Perception and Action within Ecological Context

Another significant contribution to ongoing debates on each theoretical position (i.e., unifying/integrative theories or dissociation/separative theories) has come from studies considering the ecological dimension of visuomotor control, especially during transitive actions or tool use (Michaels, 2003; Turvey, 2004; Creem-Regehr and Kunz, 2010; Engel et al., 2013). Transitive actions or tool use requires visuomotor coordination accordingly with constraints of characteristics of the body, constraints/ conceptualisations of function/context for fulfilment of agency and properties of object/ tool relevant to possibilities of (inter-) action for the agency of organism/agent within a given environment (Wagman and Carello, 2001; Stoffregen, 2003; Braund, 2008; Osiurak et al., 2010). One of the ecological approach pioneers, James Gibson, coined the term 'affordance'. It refers to the perceived action potentials specified by the properties of the target object/tool for embodied fulfilment of agency (Gibson, 1977; 1979; see also, Hirose and Ziemke, 2002; Richardson et al., 2008). In contrast to indirect perception theories of his age, Gibson asserted that affordances are grasped by direct perception sufficiently and contribute to the action guidance through direct perception (Fajen et al., 2008; Osiurak et al., 2010; Fajen and Matthis, 2011). This conceptualization of affordance plays an integrative role between perception and action in the context of transitive action and support unifying approaches (Smets et al., 1994; Ridderinkhof, 2014).

Conversely, experiments on tool use show the existence of distinct functional and neuro-anatomical systems for coding physical properties of tool for action execution/control and perception of conceptual properties of the tool using (e.g., function knowledge, semantic context) (Pellicano et al., 2010; Estany and Martinez, 2014; Myers et al., 2015; Osiurak and Badets, 2016; Wagman et al., 2016b; Osiurak et al., 2017). These results support dissociation theories (Michaels, 2000; Declerck, 2013; Ferretti, 2021). No matter what the primary concern/motivation of the theories is either separation or integration or ecological context, there is convergence across the theories on the existence of some form of integration and dissociation with changing weights (Pisella et al., 2006; Bruno and Paolo Battaglini, 2008; Gorea and Cardoso-Leite, 2010; Schenk and McIntosh, 2010; Ridderinkhof, 2014; Rossetti et al., 2017; Ray et al., 2020). However, divergent theories (e.g., conceptual ambiguities and problematics on definitions, limits, complexity and dynamism) and experimenting difficulties and limitations contribute to disagreements and diversifications of ideas (Creem-Regehr and Kunz, 2010).

Visuomotor Coordination Dynamics between Perception and Action in Behavioural Context

Additionally, research on visuomotor coordination characteristics (i.e., dynamics and elements) in different forms of behaviours (e.g., reflex, instinct, skill, and habit) deepen our understandings of the characteristics of relationships between perception and action (Clark, 2009; Gegenfurtner et al., 2011Sutton et al., 2011; Cutsuridis, 2013; Ridderinkhof, 2014; Mallek et al., 2017). The researchers paid attention to parameters of different forms of behaviours (e.g., adaptivity, context-dependency, purposiveness, pragmatic concern, and intentionality). Thus, perception with a different meaning (e.g., requisite of consciousness, non-visual modalities) and action with different phases (e.g., prediction, preparation, calibration, and appraisal) have been experimented with in different behavioural contexts (Williams et al., 2008; Goodale et al., 2005; Wenderoth and Weigelt, 2009; Ryu and Buchanan, 2012; Ridderinkhof, 2014; Pezzulo et al., 2015; Van Polanen and Davare, 2015). Furthermore, behaviour/action researches on perception-action coordination created awareness on considering the effects of different cognitive processes (of these behaviours) (e.g., learning, skill acquisition, behaviour appraisals, memory) on perception-action relationships (Schmidt, 1987; Hecht et al., 2001; Fuster, 2004; Bardy et al., 2010; Lockman, 2010; Araújo and Davids, 2011; Poeppel and Idsardi, 2011; Davids et al., 2013; Corbetta et al., 2018). In this regard, effects of perception and action on each other can be categorized into two categories as short-term online effects (immediate/instant) and long-term offline effects (e.g., evolutionary/phylogenetic, developmental/ontogenetic, learning, habituation) (Beets et al., 2010; Wood et al., 2013; Pizzera, 2016). Besides, modifications of perception-action coordination can be examined by pre-and post-event/behaviour aspects to understand the dynamism of some of the long term offline action-oriented effects (such as motor learning and skill acquisition) (Newell, 1991; DiNota, 2017; Seifert et al., 2018; Chow et al., 2019). These researches emphasize the constructive role of perception in terms of leading the action, and action can also play a role in altering the senses and can influence and specify the perception (Bruce et al., 2003; Noë and Noë, 2004; Schütz-Bosbach and Prinz, 2007; Feldman et al., 2014; Ridderinkhof, 2014; Witt and Riley, 2014).

Pragmatic Turn in Cognitive Science: Rise of Action-Oriented Theories

In cognitive neuroscience, investigations on the influential role of action on perception pave the way for new approaches investigating the dynamic and constitutive role of action on cognitive processes of the organism(s), which is called as pragmatic turn (Varela et al., 1991; Clark, 1999; O'Regan and Noë, 2001; Engel et al., 2013; 2015; Maye and Engel, 2013; Dominey et al., 2016). Pragmatic turn emphasizes the cognition as the form of practice (i.e., cognition is action) and this based on some of the ideas of pragmatism in philosophy (Bernstein, 2010; Engel, 2010; Engel et

al., 2013; 2015; Gallagher, 2014; 2016; 2017; Määttänen, 2015; Wang, 2015; Madzia and Jung, 2016; Menary, 2016; Newen et al., 2018; Candau and Schiphorst, 2020). Approaches of pragmatic turn (action-oriented views) reject representationalist approaches which posit cognitive processes as just the mental representation of the world (Hutto and Myin, 2017; Haosheng et al., 2019; Baggio, 2021; Fanaya, 2021; Schlicht and Starzak, 2021) and these approaches assume cognition is grounded on sensorimotor couplings (Van Duijn et al., 2006; Borghi, 2007; Haggard et al., 2008; Engel et al., 2013; Van Dijk et al., 2014; Ziemke, 2016; Ellis, 2018). Some of the action-oriented views can be listed as; embodied action (Varela et al., 1991), action-oriented representation (Clark, 1998; 1999), and sensorimotor contingency theory (O'Regan and Noë, 2001; Maye and Engel, 2013; Bishop and Martin, 2014), enactivism (Hutto, 2005; Baerveldt and Verheggen, 2012; Degenaar and O'Regan, 2017).

These approaches assert cognition is the product of dynamic and context-sensitive embodied (inter-)actions with the world, and extensions of the cognition (embedded, extended cognition) should be taken into account (Gallagher and Bower, 2013; Ward et al., 2017). In this regard, dynamic and context-sensitive embodied (inter-)actions influence action-oriented/-related neural development and neuro-plasticity (Engel, 2010; Wilde, 2013; Ward et al., 2017; Froese and Izquierdo, 2018; Robertson and Kirchoff, 2018). Some of the characteristics of transitive/tool-use forms of these actions (e.g., preparation, prediction, and appraisal) can also contribute conceptualizations and mnemonic effects relevant to target objects/environment of these actions (e.g., conceptualisations about function and semantic/ contextual knowledge) (Coello and Iachini, 2015; Osiurak and Badets, 2016; Sakreida et al., 2016; Iani et al., 2019; Matheson and Thompson-Schill, 2019; Federico and Brandimonte, 2020). Thanks to action-oriented approaches, action-specific effects within perception have widely been investigated (e.g., specifying effects of environmental/object properties relevant to action on perception, effects of energetic cost calculations or affective consequences relevant to action performance on perception). Action specific effects within perception have widely been applied to different areas such as human factors (e.g., safety research for vehicle control), physiotherapy and rehabilitation (e.g., rehabilitation of disabled people), physical training (e.g., target detection in the military) (Witt and Proffitt, 2008; Chan et al., 2013; Philbeck and Witt, 2015; Witt et al., 2016).

Pragmatic Context of Action: Kinaesthetic Sensation and Action Politics of Agent

These contributions draw attention to '*pragmatic forecasting*' in *noetic* awareness (see, Glossary) level, which facilitates altering conditions and is formed by pre-and post-evaluation relevant to motor experiences beyond actions (short-term) and motor learning (long-term) on affordance perception and affordance action. Pragmatic forecasting provides the formation of kinaesthetic

sensation relevant to action (e.g., velocity, effort, strength) and generation of a context-dependent image of desired action effects and practical judgements (Jeannerod, 1994; 2006; Brincker, 2014; Ridderinkhof, 2014; 2017; Gibbs Jr, 2015). Images of kinaesthetic sensations and appraisals relevant to actions and images of desired actions (e.g., anticipations, prioritizations, causes, effects, consequences) are the basis of the sense of practical idea in autonoetic awareness level and shape the action policy of organism (Järvilehto, 2009; Coghlan, 2011; Clark, 2013; 2015; Ridderinkhof, 2014; Buhrmann and Di Paolo, 2017). Action policy is based on mediation between internal bodily and external environmental sources, constraints and challenges and regulates organism-object/environment relationships (Wagman and Miller, 2003; Clark, 2008; Gupta and Bahmer, 2019; Corris, 2020; Di Paolo, 2020; Fuchs, 2020). Ecological approaches also made a significant contribution to action-oriented approaches (pragmatic turn) in terms of investigating the influences of environment-organism interactions on the constitutive role of action (Richardson et al., 2008; Lobo et al., 2018; Segundo-Ortin et al., 2019; Popova and Rączaszek-Leonardi, 2020; Heras-Escribano, 2021).

Philosophical Problematics Relevant to Perception-Action Dynamics

Theoretical positions (e.g., unifying, dissociating, ecological), behaviour research, and pragmatic turn in cognitive neuroscience (e.g., action-oriented approaches) contributed to conceptual discussions on perception-action coupling systems and mechanisms. Some of the general philosophical discussions can be listed as;

- *epistemological limits* (e.g., problematics of understanding the mechanisms of biological cognition via the concepts of cultural cognition such as perception and action, limits of dichotomous thinking about the elements of perception-action system, heuristic characteristics of the limits of definitions) (Turvey, 2004; Ridderinkhof, 2014; 2017; Wilson, 2004; Döring et al., 2015; Bogdanova, 2019),
- *ontological problems* (e.g., ontological possibility of correlating anatomy and function to explain perception-action or localization of function anatomically, ontological parity/complementarity between abstract and material domains) (Kaitaro, 2004; Price and Friston, 2005; Osumi-Sutherland et al., 2012; Viola, 2017),
- *mereological issues* (e.g., possibility of implementing predicative logic to explain formal ontological levels of perception-action system and its elements) (Turvey, 2004; Habes, 2016; Boyles and Garrison, 2017; Bennett and Hacker, 2021; Hackett, 2021),
- *hermeneutical boundaries* (e.g., limits of mechanistic analogies, metaphors to explain biological phenomena such as action-perception coupling) and so on (Borck, 2011; Boudry and Pigliucci, 2012; Suchulkin, 2012; Woodward, 2013; Bechtel, 2020).

Moreover, some discussions originate from the philosophy of neuroscience or neurophilosophy relevant to the perception-action coupling system. Some of these discussions can be listed as;

- degree of autonomy and characteristics of (inter-/in-/-) dependency of elements of the system (e.g., perception, action) (Turvey, 2007; Poljac et al., 2009; Vernon, 2015; Vernon et al., 2015; Zhu, 2019),
- continuity and complementarity between the elements of the system, parity and complementarity between the perception-action system/organism and environment (Kiverstein and Farina, 2011; Li and Xia, 2016; Greif, 2017; Gallagher, 2018), contextuality (i.e., context dependency of the system and its elements) (Turvey, 2004; Chemero and Turvey, 2007) and characteristics of the order(s) of the system (e.g., temporal order, hierarchical order) (Hard et al., 2006; Turvey, 2007; Ognibene et al., 2013; Timm et al., 2014),
- systemic characteristics (e.g., emergent characters, shared variables, dynamics, complexity, patterns) (Turvey, 2004; Ay et al., 2012; Stone et al., 2015; Byblow et al., 2019), trade-offs of different theoretical positioning (e.g., strength, weakness, opportunities, perils/limits) (Turvey, 2004; Creem-Regehr and Kunz, 2010; Ridderinkhof, 2014; Kelso and Kay, 2016) and so on.

2.3.3 The experimental research on the 'Affordance' in Cognitive Neuroscience and Psychology

Agential Information in Ecological Context: towards the Gibsonian Formulation of Affordance

Gibson formulated agential information in the light of ecological and teleosemantic context where the content of information of agents/organisms gain evolutionary ground and naturalization of agential intentionality towards the environment mediated by affordances in terms of execution/maintenance of agency within a given environment (van Dijk et al., 2015; Ramstead et al., 2016; Bruineberg, 2018; Segundo-Ortin et al., 2019; Schlicht and Starzak, 2021). In this context, affordance can be linked to *directly* perceived action potentials by agential capacity (capacity of the organism, especially self-perceived perceptual and motor capacity) within a given environment (Greeno, 1994; Bærentsen, and Trettvik, 2002; Jones, 2003; Garbarini, and Adenzato, 2004; Dotov et al., 2012; Fultot and Turvey, 2019; Corris, 2020; Chong and Proctor, 2020). Gibson associated affordance with perceived three-dimensional characteristics of the real objects directly. In most experimental studies, affordance has been examined through two-dimensional images, drawings or realistic or non-realistic models presented on the computer screen where perception becomes indirect (where inference about the spatiality of the object is needed) (Caligiore et al., 2010; Proctor and Miles 2014; Bub et al., 2018). Thus, experimental studies and conceptual discussions about affordance perception have been divorced from ecological/spatial context. It also reduced to representational content blur the boundaries

between Gibson's direct perception theory/bottom-up perception theory (Gibson, 1977; 1979) (and his direct perception-oriented affordance theory) and Gregory's indirect perception theory/top-down (Gregory, 1970; 1997) (and its potential application to the Gibsonian concept affordance) (Bub et al., 2018). However, extending the content of the affordance in terms of origins of motor inference (including not only grounded on direct perception theories-*sufficiency of perceptual content*- (Bahrick and Lickliter, 2002; Lee, 2009; Kim and Lee, 2018) but also possible implementation of indirect theories of perception on affordance, -the *necessity of schematic contribution, nurture-oriented*-) (Davidoff, 2012; Wade and Swanston, 2013) provide additional operationalization benefits in terms of experimenting and creating new theoretical discussions.

Experimenting Affordance: Clusters of Different Studies

Thanks to extension of theoretical background of affordance providing experimenting advantages, affordance has widely been studied to understand temporal and spatial resolution of underlying neuro-physiological and cognitive mechanisms. Some of the research clusters relevant to affordance can be listed as;

- *realisticity* (e.g., realistic, pictorial, virtual) (Proctor and Miles, 2014; Squires et al., 2016; Marini et al., 2019; Bhargava et al., 2020) and *dimensionality/spatiality* (Bonfiglioli et al., 2004; Pappas, 2014; Proctor et al., 2017),
- *congruence/compatibility* between afforded (response) action and affording object (Humphreys et al., 2010; Makris et al., 2011; McBride et al., 2012; Kostov and Janyan, 2015; Ambrosecchia et al., 2015; Azaad et al., 2019) and its spontaneity (Grèzes et al., 2003; Goslin et al., 2012),
- effects of physical (Vingerhoets et al., 2009) and orientation (Bub et al., 2015; Kostov and Janyan, 2020) *properties/aspects of the object* on affordance perception and action (e.g., size (Flumini et al., 2015), colour (Bub et al., 2003; Bub and Masson, 2010; Masson et al., 2011), graspability (Cho and Proctor, 2010; Lopresti-Goodman et al., 2011; Suzuki et al., 2012; Lopresti-Goodman et al., 2013), manipulability (Proverbio et al., 2011; McNair and Harris, 2012; Proverbio et al., 2013)),
- effects of *context and priming* (Tucker and Ellis, 2004; Girardi et al., 2010; Masson et al., 2011; Makris et al., 2013; McNair and Harris, 2014; Wokke et al., 2016; Zhao, 2019; Garrido-Vásquez et al., 2021),
- effects of *different affordance*(s) (e.g., nested (Wagman and Stoffregen, 2020; Seifert et al., 2021), competitive (Cisek, 2007; Wagman et al., 2016a; Borghi et al., 2017), motivational affordances (Zou and Scholer, 2016) on *control of action* (e.g., selection/decision/calibration

for e.g., risk-taking/reach/weight estimation) (Ambrosini et al., 2012; Little and Sweller, 2015; Jia et al., 2015; Wyver and Little, 2018).

Temporal and Spatial Dimensions of Neurophysiological Markers of Affordance

Although underlying mechanisms (i.e., top-down and bottom-up visual perception) (Oliver, 2005; Fischer et al., 2007; Tsagkaridis, 2011; de Wit et al., 2015; Rogers, 2021; Ferretti, 2021) and spontaneity (dependency to the attention of the participant or relevance of the given task) (Lopresti-Goodman et al., 2009; Kostov and Janyan, 2012) of the *inference of the motor potential from object* (Grezes and Decety, 2002; Giesel and Zaidi, 2010) is a controversial issue, neurophysiological and neuro-imaging studies show evidence on the existence of motor inference from observed/perceived objects on both animals (Rizzolatti et al., 1988; Murata et al., 1997; Rizzolatti and Fadiga, 1998; Cisek and Kalaska, 2005) and humans (Tucker and Ellis, 1998; Grèzes et al., 2003; Tucker and Ellis, 2004; Buccino et al., 2009; Cardellicchio et al., 2011; Makris et al., 2011; Franca et al., 2012). In terms of spatial resolution, these studies have shown that specific parieto-frontal circuits (i.e., left pre-motor cortex and inferior parietal areas) (Chao & Martin, 2000; Grèzes et al., 2003) play a crucial role in the inference of motor potentials from perceived/observed objects (Jeannerod et al., 1995; Grafton et al., 1997; Murata et al., 1997; Raos et al., 2006; Umilta et al., 2007). In terms of temporal resolution, de-synchronizations of brain oscillations in different frequency band ranges (Rüther et al., 2014; Proverbio, 2012; Kumar et al., 2013) has been detected relevant to perceived affordances. Furthermore, amplitude changes in the potentials of neurophysiological activities (evoked potentials) relevant to afforded potentials for actions accordingly the aims of the experiments have been detected from early phases of visual perception/observation such as after ~100ms (Goslin et al., 2012; Lien et al., 2013) to later time windows such as around ~600ms (Natraj et al., 2018).

Considering Tectonic Characteristics of the Object: Effect of Realisticity and Spatiality

In terms of realisticity and dimensionality effects, behavioural and neurophysiological experiments have shown evidence that realisticity and spatiality (ecological context) positively impact motor inference from perceived/observed objects. In EEG based neurophysiological study, Marini et al. (2019) found stronger event-related desynchronization of μ frequency band (8–13 Hz) as a neural signature of automatic motor preparation in real objects when compared with their images and changing event-related potentials reflecting stereoscopic differences relevant to dimensionality (3D vs 2D) between real and images of the objects (Marini et al., 2019). In their behavioural experiments, Gomez et al. (2018) found that graspable objects exert a more powerful influence on attention and manual responses than images due to the powerful effects of realisticity on motor inference (spatiality, ecological context) (Gomez et al., 2018). In behavioural

experiments, Xiong et al. (2021) associated changes of the reaction time for 3D vs 2D sessions with visual salience or, namely, stereoscopic differences relevant to dimensionality instead of ecological context (realisticity, spatiality of dimensionality) (Xiong et al., 2021). In this regard, there is ambiguity about affordance effects in terms of the origin of motor inference, either ecological context (realisticity, spatiality) or visual salience of perceived/observed objects. However, most studies about the origin of motor inference have been neglected, especially in the experiments relying on images to test affordance effects. Several studies in evolutionary, ecological, developmental and clinical psychology have shown that stereoscopic aspects of the spatiality of dimensionality (ecological context) have a positive impact on memorability and exploration of physical properties of the object for action and preparation for action (Humphrey et al., 1994; DeLoache et al., 1998; Chainay and Humphreys, 2001; Cisek and Kalaska, 2010; Snow et al., 2011; Heft, 2013a; Snow et al., 2014; Squires et al., 2016; Gomez et al., 2018).

Coding Neurophysiological Aspects of Kinaesthetic Characteristics Relevant to Affordance

Concerning ambiguity of source of motor inference as either visual salience or motor-potential-offering spatiality characteristics of object, '*two visual pathways*' hypothesis offers two different neural pathways, each of which serves each different functional aspects of affordance effects as the vision for perception and vision for action (Osiurak et al., 2017; Ferretti, 2021). In the '*two visual pathway*' hypothesis, dorsal pathway (occipito-parietal) is associated with visuomotor control and execution of the action, ventral pathway (occipito-temporal) is associated with the immediate perception of objects and intersection of dorsal and ventral pathways is associated with emergent properties of effector-action-(tool)-object system such as functional and semantic knowledge (Goodale et al., 1991; Goodale and Milner, 1992; Milner and Goodale, 1993; Goodale et al., 2004; Milner and Goodale, 2006; Milner and Goodale, 2008; Osiurak et al., 2017). In their review research, Freud et al. (2020) proposed that the dorsal cortex may selectively process visual attributes for motor inference about action potentials afforded by objects and environments, which might be supported developmental and cognitive mechanisms beyond the inference. Additionally, Freud et al. (2020) also questioned whether the effect of realisticity (also, spatiality characteristics offering motor potentials) has an additional positive impact on stimulation of the dorsal pathway, which possibly provides motor inference. They tried to justify the possibility of motor inference of the dorsal system. Because the dorsal system is sensitive to several visuospatial features of object recognition such as 3D structure and binocular depth (stereoscopic) perception, physical and locality characteristics (e.g., manipulability and orientation), realisticity and representational characteristics (e.g., shape, contour, and silhouette)

emergent properties such as structure from motion, semantic familiarity (Freud et al., 2020; see also Volcic et al., 2013; Kalénine et al., 2016; Thermos et al., 2017; Bhargava et al., 2020).

Neurophysiological Aspects of Effect of Realisticity Relevant to Affordance

In terms of the source of motor inference, Marini et al. (2019) examined the effects of realisticity on characteristics of ERPs and ERDs (e.g., suppression level, latency, lateralization, amplitude) to understand similarities and differences between brain responses accordingly the effect of realisticity. They detected powerful and longer de-synchronization and distinctive lateralization (contra-laterality with handedness) of event-related oscillations within several time-frequency regions for real objects when compared with images of the same objects. Additionally, exogenous and endogenous ERPs show differentiation in direction and amplitude, accordingly the effect of realisticity. Due to stereoscopic disparity of realisticity (Pegna et al., 2018; Gomez et al., 2018), distinctive negativity of exogenous ERPs on occipital areas, and due to positive mnemonic effects of realisticity (see for mnemonic effects of realisticty, Friedman and Johnson, 2000; Schendan and Kutas, 2003; Rugg and Curran, 2007; Harris and Wilcox, 2009), distinctive duration and amplitude of endogenous ERPs on parietal areas have been detected for real-objects over images of the same objects (Marini et al., 2019). However, Squires et al. (2016) found no changing effects of realisticity (volumetricity) on affordance priming for real vs images of the same tools. They proposed pictoriality (visual cue) affects affordance priming instead of volumetricity. Among the same categories of stimuli, they observed positive effects of emergent properties of effector-action-(tool)-object system (e.g., function knowledge, semantic context) on priming the affordance perception relevant to tools due to activation of action-specific routines in dorsal-stream motor networks via these emergent properties forming the context (Squires et al., 2016).

Neurophysiological Aspects of Perceived Volumetricity/Spatiality Relevant to Affordance

In addition to investigations on the effects of volumetricity/spatiality of realisticity on motor inference through studies comparing real vs correspondent images, studies comparing formal and shape characteristics of presented stimuli examined the effects of *perceptual volumetricity/volumetricity within perception* on motor inference which contribute to affordance effect. Some researchers investigating the effects of congruence or compatibility have investigated the effects of volumetricity within perception on motor inference, which causes the affordance effect (Bonfiglioli et al., 2004; Symes et al., 2005; Proctor and Miles, 2014). For instance, Pappas (2014) compared the effects of volumetricity vs pictoriality within perception in terms of conveying affordance effect to understand the differentiation of affordance compatibility and abstract spatial response coding as the dimensional overlap between stimulus (i.e., salient object property) and response spatial codes (i.e., Simon effect). He used photographs

and correspondent silhouettes which are spatially congruent with the effector as hand. He demonstrated that conveying affordance effect is dependent on volumetricity (formal features, depth information) instead of mere abstract shape characteristics (pictoriality), which dissociate the affordance compatibility effect from the Simon effect (Pappas, 2014). Further, Proctor et al. (2017) investigated the effects of volumetricity vs pictoriality on affordance effect regarding the spontaneity of effector specific instrumentalization characteristics and independency from task-relevant spatial coding of correspondence between stimulus and response. They dissociated the effects of spatial stimulus compatibility effect (i.e., Simon effect) from object-based correspondence effect in terms of conveying affordance to clarify underlying mechanisms of motor inference (Proctor et al., 2017).

CHAPTER 3: THE METHODOLOGY OF THE RESEARCH

In this chapter of the thesis, general aspects relevant to methodology as EEG will be briefly explained. The chapter addresses electrophysiological mechanisms of human central nervous system (CNS) (Nieuwenhuys et al., 2007; Mai and Paxinos, 2011; Rusinov, 2012), assessment (or measurement) of these mechanisms by EEG (Tyagi et al., 2012; Puce and Hämäläinen, 2017; Paszkiel, 2020b; Kumar and Mittal, 2021) and typical steps of EEG analysis process as data pre-processing (Rao and Derakhshani, 2005; Sanei and Chambers, 2013; Kim, 2018; Hu and Zhang, 2019; Peng, 2019; Sazgar and Young, 2019; Shoka et al., 2019; Robbins et al., 2020), data cleaning/artefact rejection (Jung et al., 2000; Delorme et al., 2007; Schomer, and Da Silva, 2012, p. 239-266; Vázquez et al., 2012; Tandle et al., 2015; Kaczorowska et al. 2017; Kanoga and Mitsukura, 2017; Tatum IV, 2018; Mur et al., 2019), individual level data analysis (Sanei and Chambers, 2013; Cohen, 2014; Nidal and Malik, 2014; Siuly et al., 2017; Im, 2018; Hu and Zhang, 2019; Paszkiel, 2020a; Tatum IV, 2021) and group level statistical analysis (Maris and Oostenveld, 2007; Cugliari and Ivaldi, 2015; Huster et al., 2015; Hari and Puce, 2017, p.131-132; Siuly et al., 2017; Frömer et al., 2018; Tadel et al., 2019).

In this regard, this chapter will briefly explain (1) biophysical background of electrophysiological activity of neurons (Koch, 2004; Shepherd, 2004; Graham, 2008; Conti & Torre, 2012; Feltz, 2020), (2) EEG physics and data acquisition (Nunez and Srinivasan, 2006; Handy, 2009; Brette and Destexhe, 2012; Hari and Puce, 2017; Puce and Hämäläinen, 2017; Im, 2018; Michel et al., 2019), (3) technical aspects of data pre-processing (Dickter and Kieffaber, 2014; Siuly et al., 2017; Suárez-Revelo et al., 2018; Hu and Zhang, 2019), (4) artefacts contaminating EEG recording and data cleaning (Oja et al., 1997; Jung et al., 2000; Oja et al., 2003; Sörnmo and Laguna, 2005; Li, 2016), (5) individual level data analysis and electrophysiological activity of interests (e.g., brain rhythms (Levine et al., 1999; Neuper and Pfurtscheller, 2001; Buzsaki, 2006; Fingelkurts et al., 2006; Sauseng et al., 2007; van Vugt et al., 2007; Neuper and Klimesch, 2006; Başar, 2011; Başar, 2012a; Başar, 2012b; Schutter and Knyazev, 2012; Pantev et al., 2013; Gross, 2014; Haufe et al., 2014; van Driel, 2015; Cole and Voytek, 2017; Karakaş and Barry, 2017; Samiee, 2019; Eggermont, 2021), Event-related Potential wave components (Picton et al., 1995; Polich, 2003; Handy, 2005; Bressler and Ding, 2006; Kotchoubey et al., 2006; Luck and Kappenman, 2011; Callaway, 2012; Luck, 2014; Cong et al., 2015; Sittiprapaporn, 2017)), (6) group level statistical analysis (Tong and Thankor, 2009; Oweiss et al., 2010; Kaur and Kaur, 2015; Truong and Lewis, 2016; Siuly et al., 2017; Wilcox and Rousselet, 2018).

In the first part, action potentials (Spalding and Thornborough, 1995; Levitan et al., 2002; Bean, 2007; Carter and Bean, 2009; DuBois, 2010; Clarke III, 2013; Byrne et al., 2014; Gerstner et al., 2014; Hammond, 2014), postsynaptic potentials (Gerstner and Kistler, 2002; Koch, 2004; Eccles, 2013; Pickel and Segal, 2013; Byrne et al., 2014; Gerstner et al., 2014; Hammond, 2014; Graziane and Dong, 2016) as the biophysical background of electrophysiological activity of neurons in the human central nervous system will briefly be explained. In the second part, how EEG acquired postsynaptic potentials (Olejniczak, 2006; Holmes and Khazipov, 2007; Kirschstein and Köhling, 2009; Bucci and Galderisi, 2011; Congedo and Sherlin, 2011; Cohen, 2017; Akilli and Yilmaz, 2018; Lai et al., 2018; Brienza and Mecarelli, 2019) and amplification (Kamp, 1985; Dickter and Kieffaber, 2014, p.19; Hari and Puce, 2017, p.49-51; Scanlon et al., 2020; Xu and Wang, 2021) and digitization (Gorney, 1992; Van Cott and Brenner, 1998; Mahdi and Al-Hajaj, 2012; Kim and Hwang, 2013; Ray and Issa, 2019, p.212-213) of acquired data will be examined.

In the third part, technical issues relevant to offline signal pre-processing of EEG data such as segmenting the data according to the defined trials (Procházka et al., 2010; Cohen, 2014, p. 75-78; Clerc, 2016, p.105-106; Peng, 2019); filtering some of frequency band ranges ((Kamp et al., 2005; Hari and Puce, 2017 p. 89-95; Rogasch et al., 2017; Baranowski and Piątek, 2017; de Cheveigné and Nelken, 2019; Peng, 2019) will be clarified. Additionally, in the same part, some of the signal processing methods (especially some of Harmonic Analysis methods) which are generally used for expressing temporal EEG signals in terms of temporal frequency ranges will be introduced (Sörnmo and Laguna, 2005; Jahankhani et al., 2006; Misiti et al., 2007; Prochazka et al., 2008; Akay, 2012; D'Attellis and Fernandez-Berdaguer, 2012, p.179-262; Freeman and Quiroga, 2012; Glaser, 2012; Sanei and Chambers, 2013; Hramov et al., 2015; Boashash et al., 2016; Siuly et al., 2017; Van Drongelen, 2018; Hu and Zhang, 2019).

In the fourth part, physiological and non-physiological artefacts that potentially contaminate acquired raw EEG data and methods of eliminating contaminations through data cleaning processes (especially some of the blind source separation methods) will be discussed (Vigário et al., 2000; Hyvarinen et al., 2001; Gómez-Herrero et al., 2006; Hesse and James, 2006; Delorme et al., 2007; Fitzgibbon et al., 2007; Comon and Jutten, 2010, p.737-778; Cashero and Anderson, 2011; Vázquez et al., 2012; Lee, 2013, p.145-166; Sanei, 2013, p.118-158; Naik and Wang, 2014; Sahroni et al., 2014; Soomro et al., 2014; Mowla et al., 2015; Metsomaa et al., 2016; Tatum IV, 2018). In the fifth part, technical aspects of Time-Lock/Time-Domain Analysis (Hjorth, 1970; 1973; Klonowski et al., 2002; Ivannikov, 2007; Luck and Kappenman, 2011; Makeig and Onton, 2011; Thatcher, 2012; Dickter and Kieffaber, 2014, p. 58-91; Nidal and Malik, 2014; Cong et al., 2015; Munneke et al., 2015; Yazıcı and Ulutaş, 2015; Newman, 2019, p. 61-132) and Time-Frequency

Analysis (Haykin et al., 1996; Van Hoey et al., 1997; Feige, 1999; Neuper and Pfurtscheller, 2001; Rosso et al., 2002; Miwakeichi et al., 2004; Harpale and Bairagi, 2006; Neuper and Klimesch, 2006; Wen et al., 2006; Mu et al., 2009; Van Zaen et al., 2010; Xiangtan, 2010; Jmail et al., 2011; Pfurtscheller and Da Silva, 2011; Başar and Bullock, 2012; Freeman and Quiroga, 2012, p. 21-48; Heisz and McIntosh, 2013; Cong et al., 2015; de Cheveigné and Arzounian, 2015; Hramov et al., 2015; Kiebel et al., 2015; Ridouh et al., 2017; Puranik et al., 2018; Munia and Aviyente, 2019) and analyzed ERP components and brain rhythms will briefly be explained. In the last part, some of the experiment design issues, such as repeated measures design and group-level statistical analysis will be briefly informed.

3.1. HUMAN NEUROPHYSIOLOGY AND EEG DATA ACQUISITION

Understanding the biophysical background of electrophysiological activity (i.e. bio-potentials of the human central nervous system) acquired by EEG is crucial for understanding the data acquisition process during EEG experiments. In the EEG data acquisition process, postsynaptic potentials of mainly pyramidal neurons (DeFelipe and Fariñas, 1992; Poirazi et al., 2003; Harvey and Svoboda, 2007; Spruston, 2009; Major et al., 2013) were recorded by the EEG sensors placed on the scalp (Towle et al., 1993; Khosla et al., 1999; Koessler et al., 2007; Khandpur, 2019, p. 150-153; Taberna et al., 2019; Tagawa et al., 2019, p.296-301). Acquired analog signals as the postsynaptic potentials of neuron population in the vicinity of each EEG sensor are amplified and digitized for offline signal processing and data analysis in a computer medium.

3.1.1. Biophysical background of Electrophysiological Activity of Neurons in Human CNS

Detection and measurement of brain potentials (especially on animals such as rabbits, dogs and monkeys) (Caton, 1875a; 1875b; 1887; Beck, 1890; 1891; Larionov, 1897) can be dated back to the last quarter of the 19th century (Brazier, 1957; 1984; Shipton, 1975; Halliday, 1980; Kugler, 1981; Clarke and Jacyna, 1987; Young, 1990; Greenblatt, 1995; Benton, 2000; Breidbach, 2001; Chatterjee and Coslett, 2013; Lüders, 2018; Price, 2018; Bogousslavsky et al., 2019; Barbara, 2020; Pecere, 2020). Some of the human brain rhythms (i.e., alpha and beta rhythms) were discovered in the first quarter of the 20th century (Berger, 1921; 1929; Lindsley and Rubenstein, 1937; Gloor, 1969; Jung and Berger, 1979; Empson, 1986; Collura, 1993; La Vaque, 1999; Millett, 2001; Stone and Hughes, 2003; Tudor et al., 2005; da Silva, 2009). In the second quarter of the 20th century, one of the brain rhythms associated with the motor cortex (i.e., mu rhythm) began to be examined (Berger, 1930; Adrian and Matthews, 1934; Adrian and Yamagiwa, 1935; Gastaut, 1952; Gastaut et al., 1952; Cohen-Séat et al., 1954; Gastaut and Bert, 1954; Chatrian et al., 1959; Ciganek, 1959) began to be examined. In the same decades, other human brain rhythms (i.e.,

gamma, theta and delta rhythm) (Walter, 1936; 1938; Jasper, & Andrews, 1938; Jung and Kornmüller, 1938; Empson, 1986a, p. 1-5; 1986b; Ahmed and Cash, 2013; Karakaş and Barry, 2017; Sorkin, 2017; Borck and Hentschel, 2018) and Event-Related Potentials (Adrian and Matthews, 1934; Davis and Davis, 1936; 1939; Davis et al., 1939) were also discovered. Also, in the same decades, Fourier Transform as one of the signal processing methods was implemented to brain bio-potentials to analyze their sub-components in different frequency band ranges (e.g., 10-50 Hz) (Dietsch and Berger, 1931; Grass and Gibbs, 1938; Gibbs et al., 1940; 1941; Foster et al., 1942; Knott et al., 1942; Grass and Gibbs, 1947; Grass, 1984).

In the third quarter of the 20th century, several Event-Related Potential researches were conducted (Walter et al., 1964; Sutton et al., 1965; Landa et al., 2014). In the same decades, sensory substitution researches (e.g., cross-modal neural interaction, multisensory integration) began (Cutsforth, 1933; Lashley, 1933; Ryan, 1940; Burnham, 1941; Gilbert, 1941; Thomas, 1941; Birch and Bitterman, 1949; Geldard, 1951; Deutsch, 1953; 1954; Lief, 1955; O'Hare, 1956; Talland, 1959; Sinha and Sinha, 1960; Welford, 1960; Bach-y-Rita et al., 1969; Bach-y-Rita, 1970; Marks, 1978) and several neuroplasticity researches (especially anatomical evidences) were conducted (Lashley, 1930; Hunter, 1930; Rashevsky, 1939; Snider and Stowell, 1944; Seddon, 1947; Gonzalo, 1945; 1950; 1952; Konorski, 1948; 1962; 1969; Hebb, 1949; Young, 1951; Eccles, 1958; Rosenblatt, 1958; 1961; Bennett et al., 1964; Diamond, 1964; Sperry, 1965; Levi-Montalcini, 1966; Livingston, 1966; Levi-Montalcini and Angeletti, 1968; Zieliński, 2006). Furthermore, synchronization and de-synchronization of event-related brain rhythms as oscillations were scientifically discovered (Purpura, 1966; Buser and Rougeul-Buser, 1971; Pfurtscheller and da Silva, 1971; Pfurtscheller et al., 1971; Başar, 1972; Başar et al., 1975; Başar et al., 1979; Ermentrout, and Cowan, 1979; Freeman, 1975; 1979; Pfurtscheller and Aranibar, 1979; Bressler and Freeman, 1980).

In the same decades, neurostimulation methods widely began to be implemented in cortical excitability researches (Cooper et al., 1973; Pudenz et al., 1975; 1977; Riklan et al., 1976; Babb et al., 1977; Brown et al., 1977; Delgado, 1977; Richardson and McLone, 1978; Sedan and Lazorthes, 1978; Richardson et al., 1979a; 1979b; Shugalev and Psatta, 1979; Richardson et al., 1980; Cooper et al., 1980; Davis and Gray, 1980; Gybels, 1980; Siegfried et al., 1980) and magneto-encephalography as a new neurophysiological method was discovered (Beck and Byrd, 1963; Cohen, 1968a; 1968b; 1972; Balish, 1973; Reite et al., 1976; Rosen and Inouye, 1976; Zimmerman, 1977; Okada, 1973; Press, 1973; Teyler et al., 1975; Hughes et al., 1977; Hughes, 1978; Williamson, 1978; Cuffin and Cohen, 1979; Hari, 1980).

In the last quarter of the 20th century, additional brain imaging techniques such as tomography (e.g., CT, PET, SPECT/SPET) (Lee et al., 1956; Meinardi, 1968; Roberts et al., 1973; Baker, 1975; Kramer et al., 1975; Deck et al., 1976; Kuhl et al., 1976; Phelps et al., 1976; Synek et al., 1976; Dubal and Wiggli, 1977; French and Dublin, 1977; Villafana et al., 1978; Heinz et al., 1979; Axel, 1980; Budinger, 1980; Ell et al., 1980; Ferris et al., 1980; Hawkes et al., 1980; Hill, 1980; Holland et al., 1980; Jaszczak et al., 1980; Mano et al., 1980; Ochs et al., 1980) and magnetic resonance imaging methods were invented (Matthews, 1951; Meier and Zierler, 1954; Basser, 1965; Tanskanen, 1966; Haghighi, 1970; Brasch et al., 1983; Johnson et al., 1983; 1984; Bradac et al., 1985; Brant-Zawadzki et al., 1985a; 1985b; Claussen et al., 1985; Johnson, 1985; Kirshner et al., 1985; Levin et al., 1985; Mun et al., 1985; Ono et al., 1985; Peterman et al., 1985; Schober et al., 1985; Wang and Tao, 1985) and cognitive science emerged as a new inter-/multi-/trans-disciplinary area thanks to the contributions of (cognitive) neuroscience (Hutchins, 2000; Pfeifer and Scheier, 2001; Miller, 2003; Thagard, 2005a; 2005b; 2008; Boden, 2006; Gallagher, 2012; Ren, 2019).

In the last decade of 20th century event-related fMRI researches and fMRI BOLD (Blood-Oxygen-Level-Dependent) imaging experiments began (Bandettini et al., 1993; Cohen and Bookheimer, 1994; DeYoe et al., 1994; Fox and Woldorff, 1994; Aine, 1995; Bellemann et al., 1995; Belliveau et al., 1995; Friston et al., 1995; George et al., 1995; Glover and Lee, 1995; Jueptner and Weiller, 1995; Le Bihan and Karni, 1995; Moonen, 1995; Spitzer et al., 1995; Stillman et al., 1995; Turner, 1995; Van Gelderen et al., 1995; Worden and Schneider, 1995; Worsley and Friston, 1995; Xiong et al., 1995) and early investigations on brain connectivity (i.e., anatomical connectivity and statistically dependence/functional connectivity) began (Stubbs, 1978; Cline et al., 1987; Leuchter et al., 1992; Friston et al., 1993a; 1993b; Biswal et al., 1985; 1997; Friston, 1994; Murre and Sturdy, 1995; Friston et al., 1996; Paus et al., 1996; Hüther, 1998; Lowe et al., 1998; Worsley et al., 1998; Büchel et al., 1999; Cao and Worsley, 1999; Jones et al., 1999; Xiong et al., 1999; Cordes et al., 2000; Koski and Paus, 2000; Parker and Dehmeshki, 2000; Sporns et al., 2000).

EEG and similar bio-potential measurement techniques generally deal with changes of potentials and power spectrum of frequency band range during electrophysiological activities arising from different parts of the body/organs (Northrop, 2003; Grimnes and Martinsen, 2011; Devasahayam, 2012; Najarian and Splinter, 2012; Webster, 2014; Sun and Yu, 2016) such as muscles (i.e., Electromyography) (Cros et al., 2011; Struppler and Weindl, 2012; Brown, 2013; Leis and Schenk, 2013; Naik, 2014), eyes (i.e., Electrooculography, Electroretinography) (Stern et al., 2001, p.135-140; Thorslund, 2004; Heckenlively and Arden, 2006; Belusic, 2011; Wolpert and Tsang, 2011; Ahmad, 2016; Creel, 2019; Yu et al., 2019), heart (i.e., Electrocardiography) (Conover, 2002; De

Luna, 2008; Morris et al., 2009; Wang, 2012; Goy et al., 2013; Romanò, 2015; Soto, 2015). Ions play a crucial role in these electrophysiological activities, and accordingly, the relevant function extra- and intra-cellular mediums charged positively or negatively thanks to the placement of positive and negative ions. Ion placements are regulated various feedback mechanisms to fulfil required physiological functions (Catterall, 2000; Bajic and Tan, 2005; Hong, 2005; Stockand and Shapiro, 2006; Ma and Beaven, 2009; Blaustein et al., 2011; González et al., 2012; Kessler et al., 2012; Squire et al., 2012; Contet, 2016; Gatenby and Frieden, 2017). Thus, understanding biophysical feedback mechanisms regulating ion placements to fulfil neurophysiological functions is crucial to comprehensively understanding the data acquisition process of EEG. In this regard, examining how these feedback mechanisms create biopotentials in extra- and intra-cellular becomes significant.

In the human central nervous system, mainly there are two types of cells as neurons/nerve cells and neuroglia/glia cells (Brown, 2001; Morgan and Bloom, 2006; Janigro, 2008; Matthews, 2009; Palay and Chan-Palay, 2012; Korr, 2013; Pannese, 2015). Neuroglia/glia cells play a crucial role in several vital functions for neurophysiological activities indirectly, such as supplying nutrients and oxygen to neurons, removal of dead neurons and cellular waste products, protection and isolation of neurons from other neurons and placement of neurons conveniently (Kettenmann and Ransom, 2004; Verkhratsky and Butt, 2007; Castellano et al., 2012; Matsas and Tsacopoulos, 2012; Verkhratsky and Parpura, 2014). Although some of the functions of neuroglia/glia cells relevant to the placement of neurons and spatial organization of extra-cellular medium (e.g., synaptic connectivity, neurotransmission) play some role in cognitive processes, neurophysiological activities relevant to cognitive processes (e.g., perception, attention, memory, motor functions) was mainly provided by neurons (Volterra et al., 2002; Koob, 2009; Haneka et al., 2010; Gundersen et al., 2015; Hoogland and Parpura, 2015; Kato et al., 2017; Butt and Verkhratsky, 2018). Neurons or nerve cells play a crucial role in information transmission from the external medium of the organism via the peripheral nervous system (e.g., sensation, perception, and attention) and processing transmitted information within the central nervous system (e.g., judgement, evaluating, learning, and reasoning) and also the transmission of commands of the central nervous system to peripheral nervous systems for the organization of other systems (e.g., musculoskeletal system, respiratory system, circulatory system) (Levitan, 2002; Koch, 2004; Morris et al., 2005; Holscher and Munk, 2008; Kelleher, 2010; Tovee, 2013; Dharani, 2014; Couto, 2015; Gabbiani and Cox, 2017; Yu et al., 2017).

Shortly, a neuron consists of two parts as (1) a cell body or a soma, (2) axon(s) (either myelinated or unmyelinated) and dendrites (Rattay, 1999; McIntyre and Grill, 1999; Brodal, 2020, p. 5;

Krieger, 2020, p. 88). Nerve cells/neurons can be classified in various ways. Accordingly, their function on which they play a critical role, they can be classified as sensory neurons, place neurons, face neurons, inter neurons, motor neurons, pyramidal (excitatory) neurons and so on (Bota and Swanson, 2007; Augustine, 2008, p.4; Petrovici, 2016; Vasques et al., 2016; Price et al., 2017, p.146; Hans et al., 2018, p.306; Zhang et al., 2018, p.266; Hernández-Pérez et al., 2019). In accordance with their structural features, neurons can be categorized as unipolar, bipolar, multipolar and pseudo-unipolar neurons (Siegel and Sapru, 2006, p.66-7; Augustine, 2008, p.4; Patestas and Gartner, 2016, p.29-35). In terms of the direction of transmission of information from central to the peripheral nervous system or vice versa, neurons can also be sorted out as *efferent neurons* (transmitting information from central toward peripheral nervous system) and *afferent neurons* (transmitting information from peripheral toward central nervous system). In this regard, there are two types of connections within the human nervous system (Longstaff, 2005, p.3; Applegate, 2014, p.173; Johns, 2014, p.61; Seikel et al., 2018, p.36). These connections are (1) between central and nervous systems through afferent & efferent neurons and thalamo-cortico/cortico-thalamo connections (except transmission of olfactory sensation) and (2) connections within cortex (i.e. cortico-cortico connections) (Shinoda et al., 1993; Bruno and Sakmann, 2006; Sherman and Guillery, 2013; Roland et al., 2014; Hafner et al., 2017; Huo et al., 2020). Neural connections or namely connections between nerve cells/neurons play a crucial role in the information process (Ramnani et al., 2004; Stam, 2004; 2010; Fingelkurts et al., 2005; Sepulcre et al., 2010; Wang et al., 2018; Frolov et al., 2019; Silva et al., 2020).

During the information process, stimulation of neurons/nerve cells depends on the rate of the bio-potential (i.e., action potential) of stimulation. Bio-potential value of stimulation should be more than threshold value of membrane potential of nerve cells to be the transmission of information and as a result of stimulation of each cell; information can be transmitted to other nerve cells (Spinks, 2002; Koch, 2004; Trappenberg, 2009, p.19-32; Iida et al., 2011; Pashut et al., 2011; Di Maio and Bouteiller, 2019). In this context, the value of membrane potential of each nerve plays a crucial role in the gating of information processing (Koch and Segev, 2000; Debanne, 2004; Kepecs and Raghavachari, 2007; Guo et al., 2018; Amiri et al., 2019). In the intra-cellular level, stimulated membrane potentials can be transmitted in the form of (de-, re-, -) polarizations of cell content which is called *action potentials* (Cohen, 1973; Rutecki, 1992; Stuart et al., 1997; Lytton, 2002; Naundorf et al., 2005; Bean, 2007; Fry and Jabr, 2010; Di Maio and Bouteiller, 2019). These generated bio-potentials (i.e., action potentials) transmitted through extra-cellular space to other nerve cells in the form of *postsynaptic potentials* because of de-polarization or hyper-

polarization of synaptic medium (Eccles, 2013; Pickel and Segal, 2013; Uchizono, 2013; Gerstner et al., 2014; Graziane and Dong, 2016).

Intra-cellular action potentials emerge as the results of de-/re-/-/polarizations regulated by some of changes in ion concentrations (i.e., potassium (+), sodium (+), calcium (++) and chlorine (-)) within intra- and extra-cellular mediums (Puri and Treasaden, 2009, p.411; Daroff and Aminoff, 2014, p.1034-35; Upadhyay and Iyengar, 2021, p.334-343). Bio-potential changes in intra- and extra-cellular mediums accordingly ion concentrations across the nerve cell membrane can be calculated by Goldman–Hodgkin–Katz voltage equation or shortly Goldman equation (Barr, 1965; Pickard, 1976; Heinz, 2013, p.19-21; Bracken and Bass, 2016). Goldman equation considers differences in membrane permeability in terms of transmissions of different ions between intra- and extra-cellular medium, which causes -/de-/re-polarizations of intra-cellular medium and transmission of action potentials across the nerve cells (Kimizuka and Koketsu, 1964; Barr, 1965; Koester and Siegelbaum, 1991; Wright, 2004). The Goldman equation was derived from the Nernst equation, which deals with the reduction potentials of ions (and other chemical species) undergoing reduction or oxidation by associating these potentials with standard electrode potentials to calculate membrane potential. Ion transmissions between intra- and extra-cellular levels require chemical energy use as ATPs (Adenosine Triphosphate) (Koester and Siegelbaum, 1991; Feiner and McEvoy, 1994; Johnston and Wu, 1994; Cohen, 2005; Fain, 2003). Although the total amount of ions is preserved during the transmission of the action potential across nerve cells, in accordance with the type of polarization (de-/re-/-polarization), concentrations of different ions change differently in intra- and extra-cellular levels (Somjen, 2004; Sengupta et al., 2010; Gentiletti et al., 2017; Wang et al., 2017).

Even there is no polarization; nerve cells have some number of electrical potentials, which is called the membrane potential. Similar to action potentials, membrane potentials emerge as a result of ion concentration changes in intra- and extra-cellular levels due to the vital activity of the neurons. However, differently from action potentials, membrane potentials emerge independently from information processing/stimulation of nerve cells (Volgushev et al., 1998; Moreno-Bote and Parga, 2005; Stuart and Palmer, 2006; Ma and Tang, 2017; Petersen, 2017; Feltz, 2020). Action potentials and postsynaptic potentials emerge from stimulation of cell surface receptors if the potential of stimulation is more than the threshold of membrane potential. Receptor cells can be classified into different groups accordingly to the nature of input that they deal such as chemoreceptors dealing with chemicals (olfaction and gustatory sensation), mechanoreceptors dealing with mechanical changes (tactile, haptic, auditory, proprioceptive sensations, thermoception, magnetoception, interoception), photoreceptors dealing with light

(vision), osmoreceptors (homeostasis) and so on (Brynie, 2009; Light and Cooley, 2009, p.10-22; Wicher et al., 2010; Mather, 2014, p.1-21; Murray et al., 2016). If these receptors are stimulated with inputs (coming from either environmental sources or internal mechanisms of the organism) of which potentials are more than the threshold of the membrane potential of stimulated nerve cell (i.e., receiver neuron), relevant information can be processed in the form of the action potential across the stimulated neuron via different forms of polarizations (Hardie et al., 2012; Julius and Nathans, 2012; Moller, 2013). When processed information is transmitted to the end of the stimulated neuron in the form of action potentials, the potentials are transferred over synaptic cleft and transmitted to the next neuron(s) via neurotransmitters in the form of postsynaptic potentials (Sewell, 1996; Lodish et al., 2000; Siegelbaum et al., 2000; Hyman, 2005; Forehand, 2009; Patri, 2019). Transmission of postsynaptic potentials to other neurons causes depolarization (excitatory postsynaptic potential) or hyper-polarization (inhibitory postsynaptic potential), and if the postsynaptic potential is more than the next neuron's/ neurons' threshold of membrane potential, the next nerve cell is stimulated (Von Krosigk et al., 1999; Sperelakis, 2012; Eccles, 2013; Pickel and Segal, 2013; Byrne et al., 2014, p.161-196). During transmission of postsynaptic potentials, depolarization (excitatory postsynaptic potential) is associated with the increase of the positive ions as sodium, potassium or calcium in the next neuron(s) and hyper-polarization (inhibitory postsynaptic potential) is relevant to the increase of the negative ion as chlorine in the next neuron(s) (Eccles, 2013; Pickel and Segal, 2013; Meriney and Fanselow, 2019).

The transmission of intra-cellular action potentials across each nerve cell is very short (~2 ms), and because of transmission speed, action potentials cannot be recorded by EEG. The mainly recorded electrophysiological activity in EEG systems is the postsynaptic potentials (Olejniczak, 2006; Kirschstein and Köhling, 2009; Bucci and Galderisi, 2011). When postsynaptic potentials occur in a group of neighbouring neurons, extracellular local field potentials emerge, and they can be recorded by several hundred micrometre or millimetre scale high-impedance micro-sensors (Harrison et al., 2004; Herreras, 2006; Brette and Destexhe, 2012; Pesaran et al., 2018). In contrast, EEG is acquired using sensors located on the scalp capturing signals from much larger areas than local field potentials (Xing et al., 2009; Kajikawa and Schroeder, 2011; Vinck et al., 2012). Thus, EEG-recordable extracellular signals are driven by postsynaptic potentials in the dendrites of pyramidal cells of the cerebral cortex with low spatial resolution, from larger areas than local field potentials (da Silva, 2009; Kirschstein and Köhling, 2009; Bucci and Galderisi, 2011; Hagen et al., 2018; Pesaran et al., 2018; Brienza and Mecarelli, 2019). Postsynaptic potentials generate a dipole, an electric potential difference between the soma and apical dendrite of the same pyramidal neuron (Nunez and Srinivasan, 2006; Hallez et al., 2007; Avitan et al., 2009;

Buzsáki et al., 2012; Jackson and Bolger, 2014; Gaho et al., 2018). EEG measurements of dipole electric differences are influenced by (1) the power and duration of the stimulation of the dendrites and (2) the geometric nature of the neurons and the distribution of neuron population. The power and duration of the stimulation of the dendrites influence the electrotonic distances of the dendrites. Furthermore, concave areas of the cortical surface or structurally concave neural populations (radial geometry) generate widely distributed potentials and, adversely, convex cortical surfaces or structurally convex neural populations axial geometry) produce less distributed potentials (Traub and Llinas, 1977; Ottoson, 1983; Korogod and Kulagina, 1998; Buzsáki et al., 2012; Hari and Puce, 2017, p.31-32).

The low spatial resolution of EEG prevents recordings of the neurophysiological activity of deep brain structures except for very few conditions such as theta activity of the hippocampus due to attenuation of neurophysiological potentials of deep brain structures by the different biological layers or tissues such as scalp, skull, and meninges and so on (Srinivasan, 1999; Nunez and Srinivasan, 2006; Srinivasan et al., 2006; Abbott et al., 2019, p.63; Paszkiel, 2020b). In addition to the attenuation of the amplitude of postsynaptic potentials and low spatial resolution, EEG recordings can be contaminated by biological potentials of different bodily sources as a result of volume conduction in the human body. Further contamination can come from non-physiological potentials arising from the environmental sources (Mowla et al., 2015; Mannan et al., 2018; Maswanganyi et al., 2018; Jiang et al., 2019; Peng, 2019; Echtioui et al., 2020). Hence, EEG data analyses include cleaning recorded EEG data from contaminations.

Postsynaptic potentials of neural populations can emerge in different modes such as phase-locked (synchronous) or non-phase locked (non-synchronous), time-locked or non-time locked, (Farhat et al., 1994; Kalcher and Pfurtscheller, 1995; Tallon-Baudry et al., 1996; Jung et al., 1999a; 199b; 2001; David et al., 2006). Different modes of the emergence of postsynaptic potentials of different neuron populations play a crucial role in regulating cognitive processes via different gating mechanisms (Buchholz et al., 2014; Skosnik and Cortes-Briones, 2016; Hong et al., 2018). Brain oscillations are associated with synchronous or non-synchronous emergence of postsynaptic potentials of different neuron populations, and according to the mainstream agreement, these oscillations emerge in the form of sinusoidal waveforms, which are associated with brain rhythms (Ermentrout and Chow, 2002; Keil and Senkowski, 2018; Donoghue et al., 2021). In accordance with cognitive function, frequencies of sinusoidal waveforms (i.e., frequency of brain rhythm) can change. Roughly speaking, the frequency of emerging brain rhythm increases under the complexity of cognitive function (e.g., concentration/attention level, concern about performance in terms of accuracy, cognitive demands of task) (Ward, 2003; Buzsaki, 2006;

Lu et al., 2007; Palva, 2016; van Wassenhove, 2016; Donoghue et al., 2021). In cognitive neuroscience and neuropsychology experiments, event-related neurophysiological activities are recorded. As a result of data acquisition, parameters of neurophysiological recorded signal such as frequency, amplitude and time (latency) are generally examined after pre-processing and data cleaning in computer medium (West et al., 1999; Winterer et al., 1999; Delorme and Makeig, 2004; Onton and Makeig, 2006; Puce and Hämäläinen, 2017). Thus, simultaneously with EEG recording, recorded data should be amplified and digitized to prepare data for computer medium processes.

3.1.2. Amplification and Digitization of Raw EEG Data

Recorded amplitudes of neurophysiological activity via sensors of EEG are very weak due to attenuation and need to be amplified by amplifiers before digitization (Allen et al., 2000; Zhu et al., 2009). In the BioSemi system, EEG recordings are amplified two times to cope with contamination of recorded EEG data during its transmission process from distant electrodes/sensors located on the scalp to the analog-to-digital converter. These amplifications are carried out by (1) amplifiers within electrodes and by (2) amplifier module of the analog-to-digital converter (Kam et al., 2019; Campbell et al., 2012; Usakli and Gencer, 2007). Ideal amplification devices for EEG recordings avoid the amplification of common line signals (e.g., signals arising from the system) and only amplify the neurophysiological signals as raw EEG data (Bansal et al., 2009; Salahuddin Morsalin and Lai, 2020; Teplan, 2002). The ratio between output potential to source potential (differential gain) in amplifiers shows the input signal's amplification (Nagel, 2000; Zhang et al., 2019). In EEG recording systems, referencing and grounding can be used before and after amplification and digitisation to reduce the noise and contamination of common line signals (Cutmore and James, 1999; Usakli, 2010; Sinha et al., 2015). In the BioSemi system, instead of the ‘ground’ electrode used for referencing, two separate electrodes form a circuit working via feedback loops between each electrode. These electrodes are active Common Mode Sense electrode (CMS) and passive Driven Right Leg electrode (DRL), which try to make the average potential of recorded data (the Common Mode voltage) to be as close as possible to the reference voltage of the analog-to-digital converter, which can be considered as the amplifier “0” (faq. BioSemi.com, 2021a).

Simultaneously referencing acquired data to Common Mode voltage during the data acquisition process provide important benefits for coping with noise and contamination of common line signals when compared with other types of referencing such as ground referencing (Cutmore and James, 1999; Fitzgibbon et al., 2007; Rolston et al., 2009). The CMS/DRL system referencing injects a small amount of current to minimise the noise and contaminations, and the injected

current is subtracted automatically from the data during the data pre-processing process before analysis (FieldTrip, 2021). In the BioSemi EEG recording system, data acquired by each sensor/electrode of EEG are referenced to the active CMS electrode at each time point during the data acquisition process. To improve the efficiency of the active CMS electrode, the CMS electrode should be placed at the centre of other active electrodes are used for data acquisition. Another electrode, as a passive DRL electrode, can be placed away from the active electrodes, which acquire data. It can even be placed somewhere on the arm or leg (Amin et al., 2017). Amplification of acquired data with CMS/DRL system referencing does not influence the amplitude of the acquired data. Amplification facilitates detection of the signal by analog-to-digital converter (Zhu et al., 2009; Perre et al., 2009). In addition to subtracting injected current by CMS/DRL system during the online data acquisition process, re-referencing the data accordingly with alternative referencing methods such as common average referencing is beneficial to avoid data loss during offline data pre-processing process (Torres-Garcia et al., 2016).

In order to process data in a computer medium (for data pre-processing, cleaning, analysis), analog acquired data should be digitized after amplification. Roughly speaking, digitization of analog data includes four steps as; (1) sampling, (2) holding, (3) quantization and (4) encoding the continuous analog signal (Hinrichs, 1991; Minglong et al., 2012). The basic principle beyond digitization is to represent continuous analog signals with a binary coding system following the digitisation system's sampling rate and bit depth (Lessard and Paschall, 1970). The analog-to-digital converters used in the raw EEG data acquisition process generally contain one input port receiving continuous analog signal and one output port releasing digitized continuous analog signal in the form of discrete digit units (Leung, 1990; Lee et al., 2019). Digitization is beneficial for avoiding data contamination from external noise sources and helpful in storing, preserving, and manipulating the data (e.g., copying, editing, analyzing) via software (Cruz-Garza et al., 2017; Chi et al., 2009). The first step of digitization is sampling. Sampling is implemented to continuous analog signal following sampling rate of the used the analog-to-digital converter device. In the sampling process, the continuous analog signal is transformed to equally-distributed discrete-time data by the sampling frequency of the analog-to-digital converter (Kuo et al., 2013).

The second step of digitization is the holding process. In the holding process, sampled data in the form of equally-distributed discrete-time data is recorded and preserved by the capacitor of the analog-to-digital converter following the power of the pulse of sampled discrete-time signal units. Furthermore, voltage follower operational amplifiers cause to switch on and off of semi-conductor in accordance with the sampling frequency and correspondent pulse power is

recorded. Until the next pulse receives the capacitor, previously preserved pulses become stable (Prutchi, 2005). Thus, the sampling frequency of the analog-to-digital converter should not be less than the Nyquist rate (i.e., NR ≥ $2f_{max}$, at least two times of maximum frequency of sampled continuous analog signal) to avoid aliasing problem (Hero, 2006; Anand, 2011, p. 342; Palaniappan, 2011, p.30; De Silva, 2015, p.202). The aliasing problem can cause data loss and contamination. It may create a digitised signal that is irrelevant to the recorded original analog signal or difficulties distinguishing recorded signals due to false digital representations of original ones (Campbell, 2009; Vigário, 1997). Low pass filters are also beneficial for coping with the aliasing problem by cutting the high-frequency bands that could not satisfy the Nyquist rate principle for a sampling frequency of the analog-to-digital converter (Srinivasan et al., 1998; Oken et al., 1986; Sun et al., 1993).

The third step of the digitization process is quantization. In the quantization process, sampled and preserved data units are quantified following the bit depth of the analog-to-digital converter (Nonte et al., 2017; Dickter and Kieffaber, 2014). The bit depth of the analog-to-digital converter defines the resolution of digitised signal representation and is expressed as the magnitude of quantization (Q) (Lee et al., 2013; Nasserian et al., 2019). The resolution of the digitized signal can be measured by comparing the one level change in the analogue signal's amplitude with one unit change in its digitized version (Rampil, 1998; Mollazadeh et al., 2008). The magnitude of quantization (Q) can be calculated by benefitting from (1) full-scale voltage range or voltage span (which can be digitized by ADC), (2) bit depth of the ADC and (3) number of voltage intervals (Dickter and Kieffaber, 2014; Hong et al., 2011). In this regard, the formulation giving the resolution of digitization or magnitude of quantification can be written as;

$$Q = \frac{\Delta \mathrm{V_{ref}}}{N} = \frac{\mathrm{V_{+ref}} - \mathrm{V_{-ref}}}{2^{\mathrm{n}}}$$

where Q shows resolution, $\Delta \mathrm{V_{ref}}$ shows voltage span, which equals to subtraction of lower-level voltage $\mathrm{V_{-ref}}$ from upper level $\mathrm{V_{+ref}}$, N shows the number of quantization levels, which equals two to the power of bit depth (Daube, 2002, p.45-6; Tan and Jiang, 2007, p.156-167; Pelgrom, 2013, p.91-99). In this context, each level of analog signal amplitude is represented with a new binary value accordingly resolution of chosen the analog-to-digital converter circuit defined. Following these binary values, these values are encoded by computer (Blum, 1998; Bai et al., 2008). Following the increase of the bit depth of the convertor, the digitised signal's resolution increases and the digital signal becomes more similar to the original analog one (Rampil, 1998).

Dynamic range in bit depth is also an important issue to understand the efficiency of bit depth and its effects on resolution (Schirrmeister et al., 2017; Aellen et al., 2021). Dynamic range in the

bit depth of analog-to-digital converter circuits equals the ratio between the maximum amplitude within the input signal to the noise level arising the circuit itself (Tong and Thakor, 2009; Nunez and Srinivasan, 2006). The noise level of the analog-to-digital converter decreases the efficiency, and the number of effectively digitized signal bits becomes smaller than total digitized signal bits due to the noise (Yu, 2009). Adequate bit numbers of the analog-to-digital converters can be calculated by benefitting from the dynamic range in the bit depth of the converter (Semmlow and Griffel, 2014). Calculating adequate bit numbers is crucial for selecting a convenient converter for the analog recorded bio-potential digitized (El-Damak, 2012; Singh et al., 2014).

In the BioSemi system used for data acquisition of experiments of this thesis, the bit depth of the analog-to-digital converter is 24-bit, the dynamic range is 115 dB, and the sampling rate is 8kHz, corresponding to an interval of 0.125 ms between sampling points (faq. BioSemi.com, 2021c). In this context, best the analog-to-digital converter should produce less noise, have high rate sampling and high dynamic range to reduce the data loss and acquire data within wider bandwidths during the digitization (Yang and Sarpeshkar, 2006). Thanks to the high resolution of the analog-to-digital converter of BioSemi ActiveTwo System, even very low-level frequency changes can be digitized without the requirement of high-pass filtering (i.e., for avoiding aliasing). The low pass filter of the analog-to-digital converter is also digital, thanks to high and equal sampling frequency for each channel. Additionally, the analog-to-digital converter of the BioSemi ActiveTwo System can digitize the analog recorded signal very efficiently with limited noise thanks to several advances of the BioSemi ActiveTwo System in dealing with large electrode offset voltages (e.g., minimum energy use).

3.1.3. Signal to Noise Ratio

Decreasing the noise and contamination during EEG data acquisition is very crucial for decreasing data loss and increasing the amount of recorded signal relative to noise which can be formulated as a ‘signal-to-noise ratio’ (Welvaert and Rosseel, 2013; Saini et al., 2020; Babiloni et al., 2004). In addition to choosing convenient equipment to increase the signal-to-noise ratio, proper experiment design play also crucial role in the increased signal-to-noise ratio (Lemm et al., 2006). Increasing the signal-to-noise ratio can also be achieved by increasing the number of averaged responses that cause event-related potentials. Averaging the signals for group-level analysis of event-related potentials or averaging the single trials’ responses can also increase the signal-to-noise ratio (Mouraux and Iannetti, 2008; Lemm et al., 2006). The averaging signals depend on recorded time and varying signals, including a distinct signal embedded in noise (Pfurtscheller et al., 1998; Mouraux and Iannetti, 2008). Thus, the signal-to-noise ratio is dependent on the inverse proportion of the square root of numbers of the averaged responses. Proportional increase of

signal-to-noise ratio can be formulated as $SNR = \frac{n}{\sqrt{n}}$ where 'n' is the total number of responses that cause event-related potentials (Bohorquez and Ozdamar, 2006; Rahne et al., 2008; Ivannikov et al., 2007). In addition to increasing the signal-to-noise ratio via increasing the stimuli number (i.e. increasing the responses which cause event-related potentials), some pre-processing data methods such as segmenting the data into epochs accordingly with the trial definition can be used to decrease the noise or adversely, to increase the signal-to-noise ratio (Bast et al., 2006; Lange et al., 1995. Although the decision relevant to how many trials will be used is chosen in line with the experimenter's experience, some of recent studies have given some recommendations in terms of defining trial numbers. For instance, Huffmeijer et al. (2014) suggested to be used minimum 30 trials for some spatially well-defined ERPs of less than 200 ms peak latency. Thus, ERP Analysis of Experiment 1 of this thesis falls broadly into this category of ERPs. Thigpen et al. (2017) also suggested to use minimum 40 trials for several ERP waveforms such as P100. Nevertheless, it has been argued that such recommendations may be over-generalized by Boudewyn et al. (2018). This issue will be further discussed in the Experiment 1, Chapter 4.2.1.

3.2. DATA PRE-PROCESSING

After completing data acquisition, data should be pre-processed and cleaned for data analysis. Data pre-processing and cleaning processes are crucial for eliminating the noise coming from working mechanisms of the devices, the nature of the material components of devices and artefact contaminations coming from physiological and non-physiological sources. Roughly speaking, data pre-processing includes four steps as; (1) trial definition and segmentation, (2) filtering, (3) re-referencing and (4) baseline correction (Peng, 2019; Blankertz et al., 2008).

3.2.1. Trial Definition and Segmentation

As the first step of data pre-processing, acquired raw EEG data is divided into segments. For segmentation, *trigger codes* and *time window definition* about pre-and post-stimulus periods can be called *trial definition* (Andersen, 2019; Chen et al., 2020; Lopez-Calderon and Luck, 2014). Trigger codes are defined during experiment design to detect stimuli onset for data segmentation during data pre-processing and to categorize the trials accordingly to stimuli categories during data analysis. One trigger code is defined for each factor of analysis (i.e., defined stimuli category during experiment design) (Hairston et al., 2014). During the data acquisition process, each trigger code corresponding to each factor of the experiment (i.e., each stimuli category) is sent to the data acquisition computer by Cedrus StimTracker (StimTracker.Cedrus.com, 2021) within ActiView 705 (version 8.6.1) (ActiView.BioSemi.com, 2021) as soon as stimuli were sent to experiment demonstration computer where the participant view the flow of the experiment.

Trigger code sent by Cedrus StimTracker and acquired data during participant's viewing the trigger code's correspondent stimulus type are synchronized by Optical receiver / USB 2.0 interface (Buccino et al., 2016). Synchronization of stimuli onset of acquired and digitized raw EEG data with correspondent trigger codes that define each stimuli category/factor is critical for segmenting the data. In addition to synchronization, defining the time window according to the design of the experiment (e.g., duration of stimuli/fixation cross-presentation) and aspects of data analysis (e.g., frequency of interest of the experiment, possible time window definition of baseline, the time window of the definition of ERP) also critical for defining the time window lengths of each trial/segmented epochs (Shirke et l., 2019; Dickter and Kieffaber, 2014).

Data segmentation is one of the crucial data pre-processing steps for avoiding the noise because parts of the data that will not be used for analysis can be eliminated from segmenting the data according to the relevant parts for analysis (Wang et al., 2009). Following a similar logic, the time window definition of trials should not be too long to avoid additional noise within unnecessary data. However, the time window definition of trials should also not be too short, which should be long enogh to detect the neurophysiology of interest. Thus, the time window definition of trials should be sufficient to examine the neurophysiological activity of interest of the designed experiment and define a convenient baseline with proper time length (Cohen, 2014).

3.2.2. Filtering (Low Pass, High Pass, Band-pass, Band-stop)

The second step of data pre-processing after segmentation of data accordingly with the trial definition is filtering (e.g., band-pass, band notch/band-stop/band-rejection) (Puengdang et al., 2019; Salahuddin Morsalin and Lai, 2020). Filtering the data during pre-processing is beneficial for avoiding noise, for coping with aliasing problems (especially via low-pass filters) and for avoiding the frequencies (extra data which can potentially also include additional noises) which are not the electrophysiological activity of interest of the experiments (Cheveigné and Simon, 2008; Epstein, 2003). Avoiding frequencies and also data that are not the electrophysiological activity of interest of the experiments are also crucial for time and functional efficiency in terms of dealing with big data files due to the high sampling rate of ADC (i.e., high resolution/ quality of digitized data) (Uktveris and Jusas, 2018). Filtering methods can be classified as band-pass and band-stop filters (Wang et al., 2019). Band-passing filters define some upper (i.e., low-pass filter) or lower (i.e., high-pass filter) or both upper and lower limits (low-pass + high-pass filter) in terms of frequency of the signal for allowing the signal pass following the defined limits (Avdeeva et al., 2015).

Unlike band-pass filters, band-stop filters allow all frequencies, but they attenuate some signals of which frequency range is within their stopping limits. One of the most commonly used band-stop

filters in the cognitive neuroscience domain is the notch filter. Notch filters are generally used for avoiding specific signal types, such as power line noise of which frequency range is around 50 Hz or 60 Hz (Tibdewal et al., 2016). In this thesis, Butterworth band-pass filter is used. Although Butterworth filters provide decreased roll-off steepness when compared with Elliptic and Chebyshev filters. These filters provide frequency response in their passband as flat as possible (Burgess, 2019). When compared with other filters, Butterworth filters (i.e., maximally flat magnitude filters) are easily applicable (i.e. simplest transfer function) and have the best passband flatness with smooth transition between passband and stopband without any ripples (De-xiang et al., 2008; Podder et al., 2020). In the experiments, the passband range is defined as 0.35 Hz for high-pass and 39 Hz for low pass. These limits were defined to include all classic EEG frequency bands where classic refers to exclusion of gamma frequency bands (i.e., 40 Hz and above frequency ranges). Similarly segmentation, passband range should be sufficient (neither too narrow nor too wide) to deal with frequency of interest of the experiments (Srinivasan, 2007; Grouiller et al., 2007). In our experiments, the main frequency of interest is the mu rhythm, of which the frequency range is between 8 and 13 Hz. In clinical applications, band-pass filters can be defined broader because of the wide range of frequency of interest of these researches. In some cases where the research is based on the high-gamma frequency range, band-pass filter limits can be defined up to 200 Hz (Ellenrieder et al., 2012). In these cases, choosing an analog to digital converter with a high sampling rate and high bit depth is crucial to avoid aliasing.

3.2.3. Re-Referencing

The third step of the data pre-processing is re-referencing. Re-referencing is crucial for avoiding noise from amplification and digitization processes, to cope with noise polarizations within the data due to asymmetry of head topography (non-ideal sphere, different spatial distances of channels to each other, and other physiological artefacts sources) (Harmon-Jones and Amodio, 2012). BioSemi Active Two System uses a circuit that contains two separate electrodes (i.e., active CMS and passive DRL) working as a feedback loop for referencing during amplification of the data acquisition process (faq. BioSemi.com, 2021b). These electrodes inject a small amount of current during data acquisition for minimising the effects of noise and contaminations, and for referencing and injected current are subtracted from the data during data pre-processing (Teplan, 2002). Thus, referenced data during the data acquisition process and de-referenced data at the beginning of data pre-processing should be re-referenced. In this regard, one of the most efficient referencing methods, the common average referencing method, is applied in the experiments of this thesis. Common average referencing references each amplitude value recorded each channel to the recorded data's average by all system channels at each time point. In this process, the

average of acquired data by all channels of the system in each time point is accepted as “0” and recorded data by each channel at the same time point gain new values accordingly this new “0” as new reference (Liu et al., 2015). The basic assumption beyond accepting the average recorded amplitude value of the system at each time point is that the integral of the electrical potentials over the surface of a sphere containing only concentric inhomogeneities is zero. Thus, the total potentials of evenly placed electrodes throughout the entire scalp should also be zero (Hari and Puce, 2017; Liu et al., 2020). When compared with other re-referencing methods of offline signal processing such as mastoid referencing, common average referencing is better in terms of coping with noise polarizations within data due to asymmetric head topography and different distances of various physiological artefact sources contaminating the acquired data (e.g., heart, eyes and muscles) (Harmon-Jones and Amodio, 2012; Casson, 2019).

3.2.4. Baseline Correction (Absolute, Relative, Relative Change, Norm Change, Decimal)

The last step of the data pre-processing is baseline correction. Baseline correction is beneficial to examine changes in electrophysiological activity of interest before and after event/stimulation (Maess et al., 2016). Baseline correction is also crucial to cope with potential drifts emerging through the data acquisition process and direct current offsets arising from different noise sources such as skin conductivity or sweating (Srinivasan, 2007). The signal within the chosen baseline period is used as the control signal to examine the interest's electrophysiological activity within the post-stimuli period (Sharma et al., 2018). In most cases, the baseline period is chosen from within the pre-stimuli period because of the assumption about the non-existence of electrophysiological activity of interest within this time window and its suitability for comparison (Kaskinoro et al., 2015; Jerbi et al., 2010).

There are several ways of relativizing/normalizing signal of interest (which contain the electrophysiological activity of interest) within the post-stimuli period to baseline or control signal (Hu et al., 2014). For time-frequency analysis for examining ERD/ERS, absolute type of baseline correction is based on subtraction of the mean value of the power spectrum of the baseline period from the mean value of the whole epoch/trial (default baseline type for FieldTrip) (Lago et al., 2015). Relative baseline is based on dividing mean value of power spectrum of whole epoch/trial by mean value of power spectrum of the baseline period, and relative change baseline is based on dividing the subtraction of the mean value of power spectrum of baseline condition from the mean value of power spectrum of whole trial/epoch by baseline condition (Peyk et al., 2011). Decimal baseline correction is based on multiplying exponential forces of 10 with logarithm 10 with relative baseline (Walter et al., 2017). Norm change baseline correction is formulated as dividing the subtraction of the mean value of power spectrum of baseline condition

from the mean value of power spectrum of whole epoch/trial by the sum of the mean value of power spectrum of baseline condition with the mean value of power spectrum of whole epoch/trial (Haumann et al., 2016). Fieldtrip Routines calculate these baseline types in line with "*data"* (post-stimulus) and "*meanVals*" (pre-stimulus or baseline). In this regard, formulations of baseline type can be listed as;

- Data = data - meanVals (Absolute)
- Data = data ÷ meanVals (Relative)
- Data = (data - meanVals) ÷ meanVals (Relative Change)
- Data = (data - meanVals) ÷ (data + meanVals) (Norm Change)
- Data = 10 x $\log_{10}$(data ÷ meanVals) (Decimal) (see, github.com, 2019)

In time-lock analysis for ERPs, instead of power spectrum values of baseline and whole epoch (default for Time-Frequency Analysis in FieldTrip), average signal values are used for baseline correction calculations (default for Time-Lock Analysis in FieldTrip) (Williams et al., 2020; Yang et al., 2020). Generally, absolute, relative or relative change baseline correction is used in the time-domain analysis for ERP components, but for time-frequency analysis for ERD of brain oscillations, norm change baseline correction is preferred (Allen and MacKinnon, 2010).

In the experiments of this thesis, the time window of baseline condition is defined as 300 ms to ±0 ms in the pre-stimuli period for baseline correction. In Time-Domain/Time-Lock Analysis for ERP Wave Components, *absolute type* baseline correction was chosen. In Time-Frequency Analysis for ERD of brain oscillations, the *norm change type* baseline correction was chosen.

3.3. EEG SIGNAL PROCESSING AND HARMONIC ANALYSIS

In data pre-processing and data analysis steps, digitized EEG data may need to be decomposed to its components such as frequencies, and data may need to be represented in basic waveforms (Samar et al., 1999). These basic waves can be trigonometric waves such as sine and cosine waves (i.e., Fourier Transform) (Polat and Günes, 2007; Akin, 2004) or some wavelets (i.e., Wavelet Transform) (Adeli et al., 2003). Representing digitized complex EEG data as the superposition of basic waves (e.g., trigonometric waves, wavelets) is crucial for manipulating and analysing different parameters of EEG signals such as amplitude, frequency and latency (Bénar et al., 2009). Harmonic analysis is mainly used for spectral analysis of EEG signals (i.e., for power spectrum) and implemented to EEG data for examining Event-Related Potentials (ERP) and Event-Related De-/Synchronizations (ERD/ERS) in cognitive neuroscience experiments (Eva and Lazar, 2015). In ERD/ERS analysis of brain oscillations, harmonic analysis methods (e.g., Fourier Transform) provide the decomposition of signal or pre-processed EEG data to its frequency components, and

following frequency (band) of interest of the experiment, Time-Frequency Analysis can be achieved easily (Zhang, 2019; Hu et al., 2014).

To decompose heterogeneous signals in terms of such parameters of their components as frequency, amplitude, phase, latency, angular frequency, there are several Harmonic Analysis methods. These methods use different mathematical transformations and approximation methods which break complicated curves into sums of comparatively simple manageable signal components to manipulate (Jervis et al., 2006; Jia et al., 2019; Adeli et al., 2003). In addition to applications for the decomposition of complex EEG data, different Harmonic Analysis methods are applied to different real-life problems relevant to the decomposition of complex functions/signals. Some of the application areas of Harmonic analyses are alternating electric currents, tides, vibrations, different signal processing (e.g., image, audio and video processing, radar signal processing), quantum mechanics, neuroscience, machine motions (Selesnick, 2011; Adeli et al., 2003). Harmonic analyses are used mainly to analyse periodic waves of decomposition of complex signals such as periodic brain oscillations within EEG data. Thanks to the periodicity of the brain oscillations generated by postsynaptic potentials of fired pyramidal neuronal populations, these oscillations can be easily expressed in the collection of successive sine and cosine waves or wavelets or wavelet components. Moreover, different values such as frequency and amplitude of decomposed complex signal components can easily be manipulated and calculated via basic mathematical operations (Kilicarslan and Contreras-Vidal, 2019; Adeli et al., 2003; Jervis et al., 2006).

One of the oldest and most common methods of Harmonic Analysis is Fourier Transform which was formulated by French mathematician Joseph Fourier (Gao and Yan, 2011). In Fourier Transform, complex signals/functions are expressed in successive simpler cosine and sine waves. These successive simpler cosine and sine waves are called as Fourier series, and this transformation is called as Fourier Transform (Gallagher et al., 2008). In the Fourier series, the complex signal subjected to transformation is called periodic, and all simpler successive sine and cosine components of the complex signal are called harmonic (Pollen and Ronner, 1983). An increase of harmonics or relevant variables of harmonics can increase the accuracy of harmonic approximation (Zhilenkov and Chernyi, 2015). In addition to Fourier Transform, some of the other harmonic analysis methods which are applied to EEG signal processing can be listed as Wavelet Transform (Adeli et al., 2003), Gabor Transform (Schönwald et al., 2003), Gabor-Wigner Transform (Khan et al., 2016), Laplace Transform (Jie et al., 2014), and z-Transform (Huster et al., 2015). These methods can also be divided into sub-categories following the width of their time window as continuous, discrete, discrete-time. Thus, they can be called Continuous Wavelet

Transform, Discrete Fourier Transform and so on (Yamaguchi, 2003). In EEG data analysis, choosing short time window transformation (e.g., discrete, discrete-time) instead of continuous long time windows for harmonic analyses is more efficient in terms of coping with noise and contamination of longer epochs, for better temporal specificity, and for avoiding problems arising from digitization and segmentation (Herrmann et al., 2005; Adeli et al., 2003). However, choosing efficient windowing/tapering options becomes crucial for dealing with truncated signal parts in short time window options (Quiroga, 2000;). Thus, choosing a multi-taper as the combination of different tapering options can make segmenting points of the signal smoother and minimise the data loss (Babadi and Brown, 2014). In this regard, when compared with Fourier Transform, Wavelet transform give better results for EEG signals in terms of time-frequency resolution thanks to its more flexible windowing options (Samar et al., 1995; Roach and Mathalon, 2008; Zhang, 2019).

In cognitive neuroscience and neurophysiological studies, Fourier Transforms are used for different spectral analyses of acquired EEG data such as *power spectrum analysis* where the power for each frequency is plotted along the frequency axis, *amplitude spectrum analysis* as the square root of the power spectrum, *phase spectrum analysis* based on comparison of phase as the ratio of imagery to real parts of signal with frequency (Kohtoh et al., 2008; Schwilden, 2006). These analyses are crucial for examining synchronization and de-synchronization of brain oscillations (Pfurtscheller et al., 2006). Limited and fixed window lengths can be used to optimise neural oscillations with a limited frequency range in Fourier Transforms (Stober et al., 2014).

Fourier transformations for harmonic estimation of acquired EEG data generally provide a basis for analysing the complex EEG signal (Frigo and Narduzzi, 2014). These transformations are formulated by benefitting from the sinusoidal function based on a polar representation of sine and cosine harmonics of the given signal. In this polar representation, the signal's real part is represented with cosine harmonics, and the imaginary part is represented with sine harmonics within the context of phasor or phase vector calculus (Rampil, 1998; Sigl and Chamoun, 2005). The basic principle beyond this representation is that the nature of brain oscillations is similar to transient current or alternative current, although action potentials can be considered direct currents (Hopfield and Brody, 2001). In these Fourier formulations, instead of a polar representation of sinusoidal functions, Euler equations can be used (Cohen, 2014). In these formulations, most commonly used variables can be listed as frequency (f), time (t), angular frequency (ω, which is generally considered 2π), period (T), amplitude (A), initial phase (θ), time constant (τ) (McFadden and Smith, 1984; Ozaktas et al., 2001). In addition to these parameters, different parameters can also be added, such as direct current component, ‘dirac’ impulse,

window length, numbers of windowed blocks following the content of the transform type (Huang and Zheng, 1997; Aach, 2003). The decision to select a transformation type for harmonic estimation can be made by examining the applicability of the inverse version of the transformation produced by limit function application to chosen transformation type (Wang, 1984). Some optimization algorithms help select transformation types for harmonic estimation (Khokhar et al., 2015).

By benefitting from these explanations, one of the basic transformation forms as the Real Fourier Series (Pivato, 2010) can be formulated as

$$P(t) = \frac{1}{2}a_0 + a_1\cos(\omega t) + a_2\cos(2\omega t) + \ldots\ldots\ldots + b_1\sin(\omega t) + b_2\sin(2\omega t) + \ldots\ldots\ldots$$

where the first term $\frac{1}{2}a_0$ is representing the *direct current* component, and coefficient a_n and b_n representing *alternating current* (Najarian and Splinter, 2012, p.15-38; Van Drongelen, 2018, p.81-103). By benefitting from the formulation of Real Fourier Series, Complex Fourier Transform can be formulated by replacing sine, and cosine harmonics with their correspondent harmonics expressed polar representation of Euler equation (Levermore and Oliver, 1997). Furthermore, by benefitting from the formulation of Complex Fourier Transform, formulations of Continuous, Discrete and Short-Time Fourier Transform can be derived (Ashouri et al., 2018; Portnoff, 1980). Following chosen time (domain) window, a convenient type of Fourier Transform can be chosen. Continuous Fourier Transform is used if signal processing is achieved with a continuous-time (domain) window. If signal processing is achieved with a discrete-time (domain) window, Discrete Fourier Transform is used (Heinzel et al., 2002; Ashouri et al., 2018; Portnoff, 1980). Fast Fourier Transform is used for testing the efficiency of these two Fourier Transforms (Dutt and Rokhlin, 1993). Fast Fourier Transform is also used to optimise transformations for harmonic estimation (Vidyaratne and Iftekharuddin, 2017). Fast Fourier Transform algorithm can be expressed as a flow in a diagram (Butterfly diagram) (Boyle et al., 2007). If the Fourier transform is combined with a sliding time window that provides acquisition of a spectro-temporal representation of the signal letting to track the temporal evolution of spectral values is called a Short-time Fourier Transform (Pampu, 2011).

Continuous Fourier Transform is generally used if there is no frequency range limit of the data or non-periodic signals are represented as the integrals of the linear combination of complex and infinitesimally close in frequency exponentials that provide continuity of the signal (Candan et al., 2000). Discrete Fourier Transform is derived from Continuous Fourier Transform. It converts discrete-time data sets of a signal or function to a discrete-frequency representation. Discrete

Fourier Transform is used for processing finite sequences of data such as signals known only at instants separated by sample times. Discrete Fourier Transform is mainly used in discrete-time signal processing, linear filtering, correlation analysis, and spectral analysis (Ponomareva et al., 2018). Unlike Continuous Fourier Transform, Discrete Fourier Transform is applied to real-world problems due to finite limits for time and frequency like real signals. Accuracy of Discrete Fourier Transform depends on two aspects: sampling rate, which defines high limit and period, which defines the low limit of the complex signal (Grandke, 1983).

Short-Time Fourier Transform is used for analysing changes in sinusoidal frequency and phase content in the local parts of the signal. It is a beneficial method for estimating the existing frequencies at a particular time (Griffin and Lim, 1984). Short-Time Fourier Transform decomposes the signal into successive time frames as windows, and it is very efficient for coping with a spectral leak (Pampu, 2011). There is a trade-off between frequency and time in the resolution of Short-Time Fourier Transform (Lima et al., 2018). Thus, deciding the resolution type of Short-Time Fourier Transform (i.e., either spectrum or time) in its implementations according to the requirement of the analysis is crucial due to resolution limitations (Mangueira Lima et al., 2016).

Short-Time Fourier Transform can be considered the application of Discrete Fourier Transform to each window used for dividing the complex signal. In these windows, the frequency spectrum is expressed via bins and accordingly, with the sampling rate, frequency resolution increases while the time window decrease (Schörkhuber et al., 2014). As a result of truncation of the waveforms during the implementation of Short-Time Fourier Transform, the width of each frequency bin causes a spectral leak which requires more computational power for more accuracy and to cope with data loss. Thus, Short-Time Fourier Transform overlaps windows to cope with truncation and spectral leak (Parchami et al., 2016). There are two forms of Short-Time Fourier Transform: Continuous Short-Time Fourier Transform and Discrete Short-Time Fourier Transform. The inverse version of these Short-Time Fourier Transforms can be used for checking the signal in terms of applicability (Nasih and Assitant, 2016).

Another Harmonic Analysis method is Gabor Transform derived from Short-Time Fourier Transform as windowed Fourier Transform. Gabor Transform was formulated by Hungarian-British physicist and engineer Dennis Gabor (Matthé et al., 2014). Gabor Transform benefits from the windowing function (i.e., Gaussian Window) of Short-Time Fourier Transform for time-localization to extract local information from the Fourier transform. In Gabor Transform, continuously sliding windows of Short-Time Fourier Transform has used localization, providing equivalence between attributions of the localized Fourier transform with time resolution. Like

Short-Time Fourier Transform, Gabor Transform also has continuous, discrete, and inverse versions (Chinen and Reed, 1997).

The efficiency of Gabor Transform, especially in terms of decreasing computational demands (e.g., algorithmic difficulties), has been improved via different applications such as Lapped Transform and Malvar Wavelets, which have been invented by several computer scientists and electrical engineers (Malvar, 1992; Xia and Suter, 1995). Furthermore, Wigner Distribution Function is applied to Gabor Transform to decrease computational demand and algorithmic difficulties and increase the accuracy. This transform is called as Gabor-Wigner Transform (Cheng et al., 2015). The Wigner Distribution Function can be applied to both Continuous Time, and Discrete-time Gabor Transform to analyze the signal's energy distribution over time and frequency at global and local levels (Cho et al., 2010). Gabor-Wigner Transform can be applied in various areas for signal processing where Fourier Transforms cannot work efficiently. Especially, Gabor-Wigner Transform can efficiently work in bilinear/quadratic time-frequency representations, one-dimensional deterministic scalar and multi-dimensional non-stable random vector signals, linear signal spaces and frames and linear time-variant systems when compared with Fourier Transform (Szmajda et al., 2010). Some application areas of the Gabor-Wigner Transform can be listed as; signal detection and enhancement, speech analysis, biological and medical signal analysis, seismic prospecting, image processing and pattern recognition, source localization and separation (Cho et al., 2010).

Due to Wigner Distribution's limitations, especially in terms of resolution of distribution of frequencies over time, some of Wigner Distribution's modifications which are based on smoothing in one or two dimensions, have been generated (Kun, 2007). Modified versions of Wigner Distribution are generated by combining the distribution with different statistical distributions such as Wigner–Ville, Choi–Williams, Rihaczek, Born–Jordan, Cohen and Page distributions which facilitate the decrease of trade-offs between time and frequency resolution (Thomas et al., 2012). Like Gabor Transform, Gabor-Wigner Transforms also have continuous and discrete versions, and its cross-check is achieved by Gabor Transform instead of inverse version of Gabor-Wigner Transform (Cheng et al., 2015).

3.3.1. Spectral Leak, Windowing and Multitapering

Discrete Fourier Transform assumes signal is a finite data set as one of the periods of the continuous periodic signal. This basic principle of Discrete Fourier Transform creates some problems in its applications to real-life problems, such as its applications to Time-Frequency Analysis of neural oscillations (Özaktas et al., 1996). In this regard, as a result of this fundamental

principle, if the analyzed signal is non-periodic and an integer number of periods fill the acquisition time interval; there may be some truncation with different characteristics from the original continuous-time signal at the endpoints of the waveform within the limited epoch of a time series (Zhou et al., 2014). Truncations that emerge as a result of artificial discontinuities in the time domain can cause (1) data loss (especially the loss of representation of high-frequency components due to Nyquist rate) and (2) some aliasing problems which prevent the accurate representation of the original signal. Truncated waveforms spread new frequency components into wider signals. This phenomenon is called spectral leakage (Andria et al., 1989; Xu et al., 2005). The spectral leak problem can be solved by applying windowing or tapering function to segmented or truncated signals. Windowing or tapering function reduces the amplitude of the discontinuities at the boundaries of each finite sequence acquired by the digitizer (Dumermuth and Molinari, 1987). For reduction of the amplitudes, windowing or tapering varies these amplitudes smoothly gradually toward zero at the edges and this reduction method of windowing/ tapering functions provide the meet of the edge amplitudes together to form continuity without sharp transitions (Thakor and Tong, 2004).

There are various windowing or tapering types. Before choosing the convenient type of windowing or tapering, examining the properties of the signal processed is essential. Another factor influencing the selection of convenient windowing type is frequency characteristics (e.g., location of interfering frequencies, closely located frequencies, the existence of fundamental frequency of interest, distribution of frequency range) (Herff and Krusienski, 2018). The frequency spectrum of the windowing function is organized according to the main lobe and several slide lobes. The main lobe of the frequency spectrum of the windowing function locates at the centre of each frequency component of the time domain signal. Furthermore, slide lobs gradually come closer to zero as the indicator of the effect of windowing function on the frequencies around the central lobe (Ramos-Aguilar et al., 2019). In this regard, the efficiency of the windowing function is associated with its efficiency in the prevention of spectral leak. The efficiency of prevention of spectral leak is dependent on decreasing the height of side lobes and increasing the side lobe roll-off rate as the asymptotic decay rate of the sidelobe peaks (Wallace, 2016). In EEG experiments, Hann and Hamming windows are commonly used (Solomon, 1993; Herff and Krusienski, 2018). Hann and Hamming Windows are one of the basic windows for smoothing the truncated waveforms. Hann Window is one of the members of generalized cosine windows family as Cosine-sum Windows, and it is derived by smoothing edge points of the waveform within Cosine-sum Windows to zero instead of one (Beinborn et al., 2019). Hann Window uses squared cosines

for values (Li et al., 2016). Hann Window is very efficient to cope with aliasing problems (Achermann, 2009) however; resolution of Hann windowing is slightly decreased as the trade-off.

Formulation of Hann Window Function is;

$$\omega\,(t) = \begin{cases} 0.5 + 0.5\cos\left[\frac{\pi t}{T}\right] & |t| \leq T \\ \text{else } 0 \end{cases}$$

Hann Window is sometimes wrongly called *Hanning* Window as a result of its resemblance with Hamming Window. Hamming Windows are derived from Hann Window by adjusting the 0th sampling value in time domain processing 0.54 or 24/46 instead of 0.5 (Essenwanger, 1986; Harris, 1978). Hann Windowing can also be used in several areas such as narrowband random signal (vibration data) and signal with unknown content or if the signal content is a sine wave or combination of sine waves (Gramfort et al., 2014; Rehman et al., 2013). Hann and Hamming Window functions are very beneficial for measuring noise and providing a good frequency analysis resolution (Kahlig, 1993; Pampu, 2011).

In EEG data analysis, especially Time-Frequency Analysis for examining Event-Related (De-) Synchronizations, combining different windowing functions can increase the windowing process's efficiency in smoothening the signals' truncation and minimization of the spectral leak (Faust et al., 2008). In Time-Frequency Analysis, by benefitting from periodogram or power spectrum estimation, the signal is multiplied in the time domain with a taper which would have less energy in its side lobes primarily and characterized by applied Harmonic Analysis (e.g., Fourier Transform) (Blanco et al., 1995; Tzallas et al., 2009). And then, either an average across several frequencies can be considered, or an average spectrum can be computed by benefitting from several time epochs to cope with spectral leak and noises (Felix et al., 2009). Averaging several frequencies or power spectrum can cause the reduction of spectral resolution and the production of undesirable multiple epochs. Thus, differently from using a taper characterized by one of Harmonic Analysis methods (e.g., Fourier Transform), Multitaper Power Spectral Analysis suggests more than one window, especially as pair-by-pair functions together (Prerau et al., 2017). In this regard, the orthogonality of the window pairs and their spectral concentration properties are important aspects of windowing functions in choosing the convenient ones (Baraniuk and Bayram, 2000). In Time-Frequency Analysis of the experiments of this thesis, Hann windowing based Multitaper Power Spectral Analysis is applied to data, instead of using mere Hann windowing function.

For multiplication of multi-taper spectral analysis-based time-frequency analysis within the frequency domain, convolution should be applied to processed signals (Nicknam et al., 2013). In Harmonic Analysis applications of EEG signal processing, one of the basic assumptions of

convolution theorem is that point-wise multiplication of one domain as time-domain has an equivalent value in other domain as frequency domain (Procházka et al., 2008). In this context, convolution can be defined as the formulated third function that can facilitate understanding the effects of one function on the other second function (Saadati et al., 2019). In our Time-Frequency Analyses, convolution is applied to data in the wavelet form with multi tapers as Hann tapers. Convolution wavelet is generated by multiplying the polar representation of signals via Fourier Transform at each frequency point (Mallat, 2003; Pathak, 2009). After the application of convolution for Time-Frequency Analysis, Fourier Transforms were applied to the data. And then, by benefitting from the multiplication of this transformation (i.e., polar representation of signals at each frequency point) after the computation of inverse Fourier Transform, Multitapered wavelet and element-wise products are generated. Combining Multi Taper Spectral Estimation with convolution increases the efficiency of tapering and minimizes the spectral leak (Erdöl, 2005; Vilamala et al., 2017).

3.4. ARTEFACT REJECTION AND DATA CLEANING

Data acquisition of the EEG process is so much subjected to contaminations from different sources. Also, due to the vulnerability and tininess of recorded EEG data, contaminations can shadow the electrophysiological activity of interest and violate the data analysis process (Jung et al., 2000). EEG data can be contaminated by several sources such as inevitable noise arising from data acquisition equipment, bio-potentials which are produced by different physiological sources such as participant's heart, any discrete sources independently from either equipment or the physiology of the participant (Shamsul Arefin et al., 2019). In this regard, acquired EEG data should be cleaned from these contaminations for preparing the data for analysis. For dealing with contaminations of acquired EEG data, understanding the nature of the artefacts contaminating EEG data and examining different data cleaning methods used for eliminating these artefacts contaminating become important.

3.4.1. Artefacts Contaminating EEG Data

Artefacts that contaminate EEG data can be classified into two groups; physiological artefacts and non-physiological artefacts. Physiological artefacts are bio-potentials generated by different biological sources, such as the organs of the participants. They can be listed as eye-related artefacts, muscle artefacts, cardiac artefacts, sweating related artefacts and so on (Mannan et al., 2018; Tandle and Jog, 2015). Differently, non-physiological artefacts generally emerge due to the devices and equipment used for data acquisition. Some of the non-physiological artefacts can be listed as power line, response box, sensor-related, transmission line, landline phone, electrode

pop, lead movement, perspiration artefacts and so on (Cruz-Garza et al., 2017; Peng, 2019). Among these artefacts, some of the artefacts have homogeneity in terms of distribution in time or amplitude. These artefacts which show Gaussian distribution across time or amplitude can easily be detected. In some cases, they may not need to be rejected due to their homogenous distribution within data (Delorme et al., 2001; Rombouts et al., 1995).

Among the physiological artefacts, one of the most troublesome artefacts is eye-related artefacts due to the location of the eyes (i.e., closeness to the recording area, scalp) and inevitability and arbitrary patterns of blinking and moving the eyes during the data acquisition process (Lourenço et al., 2016). Eye-related artefacts can be listed as eye blink artefacts, eye movement artefacts (either horizontal or vertical and also (micro-) saccades) and artefacts emerging as a result of electro-potentials of the retina (Plöchl et al., 2012; Ball et al., 2009). Currents of photoreceptors of the eyes influence the activation of anteriorly directed currents in the pigment epithelium of the retina during blinking or moving eyes. This cause bipolarization of the retina and cornea and contaminate acquired EEG data (Clark, 2008; Holder, 2004). Eye-related artefacts emerge as a result of these polarizations, and they contaminate acquired EEG data heavily. Especially if the data acquisition process takes long, these artefacts contaminate the acquired EEG data more powerfully in accordance with the level of drowsiness or attentiveness of the participants (Grimm et al., 2009; Katus et al., 2015).

Thus, eliminating eye-related artefacts becomes essential from the acquired EEG data to increase the efficiency of data analysis (Chang et al., 2018; Mannan et al., 2016). Eye movement-related contaminations can be reduced by the experiment design. Eye movement-related artefacts can be reduced if the experiment design does not contain participants' horizontal and vertical eye movements alternatively if the stimuli are presented to the participants with minimum visual angle (on the centre of the screen, at the participant's eye level) (Plöchl et al., 2012; Beckers and Hömberg, 2004). However, reducing the contaminations of eye blinks is very difficult. In addition to previously listed difficulties relevant to eye-related artefacts, patterns of eye blinks can vary not only within the subject during the data acquisition process but also across different participants (Roy et al., 2014).

Eye-related artefacts can be measured by electrooculography and electroretinography. Electroculography and electroretinography can also be used to detect eye-related artefacts to remove them from raw EEG data (Ozaki et al., 1993). There are several ways of removing eye-related artefacts. First of all, asking participants to try not to blink their eyes as many times as possible can be used to reduce the eye-related artefacts; however, this method can decrease the participant's performance in terms of the fulfilment of the task of the experiment due to the shift

of attention to avoid blinking eyes. Thus, it is not an efficient method. Secondly, rejecting contaminated epochs from the data can be an alternative method, but it may cause much data loss, especially in visual neuroscience studies (Jung et al., 2000). Using software to correct these artefacts can also be used as another method, but dynamism and heterogeneity of the patterns of the eye-blinks can create additional problems (Britz et al., 2010; Manojprabu and Dhulipala, 2020). Infrared eye-tracking methods can also be used if the differences are considerable between original data and eye-related artefacts (Xue et al., 2017). Alternatively, each participant's eye artefacts can be recorded before the experiment independently, and these recorded eye-related artefacts can be used to detect and reject eye-related artefacts within data in post-processing processes. However, among these methods, applying Blind Source Separation Techniques such as Independent Component Analysis (see, Section 3.4.2) to acquired EEG data is one of the most efficient eye-related artefact rejection methods (Choi et al., 2004).

Another physiological artefact contaminating EEG data is muscle artefacts. Muscle related artefacts emerge as a result of contractions of muscles and action potentials of muscle fibres (Xu et al., 2018). Action potentials of muscle fibres and contractions of muscles are regulated by electrical impulses which come from the spinal cord to muscle fibres via alpha motoneurons (Mir et al., 2019; Chen et al., 1989). Amplitude and duration of contamination of motor artefacts can vary. The contamination effect depends on the distance of the electrodes from motor fibres in the contracting motor unit and the numbers of motor fibres within the contracting motor unit. There is a directly proportional relationship between distance, contamination, density, and distance (Kovach et al., 2011; Daly et al., 2013a). Weak motor contraction activity can be detected via electromyography (Balasubramanian and Adalarasu, 2007). Large muscle artefacts can be cleaned via low pass filters if they are not in the frequency range interest of the main experiment (Clercq et al., 2006). In the EEG data acquisition process, the most common muscle artefacts contaminating the recording are produced by the head, face and neck (Fitzgibbon et al., 2007; Puce and Hämäläinen, 2017). Like rejection of eye-related artefacts, Blind Source Separation Techniques are also one of the most beneficial techniques for rejecting the muscle artefacts (Hallez et al., 2009; Fitzgibbon et al., 2007). However, independently from voluntary muscle activities, cleaning some muscle artefacts such as artefacts of autonomous contractions resulting from basal metabolism can even be hard via blind source separation techniques (Whittier, 2017; Min et al., 2011). Some other methods for reducing/avoiding muscle-related artefact contaminations can be listed as; asking participants to limit his/her own movements or measuring influences of muscle contraction in a relaxed position before the data acquisition process began, software correction methods which are based on electromyography (Muthukumaraswamy,

2013). Muscle artefacts severely influence geodesic EEG setups compared with international 10-20 systems due to their standard features (e.g., some parts placed on cheeks) (Teplan, 2002; Song et al., 2015). Removing muscle artefacts via blind source separation techniques are more complicated when compared with the eye-related artefacts of which amplitude and frequency are limited (Jung et al., 2000).

Similar to contaminations of muscle contractions, heart-related artefacts also appear due to the potentials generated by heart muscles, especially atria and ventricles (Reilly and Lee, 2010). Atria and ventricles involuntary striated muscle, unlike the smooth muscle tissue in other internal organs. Their anatomical structure is similar to striated skeletal muscles producing strong electric potentials on the body surface (Stern et al., 2001). Heart muscle artefacts arising from the cardiac cycle can be measured via electrocardiography (Iriarte et al., 2003). A cardiac cycle has three components as P wave, QRS Complex and T wave. When atria and ventricles contracted due to the cardiac cycle during the blood pumping process of the heart, P wave emerges during depolarization (contraction) of the atria, QRS complex emerges during depolarization (contraction) of the ventricles and T wave emerges during repolarisation (relaxation) of the ventricles (Dirlich et al., 1997). During de- and re-polarization processes of atria and ventricles muscles due to the cardiac cycle, generated powerful bio-potentials contaminate the EEG recording (Beasley and Grogan, 1990; Kennedy, 1989). Changing phases of respiration within each participant and changing the heart's position and pattern of the cardiac cycle across the participants create difficulties in detecting and eliminating heart-related artefacts (Sweeney et al., 2012; Porges and Byrne, 1992). However, these artefacts' typicality, frequency of approximately 1 per second, and Gaussian spatial distribution make rejection easy (He et al., 2016). In addition to blind source separation techniques, cardiac artefacts can also be rejected from data via sample recording of these activities before EEG data acquisition began (Ille et al., 2002; Tatum et al., 2011).

Sweating related artefacts have very low-level frequency, and they can only influence slow event-related potentials and infra-low and ultra-slow brain rhythms (Motamedi-Fakhr et al., 2019; Zou et al., 2016). Climate or fan which cools the experiment environment can be used to avoid sweating related artefacts. High-pass filtering can also provide very crucial benefits if the frequency of the interest of the experiment is not low-frequency brain rhythms (Frølich and Dowding, 2017; Maess et al., 2016).

In addition to physiological artefacts, non-physiological artefacts emerge due to the high voltage power tools, electrical activity of surrounding equipment, and power-line noise (Peng, 2019). Power-line noise artefacts are widespread and emerge from the alternating current supplied to

electrical wall outlets. These artefacts are generally non-periodical/harmonic and change following the country's power system (Zhong and Qi, 2018; Jiu-ming et al., 2004). They can be seen in the power spectrum of acquired EEG data. If the pairs of electrodes of EEG have impedance mismatches and also impaired common-mode rejection (see, Glossary) or if there is poor contact between electrodes and scalp or if there are some problems related with grounding loop, the amplitude of power-line noise artefacts can increase (Thompson et al., 2008; Ferree et al., 2001). Dealing with artefacts emerging as a result of power-line noise can be very hard. Choosing more efficient devices in terms of reducing/avoiding these artefacts, improving electrode positioning to achieve optimum impedances, using a Faraday Cabin which provides insulation from electro-magnetic fields can help minimise these artefacts (Lundt et al., 2016). Band-stop filters and blind source separation techniques can remove power-line related artefacts from acquired data (Kasprzak, 2014). Independently from data acquisition equipment, power-line noise artefacts can also emerge from different sources such as arc-welders or other high-voltage construction-related equipment working with high frequencies in the building outside the laboratory (Xue et al., 2006; Leske and Dalal, 2019). Additionally, in clinical applications, drips, pumps, ventilators located in the intensive-care units, or rhythmic artefacts generating operating room can also create power-line noise artefacts (Tibdewal et al., 2016; Vanitha and Krishnan, 2016). If the frequency of the experiment is high-frequency ranges such as gamma band activities, removing these artefacts becomes essential (Müller et al., 2000). Heterogeneity of spatial distribution of these artefacts makes their detection harder (Kaiser and Lutzenberger, 2005; Müller et al., 1999).

In some cases, sensor-related artefacts such as very slow baseline drifts can emerge because of the poor contact between channel and scalp (Ochoa, 2002; Niazy et al., 2005). In these cases, improving the contact quality is very beneficial. If the artefacts result from a broken channel, it can be repaired or replaced with a good channel. In some cases, drying out of electrolytic gel can cause the sudden rise and gradually fall of EEG signal intermittently in a single electrode. This can create sensor-related artefacts (Li et al., 2020; Campbell, 2009). Improving the conductivity of sensors of electrodes (e.g., checking sufficiency of electrolytic gel applications) is one of the most efficient methods to cope with sensor-related artefacts (Placidi et al., 2020; Engemann and Gramfort, 2015).

In some cases, if the weather of the experiment environment is dry, weather can create statistical electricity due to friction between movements of the experimenter's body or participant and weather (Placidi et al., 2020). The humidity of the environment can be increased to cope with these problems. Additionally, in some cases, if the experiment task requires pressing a response

key, response pads such as numerical keypads can also create some influential artefacts on acquired data because of the capacitance changes associated with keypresses (Lelis-Torres et al., 2017; Maruthachalam, 2020). In these conditions, although the pattern of artefacts is dependent on capacitance changes of these devices, which is generally typical, contamination of the data is dependent on atypical responses of the subject. Atypical participant responses can create additional difficulties in detecting and eliminating these artefacts (Jadhav et al., 2014; Sheela and Puthankattil, 2020). Choosing a convenient response pad can minimize the noise, and detection of response pad related artefacts can be more manageable. In some cases, electromagnetic signals of mobile phones or traditional phone lines can also contaminate EEG signals. Switching off the mobile phones in the experiment area, using traditional phones outside the experiment area, and using Faraday Cabin are helpful methods to cope with these signals (Kramarenko and Tan, 2003; Croft et al., 2008).

3.4.2. Blind Source Separation Techniques and Independent Component Analysis

Blind Source Separation Techniques are one of the most efficient methods of detecting and rejecting physiological and non-physiological artefacts (Mowla et al., 2015; Romero et al., 2008). Understanding the parameters which shape the characteristics of these contaminating artefacts such as waveforms, spatial distributions, sources, and mechanisms is beneficial for understanding how blind source separation techniques cope with these artefacts (Romo-Vázquez et al., 2012). The main procedures of Blind Source Separation techniques in terms of removing the artefacts are (1) extracting contaminated parts of the signal from the original signal and (2) healing the remaining signal via interpolating with minimum distortion (Davies, 2015; Mowla et al., 2015). However, in some cases, patterns of artefacts can be similar to patterns of the signal of interest. These situations create difficulties in detecting and eliminating the artefacts (Tatum et al., 2011; Tandle and Jog, 2015). If the frequency range of these artefacts is above or below the frequency range of interest of the experiment, band-pass filters can easily be used for eliminating these artefacts (Tandle and Jog, 2015). However, if the artefact and signal of interest have similar patterns and if they also have similar frequency ranges, this situation creates extra difficulties in terms of detection and elimination of these artefacts. In this regard, Blind Source Separation methods can help to detect these types of artefacts (similar pattern and frequency range with electrophysiological activity of interest) (Urigüen and García-Zapirain, 2015; Tatum et al., 2011). The most common artefact rejection methods within Blind Source Separation Techniques are Independent Component Analysis, Sparse Component Analysis, Non-negative Matrix Factorization, and Principal Component Analysis (Amari, 2005).

Blind Source Separation (BSS) Techniques as one of the powerful signal processing and artefact rejection techniques can be dated back to the late 1980s (Karhunen et al., 1997). These techniques are formulated by combining different approaches such as artificial neural networks, information theory, statistical signal processing (Tan et al., 2001; Zhou and Gotman, 2004). In addition to various signal processing areas such as earth signals, speech signals, image processing, BSS have begun to be applied to biomedical signal processing such as the processing of EEG signals since the 1980s (Chua et al., 2010). Roughly speaking, BSS is a de-/re-composition method to extract artefacts and recover the signals from multivariable statistical data. In Blind Source Separation Techniques, the term 'blind' refers to either a signal of which source is unknown or a hybrid system which is also unknown or very little known (e.g., distribution, dynamism, and statistical independence of components of the system) (Ahmadian et al., 2013). In multichannel data acquisition systems such as EEG systems, signals acquired by each channel are recorded as a mixture of signals emerging from neighbouring sources. Thus, BSS can play a crucial role in separating the influence of signals from neighbouring sources and recovery of the channel's own original signal (Latif et al., 2006). One of the most typical real-life examples of this situation is Cocktail Party Problem. Cocktail Party Problem is associated with a cocktail party where various sounds come from the surroundings to the microphones located in different places within a room. According to this scenario, the microphones will record not only local voices, such as the speaker's voice. They also record other voices such as other speeches, music, whistles coming from various sources as a mixture of signals with differentiating weighting. In these situations, BSS techniques are very efficient for differentiating desired voices from other noises (i.e., blindness characteristics of the record) (O'Sullivan et al., 2015; Bednar and Lalor, 2020).

Recovery of the original signal via BSS techniques is generally dependent on the characteristics of methods based on a nonlinear dynamic system. In this system, inputs and outputs are multiple, and the reversion of the system is also needed for recovery (Clercq et al., 2006; Daly et al., 2013b). A mixing matrix that provides the estimation of the original signal via determining the independence of sparseness of the unknown source signals is generally used in BSS techniques (Li et al., 2006; Vigon et al., 2000). Pre-processing and post-processing of the data and a priori knowledge about the signal processing system such as statistical independence, sparseness, space-time independence, and smoothness is essential for improving the efficiency of original signal recovery via the BSS methods (Choi, 2004; Cichocki, 2013).

Most BSS methods are based on either unsupervised machine learning methods or objective functions (Shoker et al., 2005; Peterson et al., 2005). Among the Blind Source Separation methods, Independent Component Analysis (ICA) benefits from high order statistics for

decomposing mutually independent signal components (Onton et al., 2006). Another Blind Source Separation method, Non-negative Matrix Factorization (NMF), is beneficial for detecting the source and optimising the source separation matrix (Damon et al., 2013). Sparse Component Analysis (SCA) deals with infrequently distributed ingredients of the mixed signal to represent the signal source in the time-frequency domain (Li e al., 2005). Principal Component Analysis deals with reducing the dimensionality of the data via preserving signal components containing more than 80% of the main features of acquired data (Acharya et al., 2012). Although objective functions of different Blind Source Separation methods follow the same principle, they apply different decomposition and recovery strategies. They benefit from different optimization algorithms to detect source/signals and artefacts (Jung et al., 2000; Fitzgibbon et al., 2007).

Thanks to the contributions of different disciplines such as high order statistics, heuristic machine learning methods, Hebb-based machine learning methods, feedback neural network models, various Blind Source Separation methods have been developed since the 1980s (Jain et al., 1996). As a result of these contributions and advances in the Blind Source Separation methods, several Independent Component Analysis methods and algorithms have emerged, such as noise ICA, nonlinear ICA, non-stationary ICA, convolution ICA since the 1990s (Mansour and Kawamoto, 2003). After the 1990s, sparse and overcomplete representations have been developed, and BSS algorithms have become one of the most common beneficial methods within the realm of information processing (Li et al., 2006). BSS algorithms commonly used in information and signal processing can be divided into three categories in terms of source signal characteristics. These categories are statistical independency, sparse characteristics and non-negative constraints, respectively (Wang et al., 2013). BSS algorithms can also be classified in terms of characteristics of the objective function, which manipulate blind source separation strategy. In this regard, BSS approaches can be classified as second-order and higher-order statistical-based approaches, neural network-based approaches, non-linear function-based approaches (Zou et al., 2020). In this regard, applications of BSS methods to signal processing areas relevant to biological systems are achieved thanks to the development of non-linear function-based approaches. However, there is no unique approach that can solve all the problems of non-linear systems, such as some biological systems, due to their complexity (Roy, 2013). Some machine learning methods and artificial neural networks such as radial basis function networks (RBF), multilayer perceptron networks (MLP) and genetic algorithms (GA) have been applied to BSS methods thanks to their flexibility and adaptability in terms of coping with the complexity arising from non-linearity of the biological systems (Ahmadi et al., 2018). Nonetheless, all their applications have their pros and cons and trade-offs in different parameters.

BSS methods can also be classified following their strategy of dealing with mixing type of the blind source within original signals. In this regard, three types of approaches define the mixing type and by the mixing type of blind source into the original signal. These are linear mixing models, linear convolution model and non-linear mixing model (Fitzgibbon et al., 2007; Li et al., 2010). The basic assumption in the linear mixing model is that a linear combination of statistically independent sources generating different signals creates each component mixture (Li et al., 2010; Bridwell et al., 2018). In the linear convolution model, BSS methods benefit from convolution operation to detect source signals (Li et al., 2010; Orosco et al., 2013). In real-life conditions, generally observed signals cannot mix in a linear way. Moreover, mostly, separating and recovering signals' combinations generated by statistically independent sources is very hard. In these situations, either extra prior information relevant to the system or some suitable limitations is needed for separating and recovering these signals' combinations (Choi, 2004; Salido-Ruiz et al., 2011). The non-linear model can be considered as the extension of the linear model and needs mapping the groups. In this regard, primarily ICA methods within BSS can be used for separating other observed signals and statistically independent noise from source signals (Mammone et al., 2012; Joyce et al., 2004). Additionally, non-linear Principal Component Analysis, Non-Linear ICA Neural Networks, Separation Algorithms for Non-Linear Mixing Systems can also be used to separate the non-linear model mixing type of the blind source within original signals (Al-Shaban et al., 2010).

Non-linear Principal Component Analysis benefits from higher-order statistics, conventional Principal Component Analysis and stochastic gradient algorithm to cope with non-linearity of the systems (Al-Shaban et al., 2010). Furthermore, the Kernel PCA method or combining PCA with support vector machine (SVM) can be advantageous to cope with the non-linearity (Subasi and Gursoy, 2010). In addition to combined PCA methods, some of the algorithms can also be used for coping with non-linearity (Liu et al., 2013; Ye et al., 2018). Some of them can be classified as; algorithms for separating Post Nonlinear Mixtures, Nonlinear ICA Neural Networks and General Separation Methods (Jutten and Karhunen, 2004). These methods have different strategies to cope with non-linearity. Some of them try to eliminate the influence of non-linearity without violating the statistical independence between each component (algorithms for separation of Post Nonlinear Mixtures) (Jutten and Karhunen, 2004). Some of the other methods try to estimate non-linearity by benefitting from different methods. Some of these methods can be listed as; different linear-mixing systems, high order statistics, machine learning and soft computing techniques, inversing the elements of the system (i.e., input and output) (Cichocki, 2004). Some functions which decrease the ambiguities arising from non-linearity can also be used. These functions benefit from several strategies such as convergence rate, unsupervised

learning, and modularized network structure features (Xianlun et al., 2019). A group of nonlinear polynomials (e.g., General Separation Methods, Nonlinear ICA Neural Networks) forms a self-adjusting nonlinear activation function in implicit strata to converge the non-linear mixing system to the linear mixing model used (Schetinin, 2005; Bhattacharya, 2000).

In addition to ICA neural networks and separation algorithms, some of the other BSS methods, such as Sparse Component Analysis (SCA) and Non-negative Matrix Factorization, can also be used efficiently for separating and recovering non-linear mixed signals (Cichocki and Zdunek, 2007; Cichocki et al., 2007). SCA analysis can be used if the majority of the signal of interest consists sparse. SCA generally benefits from the sparse base subset for modelling the big data of interest. In EEG experiments, SCA is mainly used for signal processing, feature extraction, wavelet de-noising, and spectrum estimation (Megat Ali et al., 2014; Minguillon et al., 2017). Instead of sparsity used in SCA and instead of statistical independence, which is used in ICA, one of another BSS methods Nonnegative matrix factorization (NMF) method deals with generating sparse factorized results. Nonnegative matrix factorization (NMF) is generally applied for signal processing if the signals are normalized or have significant physical characteristics (Lee and Choi, 2009). In the experiments of this thesis, among different Blind Source Separation Techniques, ICA is used to deal with artefact rejection.

The efficiency of Independent Component Analysis can be examined via information theory approaches, central limit theorem, high order statistics, system theory and neural network coding (Zhukov et al., 2000). The efficiency of ICA is mainly dependent on three elements; probability density function, objective function and optimization algorithm (Subasi and Gursoy, 2010). The probability density function plays a crucial role in providing statistical independence among the components. The objective function maintains the strategies for creating statistical independence. And, the optimization algorithm optimizes the strategies of the objective function and probability density function (Subasi, 2007; Mars, 1982). ICA uses joint probability density function (PDF) factorization to ensure statistical independence between ICA components (Sun et al., 2005). Some information theory approaches also use different strategies to assess the statistically independent components. For instance, negentropy as negative entropy is used for measuring the distance to normality in a system to evaluate statistical independence between components (Zhou, 2002). Mutual information minimization and examining maximum likelihood for estimating real probability density function can also be used to examine the components' statistical independence (Wang et al., 2009; Guo-qing, 2010). Furthermore, some of the other methods used to estimate statistical independence can be listed as; divergence of relative entropy as Kullback–Leibler (KL) divergence dealing with comparison of probability distributions

and maximization of information (Gupta et al.,2009). Compared with higher-order statistics, information theory approaches are more beneficial in estimating mutual information for examining statistical independence (Baravalle et al., 2019).

There are two strategies for examining the efficiency of ICA where higher-order statistics is used for statistical independence estimation. The first strategy is the application of series expansion to the probability density function for transforming the estimation of the probability density function to the estimation of higher-order statistics. The second strategy uses higher-order statistics to cope with the non-linearity of output (Delorme et al., 2007; Lio and Boulinguez, 2013). In high order statistics, measuring non-Gaussianity via kurtosis as a fourth-order cumulant is very beneficial in evaluating the statistical independence of components of ICA (Islam and Tcheslavski, 2015). The central limit theorem is another method used to examine the efficiency of the ICA in creating statistically independent components. The central limit theorem examines linear combinations between variables as the indicator of Gaussianity. These linear combinations are used for checking the closeness of the magnitude of same order variances and means of a group of a random variable to the Gaussian distribution to examine the efficiency of ICA in terms of statistically independence of the components (Flexer et al., 2005; Gonen and Tcheslavski, 2012). The central limit theorem can estimate statistical independence by examining where the non-Gaussian nature of the separation results reaches their maximum as the indicator of the best performance of ICA (Hoeve et al., 2003).

There are also some different methods for examining the efficiency of the objective function and optimization algorithm. Some of these methods can be listed as estimation of non-Gaussianity, removing of non-linear correlation in the observation vectors, decomposition of higher-order cumulants in the form of Eigen matrices (Matic et al., 2009). Choosing a convenient learning algorithm for the objective function of ICA can also improve the efficiency of the optimization algorithm of ICA (Hyvärinen et al., 2010).

The most common heuristic learning algorithms used for optimisation algorithms can be listed as stochastic gradient method and natural gradient method (Montoya-Martínez et al., 2017). Stochastic gradient method determines an initial value of separation matrix and calculates gradient and generates new separation matrix and benefits from maximum likelihood method to find the minimum or maximum value of the objective function. The natural gradient method uses Riemann spaces without whitening to cope with the deterioration of stability and computational complexity of the stochastic gradient method (Martinez-Peon et al., 2015).

If possible, applying a linear transformation for transforming any multidimensional signal to a white signal can reduce the complexity in the applications of ICA to the BSS problems (Chen et al., 2007; Ball et al., 2016). This process is called as whitening or sphering of the mixing vector to provide uncorrelated components. The transformation matrix is called the whitening matrix. The white signal can be defined as a signal that each component has unit variance and is uncorrelated. Thanks to the advancements in ICA, some ICA algorithms already include the whitening matrix in the separation algorithm in the pre-processing process without the requirement of additional whitening (Vigário et al., 2000; Keith et al., 2006).

There are several developed algorithmic methods to cope with ambiguities and complexities of non-linear mixed systems. Some of them can be listed as; Fast ICA, runICA, Maximum Likelihood ICA, Overcomplete ICA, Kernel ICA, Natural Gradient Flexible ICA, Non-negative ICA, Constraint ICA, Optimized ICA, and Supervised Learning ICA (Yu and Hu, 2014). Their details will not be examined within the scope of this thesis.

Thanks to the advancements of brain imaging/scanning devices which allow acquiring data in vivo, rejecting artefacts via ICA has become very crucial. In vivo data acquisition process is subjected to contamination of either bio-potentials generated by ongoing physiological activities or non-physiological sources (Wang et al., 2018). In this regard, the application of ICA to the realm of EEG signal processing is an indicator of such assumptions about the acquired signal/data as (1) the existence of statistically independent source signals and their components, (2) the existence of a mixture of the components linearly or non-linearly via sensors, (3) probability of obtaining statistically independent outputs (Lima et al., 2003; Ahamad et al., 2013). In EEG signal processing, statistical independence is associated with the minimization of mutual information between the elements of the signal processing system (Baillet et al., 1999). Minimisation of the mutual information can also be associated with statistical relations between the amplitude distributions of acquired signals and the physiology of neural structures (Kaplan et al., 2005). ICA is also a good tool for coping with electric influences of outer layers of the brain such as meninges and also skull on the brain's electrical potentials, which are smeared, mixed, and decreased by these layers (Hamidi et al., 2010). In the EEG data acquisition process, electric potentials of the brain travel at the speed of light from the brain to channels and delays between source and electrode can be negligible (Puce and Hämäläinen, 2017).

The non-stationary nature of EEG signals can be decomposed and recovered very well by considering the source signals as stochastic processes (Rankine et al., 2007). And, stationary mixing matrix of the source signals is crucial for ensuring a representative distribution of the independent components (von Bunau et al., 2010). In ICA applications to EEG signal processing,

data is considered random variables. Estimating distributions of these random variables can be achieved by examining the whole data set (Ibrahim et al., 2019). Compared with other artefact rejection methods that cause some data loss, the application of ICA to EEG signal processing provides very efficient and accurate artefact rejection. Especially ICA applications to EEG signals for artefact rejection are very efficient if the artefact(s) is/are periodic artefact signals (Iriarte et al., 2003). These artefacts can easily be detected and rejected through ICA without any knowledge about the system, which generates artefacts (i.e., blind aspects of the system) (Bono et al., 2016). In ICA artefact rejection applications to EEG signals, applying ICA to individual-level data processing instead of group level is essential to prevent confusion and identifications of artefacts. At group level identifications, some difficulties may emerge due to the possible hampering of idiosyncratic features of artefacts. Comparing time courses of ICA components can be used to check the identification of ICA components to improve the quality of cleaned data from contaminations and improve the quality of decomposition and recovery of the source signals (Akhtar et al., 2012; James and Gibson, 2003).

Objective function as mixing matrix of ICA decomposes source signals of acquired EEG data following information theory approaches, and optimization algorithm of ICA recovers the source signal. Statistical independence of artefact signals from source signals facilitates the identification and removal of artefacts by ICA very well (Hyvärinen et al., 2010). In addition to artefact rejection and EEG signal processing, ICA can also be used decomposition and recovery of ERP components in time-domain analysis. Also, ICA can be used to examine the decomposition of de-synchronizations and synchronizations of activity of different brain rhythms in time-frequency analysis (Onton et al., 2006; Cha et al., 2018).

3.5. DATA ANALYSIS: EVENT-RELATED POTENTIAL AND EVENT-RELATED (DE-) SYNCHRONIZATION ANALYSIS

In this thesis, two types of EEG data analysis were performed. One of them is time-domain or time lock analysis for examining event-related potentials (ERP), and the other one is time-frequency analysis for examining event-related (de-)synchronizations (ERS/ERD) (see, Glossary). Event-related potentials (ERP) can be defined as time-locked small voltage changes as a result of event or stimulation which provides sensory, motor or other cognitive activities in the brain and the aim of Time Domain or Time Lock Analysis of time-locked ERPs is to examine latency of these processes (Sur and Sinha, 2009; Landa et al., 2014). Differently, Event-Related (De-) Synchronizations are associated with frequency specific changes of the ongoing EEG activity which cause increase or decrease of power in given frequency bands (see, Pfurtscheller and Da Silva, 1999). ERPs are generally considered summation of postsynaptic potentials generated by

synchronous firing thousands or millions of similarly oriented cortical pyramidal neurons synchronically during the information process (Remijn et al., 2014; De Lucia et al., 2007). Unlike Time Lock or Time Domain Analysis for ERPs, Time-Frequency Analysis for ERD/ERS is a bit complicated (i.e., includes more steps). Time-Frequency Analysis for ERD/ERS is based on quantifying changes in the power of the brain rhythms at one time incredibly shortly after the event or stimulation relative to a control condition as baseline (Zhang, 2019; Qin and He, 2005). Time-Frequency Analysis for ERD/ERS is used to examine ERD of mu oscillation as one indicator of motor imagery and embodied perception, which Gert Pfurtscheller and his colleagues popularized. The Time-Frequency Analysis for ERD/ERS aims to compute and visualize the spectral or amplitude content of the signal as a function of time simultaneously for all frequencies of interest. Thus, Time-Frequency Analysis needs more steps to be examined (Pfurtscheller and Neuper, 1997; Pfurtscheller et al., 2006; Zhang, 2019). In order to understand Time Lock or Time Domain Analysis for ERPs and Time-Frequency Analysis for ERD/ERS, it is crucial to understand ERPs and neural oscillations.

3.5.1. Waveform Components of Event-Related Potentials

ERPs are time-locked bio-potentials that emerge after responses to sensory, cognitive and motor events within defined time, such as 100 ms, 200 ms or 300 ms (Singh and Singh, 2021). ERPs are named or labelled according to their latency after the event or stimulation and direction of the potential (i.e., positive or negative). In this regard, for instance, in P100 ERP, 100 refers to latency as 100 ms after stimulation or event, and P refers to the positive direction. Some common ERPs detected via EEG are P100 which means ERP emerging at 100ms after the event in a positive direction, and others can be listed as P50, N100, P200, N200, P300, N400, and P600 (Zhang et al., 2016; Olichney et al., 2011). According to their latency, ERP components can be classified as endogenous ERPs and exogenous ERPs (Barry, 2009). Exogenous ERP components generally emerge within the first 100 ms after stimulation or event. They are generally associated with sensation or perception (Santangelo et al., 2007). There are also wide ranges of ERP components between 100 ms and 300 ms that are exogenous but they are modulated by endogenous ERP components. These components sometimes called as mesogenous ERP components but it is not very common. In contrast, endogenous ERP components generally appear later, such as 300ms as or later than 300 ms, and are associated with cognitive processes (Chica et al., 2010). According to their phase characteristics, ERPs can also be classified as evoked potentials as phase-locked and time-locked potentials and induced potentials as non-phase-locked ERP potentials (Zhang et al., 2019; Ming et al., 2010). The amplitude of evoked potentials can be calculated by averaging the total amplitudes of each bio-potential of ERP. However, averaging the total power of the bio-

potential method cannot be used for induced potentials because of their non-phase locked characteristics (Paria et al., 2020). ERPs' time-domain or time lock analysis is essential for understanding the basic mechanisms beyond multi-sensory processes or coordination between attention, memory, and prediction as to the background of intended behaviour (Dulas and Duarte, 2013; Beste et al., 2011).

One of the early ERP components is the P50 wave which appears within 40 to 75 ms after stimulus onset. This stimulus is generally an auditory click, and the P50 ERP wave is associated with sensory gating. It protects the brain from information overflow (Anokhin et al., 2007; Knott et al., 2009; Oranje et al., 2006). Another ERP, P100 or P1 wave generally appears in the 65–90 ms range after event or stimulus, and it is associated with visual perception and attention of visual stimulus, especially motion and body parts (Colombatto and McCarthy, 2017; Richards, 2003). C1 or C100 is a similar wave component to P100, and it is associated with the visual perception of visual stimulus orientation within space, contours and colours of visual stimuli, and spatial frequencies (Rossi and Pourtois, 2012; Pitts et al., 2010). 100 or C1 is also considered responsible for binocular vision (Zhang et al., 2015). N100 or N1 is typically observed after auditory stimuli as opposed to P100 after visual stimuli and generally appears within 80 to 120 ms after the onset of the stimulus. In addition to auditory stimuli, it is also commonly associated with olfaction, habituation to heat, pain, somatosensory responses, sense of balance, respiration blocking (Delb et al., 2008). N1 or N100 appears on frontal and central areas of the brain and reaches maximum amplitude on Cz as vertex point (Tomé et al., 2014; Dong et al., 2019).

After N1 or N100, generally, P200 appears, and because of that, they are sometimes called N100-P200 or N1-P2 complex (Ballesteros et al., 2009). If the N100 wave appears due to visual stimulation, it is generally called visual N100 or N1. Visual N1 is generally associated with selective attention (Takeda and Kimura, 2014). Another negative ERP component is N170, and it is associated with pattern recognition of the face and parts of the face. N170 emerges due to the activation of fusiform and inferior-temporal gyri (Cauquil et al., 2000). Another positive ERP component is P200 associated with higher-order perceptual processes, memory, semantic processes, sensation-seeking behaviour, and repetition effects (Bourisly and Shuaib, 2018). P200 generally emerges from the internal representation of visual attention for language processing or memory (Niznikiewicz et al., 1997). Like P200, N200 is also associated with hidden internal representations related to language processing or high cognitive functions (Friederici, 2011). P200 generally emerges as a result of activation of frontal areas of the brain (Ford et al., 2016). N200 have four sub-categories as N2a, N2b, N2c, N2pc (Wang et al., 2004). N2a is associated with a mismatch in auditory response (Näätänen et al., 2011), N2b is associated with changes of physical

properties of task relevant-stimulus or event (Potts and Tucker, 2001). These sub-categories of N200 generally emerge on frontal areas (Hauk et al., 2008). Another sub-category of N200, N2c, is associated with the degree of visual attention required for perceiving the context and features of a visual stimulus or event (Shea, 2020). Unlike the first two sub-categories of N200, N2c emerges in posterior areas (Rathelot et al., 2017). The fourth sub-category of N200 as N2pc has similar functions with N2c. The main difference between N2c and N2pc is that N2pc is not sensitive to the probability of the target in contrast to N2c (Loughnane et al., 2016; Folstein and Van Petten, 2008).

Another positive component is P300 which is associated with some cognitive functions such as semantic processing, decision making, and classification of stimulus or event, especially oddballs within experimental setup (deviant stimulus) (Folstein and Van Petten, 2008; Patel and Azzam, 2005). P300 generally emerges as a result of activation on parietal or frontal areas (Linden, 2005). P300 have two sub-components as P3a and P3b (Polich et al., 1985). P3a is associated with adapting attention according to the changes in environment and novelty, and P3b is used to measure cognitive demand beyond tasks within an experimental setup (Polich, 2007; Hölig and Berti, 2010). P3a emerges due to activation of frontal areas (Restuccia et al., 2005), and P3b emerges on parietal areas (Verleger et al., 1994). Another negative ERP component is N400, and it is associated with semantic processes, reading, responding to words in both visual and auditory, signs of sign language, environmental sounds and smells (Balconi and Pozzoli, 2005; Calma-Roddin and Drury, 2020). N400 emerges on centro-parietal areas (Friedrich and Friederici, 2006). One of the late emerging ERP components is P600 associated with language processing; especially syntactic incongruity or errors, complex syntactic structure (Kotz et al., 2003). P600 generally emerges due to activation of frontal, parietal or temporal areas of the brain (Chen and Li, 2013).

3.5.2. Brain Rhythms (Waves) and (De-)Synchronizations of Brain Oscillations

Although the discovery of neural oscillations or brain waves can be dated back to the last decades of the 19th century, synchronizations and de-synchronizations of the neuronal oscillations could be examined via in vivo experiments in the last decades of the 20th century (Brazier, 1957; Young, 1990; Breidbach, 2001; Chatterjee and Coslett, 2013). Although ERP analysis was generally mainstream analysis method in cognitive neuroscience from the 1930s to 1960s, thanks to the developments in computer technology and advancements in neuro-imaging/scanning techniques, rising interest among the cognitive neuroscientists on ERD/ERS analysis has also increased after the 1980s (Wang et al., 2009). Unlike ERPs, oscillations are continuous ongoing activities in the brain, and following stimulus or event, their pattern changes (Classen et al., 1998). Event-related oscillations are either phase-locked or non-phase locked and ongoing spontaneous oscillations

are generally non-phase locked because there is no reference time-point. Thus, they need to be analyzed with different methods according to their phase characteristics (Kalcher and Pfurtscheller, 1995; Tallon-Baudry et al., 1996). In addition to phase characteristics, neural oscillation can also be classified according to the level or size of firing neuron populations (Bhowmik and Shanahan, 2013). If the oscillation source is the activation of a single neuron, it can be classified as micro-level oscillation or microscopic (Che et al., 2020). If the oscillation source is the activation of a group neuron, it can be classified as medium-level oscillation or mesoscopic (Prida and Trevelyan, 2011). Moreover, if the oscillation source is the activation of a brain region, it can be classified as large-level oscillation or macroscopic (Seeber et al., 2016).

Associating macroscopic or mesoscopic level neural oscillations with one type of cognitive activity are not generally correct, and it may be an oversimplification (Kunz et al., 2019). Moreover, individual cortical areas can fulfil different functions via different functional networks (Fallani et al., 2010). In this regard, it is important to understand how different forms of information from different sources are integrated via brain networks to get the meaningful representation of experience and coherent scene of the world. Neural oscillations emerge from either synchronical firing of same or different groups of neurons in mesoscopic or macroscopic level (Ward, 2003). Neural oscillations are considered crucial in obtaining cognitive processes to understand and adapt to the world via synchronizations or de-synchronizations of the same or different neural populations in thalamo-cortical or cortio-cortico networks (Uhlhaas and Singer, 2006). Coupling and uncoupling functional networks in the brain allow computational parsimony and minimise computational energy by using the same synchronizing or de-synchronising neurons for different ongoing cognitive functions (Stefanescu and Jirsa, 2008; Scheeringa et al., 2012). Synchronizations and de-synchronizations of same or different populations decrease the demand for extra neurons and neuronal networks, and they play crucial roles in the plasticity of integrating different (form of) information from different sources such as auditory or visual (e.g., multi-modal sensory integration, cross-modal neural interaction) (Vakorin et al., 2016). Synchronizations of neural oscillations increase the amplitude of acquired EEG data, whereas de-synchronizations of neural oscillations decrease the amplitude (Mathalon and Sohal, 2015).

There is some specific brain rhythms associated with specific cognitive functions due to several experimental studies. Roughly speaking, it can be assumed that the higher frequencies of the brain rhythms are, the more complicated cognitive functions are fulfilled by the neurons (Thut and Miniussi, 2009). In this regard, brain waves at higher frequencies such as gamma waves are associated with such complicated cognitive functions as language processing, long term memory or concentration (Vialatte et al., 2009). Furthermore, brain waves at medium level frequencies

such as alpha, beta, tau and mu waves are associated with sensation, attention, motor coordination and perception (Vialatte et al., 2009; Alonso-Valerdi et al., 2018; Kučikienė and Praninskienė, 2018). Brain waves at low-level frequencies such as delta and theta waves are associated with falling asleep, sleeping, unconscious cognitive activities (Jemmer, 2009). Although there is a growing interest in neural oscillations and advancements in analysing methods, it is challenging to understand associations between evoked potentials (i.e., expressed as single amplitudes) and neural oscillations at different frequencies (Zoefel et al., 2018). Additionally, underlying mechanisms beyond synchronisations versus de-synchronizations are still not known comprehensively.

One of the other interesting aspects of neural oscillations is that these oscillations are widely seen across the species of mammalians, from mice to elephants (Condorelli et al., 2000). In addition to neural oscillations, intrinsic biophysical properties of neurons and microcircuits that generate the rhythms are also common features across these species (Isa and Sparks, 2006). Furthermore, myosin and actin filaments defining muscle contraction speed have mainly remained similar across mammals (Sellers and Kachar, 1990). These common structural features also play crucial roles on the formation of neural oscillations across mammalians, and they are associated with adjustment for some fundamental aspects of timing in the brains (Akam and Kullmann, 2014). De-synchronizations and synchronizations of brain rhythms can be quantified via calculating amplitudes, density and fluctuations in electrophysiological activity of interest (Bilucaglia et al., 2019). The amplitude of electrophysiological activity of interest can be calculated via peaks of power spectra (Quinn et al., 2019), and density can be calculated via the width of spectral peak (Seeber et al., 2019). Fluctuations can also be examined via the width of the peak itself arising from different physiological mechanisms such as numbness (Kiang and Moxon, 1972). In Time-Frequency analysis of ERD/ERS, just computing the relevant features (e.g., amplitude, density) of neural oscillation frequencies is insufficient because some brain waves such as alpha and mu have similar frequency ranges but emerge in different areas of the brain. Thus, it is essential to consider different variables (e.g., spatial resolution, formal features of the waves, associated cognitive functions) to examine neural oscillations.

In addition to general explanations about the characteristics of neural oscillations, understanding different brain waves and their functions discovered via neuroscientific experiments also becomes important. Compared with other brain rhythms, alpha, mu, and beta rhythms are widely analyzed due to the investigations on sensory and motor modalities (Coll et al., 2017). Alpha rhythm generally emerges on the brain's posterior areas, especially on parieto-occipital areas and calcarine sulcus (Salenius et al., 1995). The frequency range of alpha rhythm is around 10 Hz

(between 8-13 Hz), and its amplitude is 50-100 μV electrical potential (Hogan and Fitzpatrick, 1988). Alpha rhythm is associated with the resting state of the visual processing system, and it is maximally activated when eyes are closed in healthy subjects (Pfurtscheller et al., 1994). However, it can also be active when eyes are open if the subject is faced with a monotonous stimulus (Konishi and Hagiwara, 2015) or if the subject is in the darkness (Ben-Simon et al., 2013) or if the subject has some visual disorders (Ros et al., 2017). Alpha suppression is very persistent, and it can influence other brain areas such as central and frontal areas or areas within the occipital cortex itself (Harmon-Jones, 2006). In this context, if the frequency of interest of the experiment is within a similar frequency range with alpha oscillations (e.g., mu oscillations) where visual stimuli is used, the design of the experiment should be adjusted in such a way that alpha could not prevent the detection of the other oscillations in data analysis becomes important.

Another brain rhythm within the similar frequency range with alpha rhythm is mu rhythm (around 8 to 12/13 Hz) (Tiihonen et al., 1989). The activity of mu rhythm generally emerges in the motor cortex. Because of the size of the hand representation area of the primary motor cortex, mu rhythm can be detected on close areas to the hand representation areas of the primary motor cortex (Hari, 2006). Mu rhythm is sometimes called Rolandic mu rhythm in literature because the relevant area to mu rhythm in the motor cortex (Rolandic area) is named after Luigi Rolando, Italian anatomist (Boling et al., 2002). When subjects are in a relaxed position without movement, the activity of mu rhythm reaches its maximum level (Madsen et al., 2019), and mu rhythm is suppressed during motor imagery, observation or execution (Tangwiriyasakul et al., 2013). Mu rhythm is an arc-shaped wave, and this formal characteristic of mu rhythm is associated with heterogeneity in terms of frequencies of its subcomponents and varies between ~10 Hz to ~20 Hz (Pernet et al., 2018). ~20 Hz components of mu oscillations come from anterior areas (pre-motor cortex). During its suppression period, rebounds of these components move along the motor cortex following the 'mototopic' representation area of the stimulated body part (especially from central to lateral areas) (Pfurtscheller et al., 1996). On the contrary, ~20 Hz components, ~10 Hz components of mu oscillation are stable on hand areas independently from stimulation of any body part (Salmelin and Hari, 1994). Thus, 20 Hz components of mu rhythm are generally associated with motor action (Hari, 2006; McGarry, 2012), but 10 Hz of mu suppression components are predominantly associated with somatosensory (Cheng et al., 2008). In the experiments of this thesis, Time-Frequency Analysis was performed for event-related de-synchronizations of mu oscillation and 8-13 Hz was chosen as the frequency of experiments of the thesis.

In addition to alpha and mu rhythms, one of the earliest discovered brain rhythms with alpha rhythm is beta rhythm (Kozelka and Pedley, 1990). Although there is no strong consensus about the frequency range of beta rhythms due to their changing pattern across different individuals, beta rhythm's frequency range is accepted from 12 to 30 Hz (up to 38 Hz or 40 Hz) (Pfurtscheller et al., 1997). Beta rhythm is associated with normal waking consciousness (Roohi-Azizi et al., 2017). According to frequency range, beta rhythm has three sub-categories. These are low beta rhythm (12-16 Hz), mid-range beta rhythm (16-20/22 Hz) and high beta rhythm (20/22-38/40 Hz) (Park and Whang, 2018). Low beta rhythm is associated with *'fast idle'*, or musing (Sangam et al., 2020), mid-range beta rhythm is associated with high engagement or actively figuring something out (HernánDíaz et al., 2019), and high beta rhythm is associated with highly complex thought, integrating new experiences, high anxiety, or excitement (Kim, 1993; HernánDíaz et al., 2019). The brain cannot process brain rhythms in high frequencies such as beta and gamma rhythms for very long because of computational parsimony, energy consumption and efficiency (Cannon et al., 2014). Sources of beta rhythm can be listed as the fissural portion of the primary motor cortex, basal ganglia, thalamus, supplementary motor cortex and cerebellum (Werf et al., 2006; Brown et al., 2009). Beta rhythm also has crucial roles on voluntary movements via frequency couplings as bridging effect between primary motor cortex (M1), the primary somatosensory cortex (S1) and supplementary motor area (SMA) (Ohara et al., 2000; Ohara et al., 2001).

Sensorimotor rhythm is another brain rhythm that emerges in the sensorimotor cortex (Pichiorri et al., 2011). Its frequency range is similar to the low Beta frequency range and mainly around 13 to 15 Hz among different individuals (Egner and Gruzelier, 2004). The activity of sensorimotor rhythms is generally maximal when the subject is closed himself/herself to external events (Cravo et al., 2011) or when there is stimulation of sensorimotor areas (for instance, during states of immobility) (Gould et al., 2012). On the contrary, the amplitude of sensorimotor rhythm activity decreases during motor execution or somatosensory interaction with the world or even sensorimotor imagery (Tsuchimoto et al., 2017). Detection of sensorimotor rhythm can sometimes be complex due to the dominant and prevalent posterior alpha activity (Cochin et al., 1998). Thus, it needs appropriate spatial filtering (McFarland et al., 2006).

Another brain rhythm that has one of the lowest frequency ranges is theta rhythm. The frequency range of theta rhythm is 4 to 7.5 or 8 Hz (Leung, 1984; Gray and Ball, 1970), and it is associated with sleepy situations, sleeping, some pathology in the brain, subconscious cognitive operations, processing of incoming speech and so on. Furthermore, the theta activity of the hippocampus is associated with the maintenance of working memory, encoding spatial layout and retrieving coded spatial information from episodic memory (Kavanau, 1997). Theta activity also plays a

crucial role in bridging different brain oscillations to fulfil different cognitive functions (e.g., cross-frequency couplings) (Kahana et al., 2001).

Among the other brain rhythms, the brain rhythm with the highest frequency band range is gamma rhythm (Jia and Kohn, 2011). Like beta rhythm, although there is no consensus about the frequency range of gamma rhythm, the frequency range of gamma rhythm is generally accepted between 30 to 100 Hz (Fries et al., 2008). However, in some extreme conditions (especially in clinical studies), the frequency range of gamma rhythm can be accepted up to 600 Hz (Belluscio et al., 2012). Gamma rhythm is also classified following frequency range like beta rhythm due to its wide frequency range (Jia and Kohn, 2011). These are low gamma (30-100 Hz), high gamma (100-200 Hz), and ultrafast gamma (200-600 Hz) (Hughes, 2008). According to the width of the distribution of frequencies within gamma oscillations, gamma rhythms can also be classified as narrowband and broadband gamma rhythms (Hermes et al., 2015). One of the most analyzed gamma frequencies is around 40 Hz (Pastor et al., 2002) as one of the most omnipresent frequency ranges of gamma rhythm within broadband of gamma rhythm (van Wijk et al.,2012). Gamma activities of which frequency range are especially up to 100 Hz (i.e., low and fast gamma bands) is associated with attention-dependent signal detection, feature binding, multisensory integration, sensorimotor coordination, manipulation of contents of working memory, and the formation of long-term memories (Tallon-Baudry and Bertrand, 1999; Herrmann et al., 2004). Furthermore, gamma (de-) synchronizations can play a role in activation or inhibition on perception, cognition or memory (Herrmann et al., 2004; Gruber et al., 2002) and also play a crucial role in frequency (un-) couplings similar to theta and beta rhythms (Scheffer-Teixeira and Tort, 2016). In cross-frequency couplings, brain rhythms that have higher frequencies (e.g., beta rhythms and gamma rhythms) are generally modulated by brain rhythms that have slower frequencies (e.g., theta rhythms) (Canolty and Knight, 2010; Fiebelkorn et al., 2013). Some of the most common cross-frequency coupling examples are theta rhythm and gamma rhythm couplings, alpha rhythm and gamma rhythm couplings associated with information processing and adjustment of timing between sensory modalities (Ceni et al., 2020; Herman et al., 2013).

Among all other brain rhythms, the brain rhythm with the lowest frequency band range is delta rhythm (except infra-low brain rhythms and K-complex rhythm that emerges during stage 2 of NREM sleeping) (Carracedo et al., 2013). Delta rhythm generally has a 0.5 to 3 or 3.5 Hz frequency band range, and it only occurs during deep sleep in healthy subjects. In normal conditions except sleep, the existence of delta rhythm in EEG recordings of healthy subjects is associated with a sign of brain pathologies such as stroke, brain trauma, or severe brain infection, such as encephalitis (Zappasodi et al., 2007). In these conditions, the acquired delta rhythm is asymmetric in

lateralization in different hemispheres (Hussain and Park, 2021). Delta waves can block the perception of the external world and play an important role in some cognitive activities such as contemplation, reflexive thinking and empathy (Ismail et al., 2016). They play a crucial role in regenerating and healing both body and brain via deep restorative sleep. As sleep deepens, delta activity and other brain rhythms within a similar frequency band range become dominant (Chauhan, 2016; Shapiro, 1982).

One of the brain rhythms with a slower frequency band range than delta rhythm is infra-low (ultra-slow) brain rhythms or slow cortical potentials. Their frequency range is less than 0.5 Hz, and they only emerge during sleep, similar to delta oscillation (Grin-Yatsenko et al., 2020). Infra-low (ultra-slow) brain rhythms can be detected in awake subjects to fulfil a somatosensory detection task. The task should let the participant interpret fluctuations emerging from their performance of sensorimotor detections (i.e., task fulfilment) as the indicators of changes in the excitability of cortical networks (Othmer and Othmer, 2017). Limited information about infra-low (ultra-slow) brain rhythms is known due to their low frequencies and their detection and accurate measurement difficulties. In this context, they are considered to play an essential role in more complicated brain functions, and they adjust some of the timing mechanisms of cognitive network functions (Smith et al., 2014; Grin-Yatsenko and Kropotov, 2020). In addition to these brain rhythms, there are some sleeping brain rhythms such as K-complex (Colrain, 2005) or sleep spindles (Dang-Vu et al., 2010). However, they will not be mentioned within the context of this thesis because they have never been recorded. In the experiments of the thesis, only alpha and mu rhythm among the other brain rhythms have been examined because these rhythms are associated with visual processes (i.e., posterior alpha rhythm) and embodied/motor processes (i.e., central mu rhythm).

In addition to brain rhythms of cortical areas, some neural oscillations emerge due to interaction between different cortical areas and the thalamus. The oscillations play a crucial role in integrating sensory information for producing meaningful experience and perception of the world via temporal binding as the synchronization of different cortical and thalamic areas of the brain (Singer, 1993). These oscillations are called thalamocortical oscillations, and they can synchronize at different frequency levels by the content of carried out the cognitive activity (Steriade et al., 1993). These synchronizations are also vital for sensory gating mechanisms and maintaining/regulating feedbacks from cortical pyramidal cells (Koch et al., 1990). Moreover, they have a position in the organization of information flow via gating/blocking and directing/regulating information flow in different cognitive activities such as during conscious state, REM-sleep and NREM-sleep. These oscillations produced by three types of neurons located

in the thalamus and cortex form the thalamocortical network (Furness, 2000). The neurons can be listed as thalamocortical, reticular thalamic, and corticothalamic neurons (Steriade and Timofeev, 2001).

3.6. STATISTICAL ANALYSIS

After completing all data analysis at the individual level, it is also important to examine data in the group level for either ERP analysis results or ERD analysis results. In order to achieve group-level analysis, statistical analysis is performed either via SPSS or R Programming Language and R Studio. In the experiments conducted within the scope of this PhD, we have conducted repeated measure-based ANOVA tests and calculated estimated marginal means for statistically significant factors or interactions.

4.1.1. INTRODUCTION: GENERAL CONCEPTUAL FRAMEWORK OF THE EXPERIMENTS

Rise of New Inter-Disciplinary Area: Architectural Neuroscience in the 21st Century

Although there has been an interest among the architect in the influential role of architecture on human experience and its potentials for creating new architectural products, these issues could have only been addressed to the realm of science (*'in modern meaning'*) in the second half of 20th century. Thanks to the contributions of some of the philosophical schools (especially phenomenology) (Seamon, 2000; Mallgrave, 2010; 2013a; 2015b; Mallgrave and Goodman, 2011; Otero-Pailos, 2013; Seamon, 2021) and some forms of (experimental) psychology (e.g., environmental psychology, ecological psychology) (see, Pol, 2006; 2007; Zeisel, 2006; Cassidy, 2013; Steg et al., 2018), and the rise of new disciplines such as design science (see, Cross, 1993; 2001a; 2001b; Chakrabarti and Blessing, 2016; Hodges et al., 2017) a vast literature is investigating both architectural user and design experience has emerged. However, mainly conventional psychology or scientific research methods (e.g., observations, surveys, questionnaires, and performance/task-based measurements) have been used in these studies. By the influence of technological advancements, especially on computer science (e.g., new software for analysing neuro-functional data) and on brain imaging/scanning and neuro-stimulation techniques (e.g., fMRI, PET, CT, fNIRS, TMS, tA/DCS, tRNS) in the last quarter of the 20th century (see, Savoy, 2001; Minati, 2006; Peterson and Deer, 2013; Deer and Mali, 2016; Bigler, 2017; Ponce et al., 2021), cognitive science gain neural content which may be called as neural revolution (see, Dupuy, 2009; Mandler, 2011; Thagard, 2013). However, early attempts to investigate architectural user/ design experience using cognitive (neuro-) science tools can only begin in the first decade of the 21st century (see, Salingaros and Masden, 2008; Eberhard, 2009a; 2009b; Karakas and Yildiz, 2020).

Research Clusters in Architectural Neuroscience and Problematics of Inter-Disciplinary Methodology

Researches in the realm of architecture within the context of '*neural revolution*' can roughly be classified into five categories as; 1) theoretical discussions on potentials (e.g., possibilities and horizons of new emerging interdisciplinary areas, possible educational strategies for architects, potentials of different scientific organisations/activities such as ANFA (**A**cademy **N**euroscience **F**or **A**rchitects)) (see, Zeisel, 2006; Eberhard, 2009b; Mallgrave, 2013b); 2) studies on neural influences of architectural properties on the immediate cognitive processes/experience (see, Arbib, 2013; Albright, 2015; Mallgrave, 2015a; Robinson, 2015), 3) studies on neural influences of

architectural properties for long term effects (e.g., efficiency, well-being, coping with mental and neurological disorders, sustainability) (see, Eberhard and Patoine,2004; Sternberg, 2009; Rassia and Pardalos, 2011; Sussman and Hollander, 2014), 4) studies instrumentalising architectural stimuli to reveal different neuro-cognitive mechanisms (see, Conway and Rahding, 2013; Mickay, 2014; Zeki, 2014), 5) studies investigating neural mechanisms underlying architectural design cognition and creativity (see, Zeisel, 2006; Arbib, 2013; Farling, 2015). In this regard, the experiments of this thesis can be classified within the second group of studies. As a result of these two disciplines' inter-disciplinary characteristics and the different research characteristics (especially methodological approaches), some problematics emerge in designing experiments. Architectural experience research mainly uses qualitative methodologies of humanities and social sciences and focuses on the chaotic and dynamic (architectural) environment on a big scale, even in some cases in urban scale, in a more descriptive way (see, Kuniavsky, 2003; Franz, 2005; Lucas and Lucas, 2006; Groat and Wang, 2013; Mallgrave, 2018). Conversely, cognitive neuroscience and neuro-psychology researches mainly use statistical experiment design and quantitative methods of experimental psychology and focus on complex and dynamic neural mechanisms with scientific rigorosity (see, Maroof, 2012; Bauer and Dunn, 2013; Jeeves and Baumgartner, 2013; Peranti and Cabba, 2020). Thus, decisions relevant to experiment design and methodology become very significant for inter-disciplinary experimenting, which possibly will integrate two dynamic phenomena (i.e., architectural environment and brain).

Epistemic Space of Possible Ways of Experimenting Within Architectural Neuroscience

In these interdisciplinary experimental researches, architects mainly concentrate on neural influences of chaotic and dynamic environmental changes without concerning experiment design strategies of cognitive neuroscience and neuropsychology domain (e.g., thinking about control conditions, defining variables and creating statistically comparable conditions). These researches ignore the chaotic and dynamic nature of the brain for the sake of enthusiasm for new research horizons. Neuropsychologists and cognitive neuroscientists regard manipulating neural mechanisms via experiment design strategies (e.g., giving tasks, optimising the experiment conditions such as light, duration, and coping with the noise and artefacts) for the sake of scientific rigorosity. Nevertheless, these researches could not deal with the changes of the chaotic and dynamic environment directly and could only deal with statistically comparable produced realities for experimenting within isolated laboratory conditions. Thanks to the advancements of virtual reality technologies, some of the realistic architectural environments can be simulated/ modelled and used in cognitive neuroscience experiments (see, Vecchiato et al., 2015; Chiamulera et al., 2017; Hu and Roberts, 2020; Pektaş, 2021). Additionally, researchers with

architectural backgrounds also use portable EEG devices to measure the brain's electrophysiological activity within real-life experiences without so much concerning statistically comparable conditions (see, Hollander and Foster, 2016; Karandinou and Turner, 2017a; 2017b; Vijayan and Embi, 2019; Bacevice and Ducao, 2021). In this regard, there can be currently mentioned four ways of experimenting in terms of how these researches relate with environmental/architectural reality of interest (i.e., direct architectural experience or simulation of experience via images, movies and so on) and whether they manipulate the neurophysiological activity of interest with statistically comparable conditions (i.e., with concern for statistical comparison, with no concern for statistical comparison).

The Justification of/Positioning the Experiments within the Epistemic Space of Ways of Experimenting

Direct architectural experience can increase difficulties in terms of statistical comparison for understanding how environmental changes influence the brain differently because, roughly speaking, the architectural experience cannot be experienced statistically comparable conditions in real life. Contrarily, too much statistical comparison concern may lead the research to deal with artificially produced statistically comparable conditions isolated from real life. In this regard, experiments of this thesis were designed in such a way where participants faced some of the images of architectural elements (i.e. doors) in little scale (fit to computer screen) (indirect architectural experience), which were chosen from real-life conditions (instead of artificially modelled doors). Although all images were chosen from real-life examples, they were grouped with the strategy of statistical comparison (i.e., satisfy experiment design conditions of cognitive neuroscience and neuropsychology without too much concern, which may lead to isolation from real conditions). Due to technical limitations, these images were used in little scale to fit the computer screen. Reducing the size due to the limits may bring trade-offs between effects expected from real-life conditions and conducting the experiment with the equipment of EEG lab, School of Psychology (see for effects of size, Warren, 1984; Ono et al., 2013; Brandl et al., 2015; Sollfrank et al., 2015; Alimardani et al., 2018; Kourtis et al., 2018; Ono et al., 2018; Choi et al., 2020; Carrere et al., 2021).

Some Philosophical Problematics Relevant to Experimenting in Architectural Neuroscience

In addition to problematics relevant to methodological strategies of integrating two disciplines in general and specific to this thesis, there are also some other problematics arising from the philosophical point of view. Independently from epistemological, ontological, and other relevant philosophy disciplines (e.g., philosophy of science, neurophilosophy, philosophy of biology), these interdisciplinary experiments mainly assume architecture-specific characteristics specifically

detected by the brain as the primary motivation point. However, it is tough to say whether culturally formulated concepts (e.g., architectural element, object, tool, and thing) are coded in the same way by the biological brain. Although neurophenomenology is mainly concerned with examining phenomenological concepts (e.g., embodiment, consciousness, embodied cognition, perception, experience) with the tools of neuroscience (see, Lutz and Thompson, 2003; Rudrauf et al., 2003; Thompson, 2004; Thompson et al., 2005), the philosophical investigations on the limits of 'investigating biological brain from the perspective of cultural mind' have widely been ignored. Conversely, Eliminativism or eliminative materialism mainly question the conceptualisations, categories, statements and propositions of psychology (especially folk psychology) in terms of their capacity to explain cognition/mind and their relationships and contribute to the emergence of Neurophilosophy (see, Mills, 1987; Hunter, 1995; Repko, 2006; Bickle, 2013; Klar, 2020; Cassini, 2021). However, how much either neurophilosophy or eliminative materialism has made satisfactory explanations about the possibility/limits of relating psychological/cultural phenomena to neural/biological phenomena is under suspicion. The question can be considered one modern form of the general questions relevant to the possibility of relating/integrating several dichotomous conceptualisations such as soul/matter, mind/body and so on since the ancient times of philosophy. There is also a similar problem beyond relating participants' experience or interpretations of experimenter about the experiment's results with the electrophysiological activity of interest of the experiments (for further explanations, see Frege's third realm, Frege, 1918; Lupasco's tripartite epistemology, Lupasco, 1952; Popper's three worlds, Popper, 1968).

Coping with the Dichotomies and Seeking for Optimum Research Model for Interdisciplinary Research

In this regard, it is hard to decide whether the researchers examine the effects of different architectural environments on the brain or these researchers instrumentalise architectural stimuli to reveal some aspects of neural processing in these inter-disciplinary researches. Therefore, considering organism/brain and architectural environment framework as the proper unit of these inter-disciplinary researches can be a good strategy for coping with dichotomous thinking (i.e., brain and environment) (see, Jarvilehto, 2000; Carello, 2002; Richardson et al., 2008; Hutchins, 2010; Heras-Escribano, 2020; Pagano et al., 2021). Additionally, paying attention to characteristics of relationships/interactions between organism/brain and architectural environment(s) (e.g., dynamism, order(s), asymmetry, trade-offs, modes) by satisfying the research concerns of each discipline can be a helpful strategy for forming the optimum method. By starting from these considerations, the agency with its ecological context (i.e., perception

capacity of the agent to perform goal-oriented actions) has been addressed in the experiments of this thesis (see, Costall, 2008). The ecological context of the architectural agency has been examined with the emphasis on two concepts as affordance and embodiment (also embodied cognition and embodied perception). From an ecological perspective, the embodiment can be considered the primary source and ontological ground of affordance, which emerges from dynamic perception-action cycles and fulfils the function of specification of environmental information within the emergent and self-organised behaviour. Specification of environmental information in perceived potentials for actions form the normativity of affordance and influences the way (inter-) acting (see, Sanders, 2002; Bruineberg and Rietveld, 2014; Jelić et al., 2016; Spatz, 2017). These aspects make affordance very special for architects in understanding and designing the characteristics of architectural experience via designing the affordances within the given environment.

Primary-Secondary Quality Distinction and Clusters of Affordance-based Studies in Neuropsychology

Although the term 'affordance' was coined by James J. Gibson, one of the pioneers of ecological psychology, in the second half of the 20th century (Gibson and Carmichael 1966; Gibson, 1977; 1979), its historical roots can be traced back to philosophical discussions on the primary-secondary quality distinction of reality in the 17th century (see, Locke, 1689/1970; Davidson and Hornstein, 1984; McKitrick, 2002; Kulvicki, 2005). In terms of modern psychological discussions on action-perception couplings, the distinction between primary (ontological and objective such as volume) qualities can be associated with properties relevant to perceived potentials for action and characteristics of the corporeality of agent (e.g., volumetricity and materiality). Thus, secondary qualities (epistemological and subjective such as colour) can be associated with perceptive qualities (e.g., visual features). These qualities have been addressed to experiments on affordance in neuropsychology in the last quarter of the 20th century. In this regard, there are two clusters of experiments (i.e., experiments dealing with kinaesthetic/visuomotor aspects vs experiments dealing with semantic/conceptual aspects of the agent-action-object/environment system) on affordance within cognitive neuroscience and neuropsychology literature (see, Harré, 1999; Scarantino, 2003; Jamone et al., 2016; Osiurak et al., 2017). These are 1) experiments examining the characteristics of effects of *primary-secondary qualities of object(s)* on affordance perception (e.g., Bub et al., 2003; Bonfiglioli et al., 2004; Bub and Masson, 2010; Lopresti-Goodman et al., 2011; Masson et al., 2011; Proverbio et al., 2011; McNair and Harris, 2012; Pappas, 2014; Proctor and Miles, 2014; Bub et al., 2015; Squires et al., 2016; Marini et al., 2019; Bhargava et al., 2020; Kostov and Janyan, 2020) and 2) experiments examining the characteristics

of effects of manipulation of conceptualisations relevant to *(ecological) context* of/within the agent-action-environment framework (e.g., compatibility, congruence, context, and priming) (see, Tucker and Ellis, 2004; Girardi et al., 2010; Humphreys et al., 2010; Masson et al., 2011; Makris et al., 2011; 2013; McBride et al., 2012; McNair and Harris, 2014; Kostov and Janyan, 2015; Ambrosecchia et al., 2015; Wokke et al., 2016; Azaad et al., 2019; Zhao, 2019; Garrido-Vásquez et al., 2021). In this context, experiments of this thesis can mainly be categorised within the first cluster experiments of the literature because experiments focus on properties relevant to perceived potentials for actions (e.g., handles of doors and cups/mugs).

Some Characteristics of Affordance Studies in Neuropsychology and Neurophenomenological Insights on Affordance in Architectural Neuroscience

In his conceptual horizon, Gibson mainly referred to the term 'affordance' for real (inter-/ action) situations, environment(s)/object(s) (see for real vs image comparison, Symes et al., 2007; Caiani, 2014; Squires et al., 2016; Gomez et al., 2018; Fairchild et al., 2021). However, affordance has widely been studied in neuropsychology literature with images of situations, environments and objects (objects, environments in visual perception) instead of real ones (e.g., Bub et al., 2003; Bub and Masson, 2010; Masson et al., 2011; Bub et al., 2015; Kostov and Janyan, 2020; Cho and Proctor, 2010; Lopresti-Goodman et al., 2011; Suzuki et al., 2012; Proverbio et al., 2011; McNair and Harris, 2012; Proverbio et al., 2013). Even images were exposed to participants in these experiments, motor cortex activation (i.e., Event-Related De-synchronisation of mu oscillation) was found despite no interaction (e.g., Proverbio, 2012; Rüther et al., 2014; Kalénine et al., 2016). Furthermore, daily hand scale objects (e.g., cups/mugs, scissors, tools) have mainly been used in these experiments (e.g., Yoon et al., 2010; Proverbio et al., 2013; Natraj et al., 2015; 2018; Wokke et al., 2016; Rounis et al., 2018) instead of architectural elements. Conversely, affordance has become a trending topic of architectural neuroscience in a new rising inter-disciplinary field. However, these interests are mainly based on theoretical discussions, especially within post-cognitivism, especially enactivism, embodied cognition account and neurophenomenology (e.g., Bruineberg and Rietveld, 2014; Rietveld and Kiverstein, 2014; Jelić, 2015; Robinson and Pallasmaa, 2015; Jelić et al., 2016; Van Dijk and Rietveld, 2017; Bruineberg, 2018; Rietveld et al., 2018; Djebbara et al., 2020b; Jelić, 2020; 2021). For instance, in her neurophenomenological investigations, Jelic (2015) discussed (1) primordial characteristics (e.g., pre-reflectivity, inseparability), (2) constitutive role (e.g., enactive sense-making, embodied metaphor, emotion) and (3) contextuality (e.g., body schema, proprioception) of corporeality within agent/organism-(inter-)action-architectural environment framework from the phenomenological point of view (e.g., intentionality, engagement, embodiment) and (4) potentials of neurophenomenological

considerations for design (Jelić, 2015). In the same years, by starting from (1) complex, dynamic and non-linear nature of living and cognitive systems (e.g., self-organisation, free-energy minimisation, optimal control, predictive processing) and (2) (neuro-)dynamic characteristics of (inter-) actions within architectural experience (e.g., engagement, (skilled) intentionality and practice, meta-stability) and (3) phenomenological investigations on affordance (e.g., (relational) ontology, normativity), Erik Rietveld, Julian Kiverstein and Jelle Pieter Bruineberg radicalised the conceptualisations of embodied cognitive neuroscience and paved the way of enactivism (see, Bruineberg and Rietveld, 2014; Rietveld and Kiverstein, 2014; Bruineberg, 2018).

Rise of Enactivism: Shifts of Theoretizations of Affordance in Architectural Neuroscience

After their conceptual contributions, enactivism became one of the most used conceptual frameworks in theoretical investigations on affordance within architectural neuroscience or neuro-architecture literature. Julian Kiverstein and Erik Rietveld expanded their investigations by considering temporal scale. They focus on dynamic & immediate actualisation of agency (e.g., the field of affordance) and long term effects of agency (e.g., skilled intentionality framework) and generate/implement new frameworks and conceptualisations. Some of them can be listed as *skilled intentionality framework*, *affordances for higher cognition*, *socio-material*/*constitutive entanglement*, the *landscape of affordance*, and *field of affordance* (Van Dijk and Rietveld, 2017; Bruineberg, 2018; Rietveld et al., 2018; Bruineberg et al., 2019; Kiverstein, 2020; Kiverstein and Rietveld, 2020; Kiverstein et al., 2021). By starting from previous neurophenomenological investigations, Andrea Jelic and her colleagues (2016) (1) expanded their investigations on perception-action coupling theories (especially (embodied) phenomenological and function-oriented unifying approaches such as embodied simulation theory) and (2) radicalised the architectural affordance conceptualisations by enactivism and (3) investigate possible ways and limits of neuro-physiological investigations of enactive architectural affordance through immersive virtual reality technologies (Jelić et al., 2016). Additionally, several architects and architectural theoreticians address these theoretical architectural affordance discussions to the area of architectural design experience (e.g., considering phenomenological, enactive or ecological aspects of affordances in architectural design, complementarity between design and user experience via architectural affordances) (see, Condia et al., 2020). Erik Rietveld and his colleagues also address these discussions to one architectural installation to examine the relationships between architectural design, user, and affordance by manipulating the act of sitting via architectural design in their project (i.e., 'The End of Sitting' project) (see, Rietveld, 2016; Jelić, 2021).

Towards Better Theoretical Framework for Studying Architectural Affordance: Convergent Points of Ecological Psychology and Enactivism

Although enactivism has been chosen as a theoretical framework by architects due to its strong explaining capacity on the constitutive role of dynamic and complex agent-environment connectedness on cognition, there are some discussions between ecological psychology and enactivism in general and affordance-specific characteristics which create convergence/ complementary or divergence/ conflict (see, Heft, 2020; McGann et al., 2020; Ryan and Gallagher, 2020). Some neurophilosophers emphasise convergence and complementary and seek possible integration or cross-fertilisation (see, Di Paolo, 2016; McGann, 2016; Stapleton, 2016; Bruineberg et al., 2018; Kiverstein and Rietveld, 2018; Rietveld et al., 2018 Heras-Escribano, 2019; Machielsen, 2019; Carvalho and Rolla, 2020; McGann et al., 2020; Rolla and Novaes, 2020); conversely, some neurophilosophers emphasise divergence and separation (see, Fultot et al., 2016; Van Dijk et al., 2017; Baggs and Chemero, 2018; Segundo-Ortin et al., 2019; Heft, 2020; Popova and Rączaszek-Leonardi, 2020; Read and Szokolszky, 2020; Myin, 2021). Additionally, theoretical developments and rectifications within ecological psychology (see, Heft, 2001; 2013a; Lombardo, 2017; Lobo et al., 2018) and degree of radicalisations (non-representationalism) and emphasise on the sensorimotor grounding of cognition within varieties of enactivism (Hutto and Myin, 2012; 2017; Hutto et al., 2014; Ward et al., 2017; Barrett, 2019a) make the converge-divergence and complementarity discussions more complicated. In this regard, generally shared characteristics between ecological psychology and enactivism can be listed as; 1) *anti-representationalism* a*nd active role of brain and embodied agent* (i.e., cognition is the performance between bodily agent and environment instead of a mere representation of passive recipient brain), 2) *dynamism* (i.e., cognition is the dynamic product of complex agent-environment engagement), 3) (*bodily and ecological) contextuality* (i.e., cognition cannot be separated/isolated from *the* body and environment), 4) *instrumentalisation of affordance* (i.e., one of the best tool which can be addressed to experiments directly in addition to metaphorical theoretizations) (see, Di Paolo, 2016; McGann, 2016; Stapleton, 2016; Zahidi and Eemeren, 2016; Bruineberg et al., 2018; Kiverstein and Rietveld, 2018; Rietveld et al., 2018 Heras-Escribano, 2019; Machielsen, 2019; Carvalho and Rolla, 2020; Crippen, 2020; Feiten, 2020; Gastelum, 2020; James, 2020; McGann, 2020; McGann et al., 2020; Ryan and Gallagher, 2020; Rolla and Novaes, 2020; Travieso et al., 2020).

Towards Better Theoretical Framework for Studying Architectural Affordance: Divergent Points of Ecological Psychology and Enactivism

Conversely, conflict issues between Ecological Psychology and Enactivism mainly arise from 1) motivation and background and 2) degree of radicalisation of these two approaches and 3) general problem as heuristic limits of definitions of elements of each system. Ecological psychology pays attention to the ontology of mutuality of agent-environment framework within the ecological context and prioritises epistemological explorations of animate organism's perceptual processes (or perceptually guided actions). Differently, enactivism attaches importance to ontic and ontological considerations of dynamic and complex embodied epistemological/cognitive processes between enacted agents and organisms with strong concerns on avoiding representationalism by dynamisation and sensorimotor grounding. Ecological psychology has been criticised in conceptualisations about the perception of the prioritised animate agent within its static ontology by enactivists. In this context, enactivists emphasise the perils fall to representationalism (i.e., the hard problem of content), especially on the content of perception (e.g., information content, semantic content). Ecological psychologists have criticised Enactivism due to its dynamisation of cognitive/epistemological processes to the level where enacted agent and environment melted within the dynamism of the process for the sake of radicalisation of anti-representationalism and sensorimotor-grounding. In this regard, ecological psychologists emphasise the difference from perceptually guided action from enacted sense-making and insufficiency of sensorimotor grounding for explaining constitutive relatedness, the importance of the ontological stability of the agent-environment system and prioritisation of perceiving agent (see, Fultot et al., 2016; Baggs and Chemero, 2018; Segundo-Ortin et al., 2019; Heft, 2020; Popova and Rączaszek-Leonardi, 2020; Read and Szokolszky, 2020; Myin, 2021).

Between Theoretization and Experimenting: Enactivism vs. Ecological Psychology for Architects vs. Neuropsychologists

Therefore some of the divergent/conflict issues can be categorised within aforementioned three categories as; 1) *heuristic limits of definitions* (e.g., perception, habitat, umwelt, self-organisation, autopoiesis, biological autonomy, and embodiment), 2) *motivations and background* (e.g., ecology of mutuality (species-specific rich environment) reciprocality within umwelt (individual-specific specified environment), prioritisation of animate perceiving agent, dynamisation of cognitive system of enacted agent, situated body, enacted body, directly perceived environment as the source of information/meaning (realism), constructive sensation/sense making as the source of information/meaning (constructivism), constitutive relatedness, sensorimotor coupling, sensorimotor equilibration), 3) *concerns relevant to radicalism or non-/anti-representationalism*

(e.g., direct perception vs. skill-oriented perception of affordance, the hard problem of content (e.g., perception, meaning, information), redundancy and specification of information/perception/meaning, sensorimotor grounding, temporal dimension (e.g., learning, development, skill acquisition), history of normativity of agent(s), natural vs. socio-cultural context/agency) (see, Heft, 2013b; Fultot et al., 2016; Baggs and Chemero, 2018; Read and Szokolszky, 2018; Szokolszky and Read, 2018; Segundo-Ortin et al., 2019; Heft, 2020; Popova and Rączaszek-Leonardi, 2020; Read and Szokolszky, 2020; Myin, 2021). Regarding affordance-specific distinction, general distinct characteristics of ecological psychology and enactivism can also be seen in their conceptualisations of the ontological status of affordance. Ecological psychologists assert affordance information can be actualised via natural disposition and interpret affordance within neutral monism context (i.e., rejection of duality of physical vs perceived environment and attempt to unification them in cognition). However, enactivists specify affordance information to enacted agent's individual background (e.g., learning, skills) and posit affordance more relational context (Baggs and Chemero, 2018; Caiani, 2018; de Pinado Garcia, 2020; Read and Szokolszky, 2020; Ryan and Gallagher, 2020). In this regard, enactivism offers more dynamic and relational potentials for theoretical conceptualisations and descriptive or generative architectural discussions for architects. Conversely, ecological psychology suggests more systemic (agent-environment framework) and prioritisation of perceiving agent's dispositions for experimental research and neurophysiological investigations for neuropsychologists.

Characteristics of Interaction with Architectural Affordance and Experiments in Architectural Neuroscience

Several experiments have been conducted on the affordance of hand scale daily objects in cognitive and neuropsychology literature (e.g., Yoon et al., 2010; Proverbio et al., 2013; Natraj et al., 2015; 2018; Wokke et al., 2016; Rounis et al., 2018) since the formulation of the term by J. J. Gibson (Gibson and Carmichael 1966; Gibson, 1977; 1979). A rising interest in architectural affordance among architectural neuroscience researchers and architects has happened. But, there have been limited experiments investigating architectural affordance. One of the most interesting aspects of human architecture differentiating it from animal architecture is its manipulatable elements (e.g., doors, windows) (Hansell, 2005; 2007). In this context, although most of our life passes within the architectural environments, our bodily existence can only communicate with architectural surroundings through these manipulatable elements of the buildings (see, Pallasmaa, 1994; 2012; Schafer, 2020). Furthermore, differently from daily hand-scale objects (e.g., scissors, cups, kitchen utensils), architectural elements are close to/larger than body scale. Our transitive actions with architectural elements are based on cross-lateral (inter-

)action instead of ipsi-lateral like hand-scale daily objects. These features (e.g., unique to humans, communication mediums, contra-lateral transitive action) make architectural affordances special. Especially, contra-laterality of transitive action with these elements gives a chance to experimenters to dissociate stimulus-response compatibility effects (e.g., Simon-Effect) (see, Simon and Wolf, 1963; Simon and Rudell, 1967; Hasbroucq and Guiard, 1991; Hommel, 1993; 1995; Zorzi and Umiltá, 1995; Hommel and Prinz, 1997; Hommel, 2000; Ansorge and Wühr, 2004; Vallesi et al. 2005; Wühr and Ansorge, 2005; Hommel, 2011; Leuthold, 2011; Dittrich et al., 2013; Dolk et al., 2014) from object-based correspondence effects (e.g., Affordance Effect) (see, for object based compatibility effects, Tucker and Ellis, 1998; Shomstein and Yantis, 2002; Tipper et al., 2006; Sevos et al., 2013; Thill et al., 2013; Osiurak and Badets, 2016; Azaad et al., 2019; Gordon et al., 2019; Azaad and Laham, 2020; see for spatial vs./and object based compatibility effects, Proctor et al., 1993; Michaels, 1993; Proctor et al., 1994; Symes et al., 2005; Cho and Proctor, 2010; Pellicano et al., 2010; Borghi et al., 2011; Galpin et al., 2011; Iani et al., 2011; Caligiore et al., 2013; Wilf et al., 2013; Couth et al., 2014; Pappas, 2014; Proctor and Miles, 2014; Song et al., 2014; Kostov and Janyan, 2015; Ambrosecchia et al., 2015; Kume et al., 2016; Saccone et al., 2016). In cognitive and neuropsychology experiments, architectural affordance has been studied with/without augmented/virtual reality mainly (without AR/VR, Tipper et al., 2006; Loach et al., 2008; Cho and Proctor, 2011; 2013; Lien et al., 2014; with AR/VR, Djebbara et al., 2019; 2021; Florescu and Nistor, 2020) via door handles (Tipper et al., 2006; Loach et al., 2008; Cho and Proctor, 2011; 2013; Lien et al., 2014) in addition to door apertures (Djebbara et al., 2019; 2021) and architectural models (Florescu and Nistor, 2020). In these experiments, architectural affordance has been examined via error rate and reaction times (Tipper et al., 2006; Loach et al., 2008; Cho and Proctor, 2011; 2013), event-related potentials (i.e., P1 and N1) (Lien et al., 2014; Djebbara et al., 2019), event-related de-synchronization of brain oscillations (ERSP Analysis) (see, Glossary) (i.e., theta oscillations, alpha/mu oscillations, and low beta oscillations) (Florescu and Nistor, 2020; Djebbara et al., 2021).

Early Attempts of Experimenting Architectural Affordance: Some Behavioural Investigations

In terms of architectural affordance, Tipper et al. (2006) investigated the 1) role of attention to primary-secondary features of the images of door handles (i.e., shape/form and colour) on affordance effect. Additionally, they also examine 2) effects of action states (without action observation) relevant to primary features (i.e., shape/form) of images of door handles (i.e., active vs passive object) on affordance effects similar to mirror neurons effects (i.e., motor empathy) through two behavioural experiments. They could not find any significant effect relevant to stimuli properties (i.e., shape/form, colour) due to the similar speed of their cognitive processing.

However, when participants attention was directed to primary features (i.e., shape/form) via a task (i.e., shape discrimination task), they found a significant affordance effect. Additionally, they found that active action state objects (rotated 45^0) activates visual–motor systems (like mirror neurons) and supports affordance effect (Tipper et al., 2006). Loach et al. (2008) used similar stimuli with different orientations (in both horizontal and vertical). They examined the 1) effects of attention to primary-secondary features and 2) effects of compatibility between the compatibility of the orientation of two door handles within a sequence and motor program of compatible response hand (i.e., facilitation, inhibition) on affordance effect. They found significantly faster responses if there is compatibility between identical (horizontal) orientations within the sequence and compatible response hand during texture discrimination task (attention to primary features). However, significantly faster responses were found if there is no identical (horizontal) orientation for a compatible hand. They could not find any significant effect for the colour discrimination task (Loach et al., 2008).

Cho and Proctor (2011) investigated the effect of position of presentation of the images of door handles on stimulus-response compatibility (i.e., Simon Effect, reverse Affordance Effect for contra-lateral transitive actions). They used the same stimuli in the same size of Tipper et al., 2006 with two display conditions as; 1) the bases of each door handle were centred and 2) only door handles were centred between subjects effect. They found the Simon Effect, where the bases of the images of door handles were presented on the centre of the screen in colour judgement task condition. Conversely, they could not find Simon Effect, but they found a tendency towards object-based correspondence effect (i.e., reverse Simon Effect or Affordance Effect) where the stimuli were presented on the centre in the same task condition (Cho and Proctor, 2011).

They (Cho and Proctor, 2013) expanded their research with additional parameters such as three different properties of the object (i.e., shape/form, colour, orientation) and action state (i.e., active vs passive object). In their six experiments, they examined the effects of judgements (as tasks) about shape (i.e., round vs square handle) with/without video clip before the experiment starts (Experiment 1), about colour (i.e., blue and green) vs shape (Experiment 2), about orientation (i.e., horizontal=passive, diagonal=active) (Experiment 6) on Simon effect. Furthermore, they investigated the effects of colouring the stimuli (i.e., coloured handle (Experiment 3), coloured tip, middle and near of the handle (Experiment 4) and the coloured base of the handle (Experiment 5)) on Simon Effect. They also considered the action state (active vs passive object) in all their experiments as an additional experiment condition. They found colour judgements showed Simon effect in contrast to shape or orientation judgements (Experiment 1-3

and 6). Additionally, they found that the location of the coloured area influence location of the Simon Effect (Experiment 4) and the active action state decreases the Simon Effect (Experiment 5) in the base coloured condition. In this context, the Simon effect can be associated with secondary qualities (i.e., visual features), visual stimulation and passive action state of the object. However, the Affordance effect (reverse Simon effect in door handles due to cross-modal transitive action) can also be associated with primary qualities (i.e., shape/form and orientation), motor stimulation through the object's active state (Cho and Proctor, 2013).

Early Neurophysiological Investigations on Experimenting Architectural Affordance: Rise of Event-Related Potential Studies

In addition to behavioural experiments in cognitive psychology, architectural affordance has also been studied through Event-Related Potentials in neuropsychology. In this regard, Lien et al., (2014) replicated Cho and Proctor (2011)'s experiment design with behavioural (i.e., response time and error rate) and event-related potential measures (P1 and N1). They choose P1 and N1 ERP components because these two exogenous components are associated with visual feature processing relevant to attended or cued aspects of the objects (e.g., Hillyard et al., 1973; Luck and Hillyard, 1995; Müller and Hillyard, 2000). In their experiments, they give shape/form judgement (i.e., round vs. square) (Experiment 1) and colour judgement (i.e., blue vs green) (Experiment2) task to examine Simon Effect and Affordance Effect (reverse Simon Effect for door handles) in two different stimuli presentation conditions (i.e., base-centred, object-centred) and with two action states (i.e., active object, passive object) within-subjects design. Although they could not find any significant main effect or interactions in P1 and N1 ERP analysis, they could find a trend towards significance in active action state condition for P1 ERP and passive action state condition for N1 ERP where the stimuli were presented in the base-centred condition in Experiment 2. In behavioural results, object-based correspondence effect has been found where the stimuli presented in the base-centred condition in both of the experiments and in colour judgement tasks (Experiment 2), the effect was larger than in shape judgement task (Experiment 1). These findings (strong effects in colour judgement task condition and base-centred presentation conditions) question whether object-based correspondence effects are driven by visual and orientation properties (i.e., coding spatial features) instead of the motor program (e.g., grasping affordance) relevant to presented objects (Lien et al., 2014).

In addition to door handles, the relationship between architectural affordance of doors without handles in different widths and transition behaviour was also studied through neurophysiological measurements (i.e., event-related potentials) in a virtual reality environment. Djebbara et al. (2019) used a mobile brain imaging approach with Go/No Go task. In each trial, participants

began with the condition that lights turned off in a virtual room. And then, lights were turned on, and participants were faced with a room with either green or red door in different widths (i.e., 20 cm=narrow, 100 cm=mid, 150 cm=wide). And then, participants were instructed to wait for a while and accordingly the colour of the door (i.e., green door=Go, red door=No Go), either they passed to the subsequent space and find & virtually touched a red rotating circle using the controller (transition) or they waited within the starting room (no transition). If participants touch the walls in transition conditions, a warning signal emerged (i.e., walls turned). After each condition (i.e., transition vs non-transition), participants completed a virtual Self-Assessment Manikin (SAM) questionnaire (i.e., a questionnaire measuring pleasure, arousal, dominance via 5-point Likert scale) and trial was finished. Experimenters examined anterior and posterior N1-P2/ P1-N2 complexes. For transition condition, they found significant effects of interactions between door width for dominance and valence (except, wide vs mid), significant effects of wide doors relevant to task performance, and significant effects of interactions of door widths (i.e., narrow x mid (for only posterior) and narrow x wide (for both anterior and posterior)) relevant to the amplitude of N1-P2/ P1-N2 complexes. Their findings provided strong evidence that the effects of architectural affordances can be detected even in the early phases of perception (Djebbara et al., 2019).

Early Investigation on Neurophysiological Dynamics Relevant to Architectural Affordance: Rise of Event-Related (De-) Synchronization Studies

Neurophysiological investigations on architectural affordance have been deepened by years, and in addition to behavioural and event-related potential analysis, event-related spectral dynamics (i.e., ERD and ERS) relevant to architectural affordance have been investigated. In this regard, Florescu and Nistor (2020) expanded the term architectural affordance by the term 'cognitive affordance' referring to familiarization of user to the architectural environment (i.e., emotional bonding) via virtual enhancements (through using mixed reality technologies such as augmented (AR) or virtual reality (VR)) for well being or comfort. In their experiments, participants experienced various augmented reality environments over a physical model during data acquisition via portable EEG and, in pre- and post-experiments, answered questionnaires relevant to emotional states. They added a virtual layer including architectural elements, details and materials to the physical model through augmented reality to enhance visual information for higher cognitive affordance. Before the experiment, 6 questions were asked (i.e., general questions (age, gender, neurological history) and questions relevant to assessments about the physical model (landscape type, geographical location, function of the foreground building). And then, they measured electrophysiological activity in terms of frequency, morphology and

amplitude. They associated strength of emotions and well-being (e.g., attention, mediation) with high alpha and low beta-band activity. In the post-experiment questionnaire, participants were asked questions relevant to visually enhanced mixed-reality model (e.g., comfortability, landscape type, geographical location) and the effect of AR (sufficiency of detail, memorized architectural detail, emotion state). They found there is a strong influence of cognitive affordance (i.e. visual enhancement) on the emotional state and different cognitive processes (e.g., decision making, perception) of the participants (Florescu and Nistor, 2020).

Djebbara et al. (2021) expanded their previous research (Djebbara et al., 2019) and examined event-related neurophysiological dynamics (i.e., ERD and ERS) of the previously acquired data. Event-related spectral perturbations (i.e., ERD of alpha band, 8-14 Hz) on parietal, occipital and motor cortices in both mobile and non-mobile phases of the experiments were examined through adaptive mixture independent component analysis. Four regions of interests were defined through Talairach coordinates as the posterior cingulate cortex (PCC) (also retrosplenial cortex), temporo-occipital region (parahippocampal cortex) (PHC), occipital extra-striate areas (OCC), and supplementary motor area (SMA). In group-level statistical analysis, repeated-measures ANOVA was performed for 3 level *door width* factor (i.e., wide, mid, narrow), 2 level *phases of experiment* factor (i.e., mobile, immobile) and 8 level *time windows* (500 ms within each 4000 ms trial). In the immobile phase, they found significant main effect of door width for OCC, and PHC areas (no significant interaction). In the mobile phase, they found a significant main effect of door width for PCC and SMA via post-hoc Tukey HSD tests (no significant interaction). They associated PCC activity with internal-external attention balance and sensorimotor integration through cortico-thalamic networks for action-selections relevant to architectural affordance and body constraints during the mobile phase. Relevant to the same phase, they associated SMA activity with the action itself instead of preparation of action. In immobile phase, PHC and OCC activity has been associated with scene and environmental perception, contextual information processing and embodied predictions (Djebbara et al., 2021).

Seeking Proper Stimuli for Experiments on Architectural Affordance within Architectural Neuroscience

Although examining relationships between embodied cognition/action/perception and architectural affordance can be considered an excellent strategy to cope with dichotomies (i.e., brain and architectural environment) and the instrumental relationships between each research phenomenon, there are very limited experiments conducted. In terms of stimuli characteristics, in these cognitive or/and neuropsychology experiments, mainly either door handles without doors (without context) (Tipper et al., 2006; Loach et al., 2008; Cho and Proctor, 2011; 2013; Lien et al.,

2014) or doors without handles (lacking affordance specific element) (Djebbara et al., 2019; 2021) was used as the stimuli. In this regard, it is essential to decide what should be the ideal stimuli characteristics for the favour of architecture (to investigate architecture-specific characteristics to some degree) to conduct an interdisciplinary architecture neuroscience experiment. To cope with the instrumentalization of architectural stimuli to reveal some of the neurophysiological processes as much as possible, both specific elements relevant to architectural affordance and context relevant to bodily interaction should be considered. The same experiment can be replicated in doors without handles condition by examining transition behaviour within virtual natural environments (i.e., cave including different passages in different widths) similar to virtual architectural ones. Conversely, using only door handles without doors (context) may decrease the architecture-specific characteristics of these handles (i.e., contra-lateral interaction between hand and handle), and the affordance effect of these elements can become similar to daily hand-scale objects (ipsi-lateral interaction). In this regard, combining both context of body-scale interaction and affordance-specific details can provide a deeper understanding of the architectural agency in terms of embodiment and affordance.

Problematics and Limits of Experimenting Architectural Affordance

In addition to the selection of proper stimuli characteristics for experiment design, there are additional problematics or limitations of architectural affordance experiments within architectural neuroscience. These problematics and limits can be categorized in the categories as 1) general philosophical problematics 2) experiment-specific theoretical problematics and 3) technical limitations. In terms of general philosophical problematics, mainly these problematics can be categorized as; 1) epistemological (e.g., heuristic limits of definitions, limits of proper epistemological categorizations and manipulations within/between them), 2) ontological and metaphysical (e.g., the possibility of localization of function/cognition via anatomy/brain and mind-matter relationships), 3) mereological and logical (e.g., relationships between different information domains and experiment itself, reasoning and validation, deduction and induction), 4) axiological (e.g., ethical considerations), 5) philosophy of science (e.g., perspectivism and nomology, beliefs and assumptions, generalisations relevant to cause and reason, abstraction), 6) problematics within different science/discipline philosophies (i.e., neurophilosophy, philosophy of biology).

Possible Conceptualisation and Experimenting Problematics of Architectural Affordance Experiments

In addition to general problematics, theoretical problematics relevant to experimenting with architectural affordance in cognitive and neuropsychology can be considered in two groups as; 1)

problematics relevant to the conceptual domain of the experiment (i.e., addressing previous philosophical considerations to or philosophication of the conceptual domain of experiment), 2) problematics arising from experimenting (i.e., problematics and limits of addressing conceptual domain to experiment design and proper way of experimenting). Problematics of the experiment's conceptual domain can be considered the implementations of general problems of epistemology, logic, philosophy of science or philosophies of different sciences to the conceptual domain of the experiment specifically. In this regard, some of the problematics of relevant to theorization of architectural affordance and embodiment can be listed as 1) *heuristic limits of definitions* of affordance and embodiment and their liberal uses (i.e., extending the contents of concepts or using terms with totally different meanings) providing additional problematics (i.e., new dimensions and new ambiguities) (e.g., Florescu and Nistor, 2020), 2) *motivations and backgrounds* (perspectivism as a result of basic assumptions and emphasized points of embodiment/embodied cognition/perception and architectural affordance for experiment design) (e.g., Djebbara et al., 2019; 2021), 3) *metaphysical, ontological and mereological problematics* (truthmaking between architectural interaction (fact/existence) and its experiential conceptualisation (concept/truth), requirement of meta-ontological or inter-subjective system transcending interaction between architectural affordance and embodiment due to incompleteness of the architecture-human interaction system) (e.g., Cho and Proctor, 2013 vs. Lien et al., 2014). These problems can be extended, but they will not be further elaborated within this thesis.

Possible Problematics of Experimenting and Technical Limits of Architectural Affordance Experiments

In addition to experiment-specific problematics relevant to experimenting, such as proper stimuli selection to cope with problematics relevant to the dichotomy of instrumentalization within architectural neuroscience, general problematics of meta-science can also be considered within this group. These problematics can be considered as addressing theoretical discussions to the realm of experiment design (e.g., defining proper experiment and control conditions, defining the sample size), applying statistical manipulations to data in proper way (statistical control) and proper evaluation (e.g., avoiding statistical biases or biased use of statistics, avoiding false positives), designing research policy and standardization considerations (e.g., reporting analysis properly accordingly with standards, backing-up data and recording the process, proper data management and ethical consideration of data privacy) and so on (see, Bickle, 2016; Barrett, 2019b; Rozeboom, 2019; Elson et al., 2020; Reischer et al., 2020). Furthermore, technical limits can also be considered in two categories as 1) technical limits relevant to research phenomena of

the architectural affordance experiments (i.e., problems of realisticity -as addressing architectural affordance in statistically comparable conditions either by mixed reality applications (e.g., Florescu and Nistor, 2020; Djebbara et al., 2019; 2021) or by using the images (e.g., Tipper et al., 2006; Loach et al., 2008; Cho and Proctor, 2011; 2013; Lien et al., 2014),- and problem of statistical comparability of real conditions within the context of architectural affordance) (e.g., Hollander and Foster, 2016; Karandinou and Turner, 2017a; 2017b; Vijayan and Embi, 2019; Bacevice and Ducao, 2021) and 2) technical limits relevant to advancements in experiment devices (e.g., spatial precision limits, temporal and spatial resolution, artefact contaminations, limited moveability of participant(s) or limited portability of devices, controlling dynamic environmental conditions within experimenting area) and so on (e.g., Constable, 2006; Logothetis, 2008; Madhyastha et al., 2008; Freyer et al., 2009; Grover, 2016; Abreu et al., 2020; Narayanan et al., 2021).

General Characteristics of the Experiments of the Thesis

By starting from these considerations, we have examined the relationships between architectural affordance and embodied perception/implicit motor imagery through the images of doors with varying handles. In the experiments of this thesis, de-synchronization of mu oscillation on motor cortex as one of the indicators of embodied perception/implicit motor imagery was examined with/without action observation/embodied simulation (with action priming/observation, e.g., Tucker and Ellis, 1998; 2004; Kumar et al., 2013; Wriessnegger et al., 2013; Coll et al., 2015; Drew et al., 2015; Kim and Kim, 2016; Hailperin-Lausch, 2017; Angelini et al., 2018; Bechtold et al., 2018; Sharma et al., 2018; de Vega et al., 2019; without action priming/observation, e.g., Vainio et al., 2011; Proverbio, 2012; Kourtis and Vingerhoets, 2015; Vecchiato et al., 2015; Kalénine et al., 2016; Wamain et al., 2018). Additionally, early phases of dynamic action-perception relationships or reflection of affordance characteristics relevant to potential actions on early processes of perception were examined through posterior P100 ERP wave component on striate and extra-striate cortices (e.g., Proverbio et al., 2011; 2013; Goslin et al., 2012; Jardin et al., 2012; Lien et al., 2014; Proctor and Miles, 2014; Djebbara et al., 2019; Garrido-Vásquez et al., 2021). Due to technical limits, images of doors with different types of handles were presented to participants in hand-scale (close to screen height in y-axis) where participants exposed these images in static positions (without any dynamic interaction or transition). Differently from architectural affordance where handle-hand interaction is contra-lateral, in the third experiment (as the control experiment), affordance relevant to ipsi-lateral interaction between handle and hand was examined via one of the hand-scale objects as cups/mugs (e.g., Yoon et al., 2010; Proverbio et al., 2011; 2013; Proverbio, 2012; Natraj et al., 2013; 2015; 2018; Wokke et al., 2016;

Rounis et al., 2018). In the experiments of this thesis, neurophysiological (i.e., P100 ERP wave component, ERD of mu oscillation) and cognitive processes (i.e., reaction times) relevant to architectural affordance (i.e., Experiment 1, Experiment 2, Experiment 4) and neurophysiological processes (i.e., ERD of mu oscillation) relevant to hand-scale object affordance (i.e., Experiment 3) have been studied through different experiments.

Strengths and Weaknesses of the Experiments of the Thesis

By considering previous issues listed in this chapter, some of the strengths of the experiments of this thesis can be listed as; 1) proper stimuli selection to study architectural affordance (doors with handles, neither just doors, not just handles), 2) balancing different concerns of two disciplines (direct reality and descriptive concerns of architecture vs isolated/fictive reality for the sake of statistical considerations of neuropsychology), 3) proper experiment design, analysis, research policy and ethical consideration (self-explanatory). Some of the weaknesses or limits of the experiments of this thesis can be listed as; 1) technical limits such as static presentation (without dynamic interaction), realisticity and sense of presence (use of images and using them in little size), 2) theoretical problematics (e.g., perspectivism and truthmaking in terms of interactions between embodied perception and (architectural) affordance due to the incompleteness of the system). Due to many technical limits in architectural affordance experiments, problematics of perspectivism and truthmaking relevant to dissociating stimulus-response compatibility (i.e., Simon Effect, coding spatial properties visually) and object-based correspondence effects (i.e., Affordance Effect, coding motor program/grasping affordance) create serious difficulties in terms of experiment design.

EXPERIMENT 1 (EEG)

4.1.2. LITERATURE REVIEW OF EXPERIMENT 1

First Experiment and Predictions

In the first experiment, neurophysiological aspects of architectural affordance of doors with five different handle types (i.e., horizontal bar, vertical bar, push plate, lever, and knob) and embodied perception/implicit motor imagery will be investigated through ERD of mu oscillation (see, Vainio et al., 2011; Proverbio, 2012; Kourtis and Vingerhoets, 2015; Vecchiato et al., 2015; Kalénine et al., 2016; Wamain et al., 2018). Additionally, early phases of perceived potential actions specific to each category of doors with different handles will be examined through P100 ERP Waveform like to previous literature (Proverbio et al., 2011; 2013; Goslin et al., 2012; Jardin et al., 2012; Lien et al., 2014; Proctor and Miles, 2014; Djebbara et al., 2019; Garrido-Vásquez et al., 2021). Due to contra-lateral hand-handle interaction of architectural affordance, we predict

that 1) neurophysiological activity relevant to visual processing (i.e., ERD of posterior alpha) should emerge on the contra-lateral hemisphere of the brain with handle and 1.1) neurophysiological activity relevant to motor processing/embodied perception/implicit motor imagery (i.e., ERD of central mu) should emerge on the ipsi-lateral hemisphere of the brain with handle (i.e., contra-lateral with hand operation) **(see, Figure-4.1)**, 1.2) relative amplitude of neurophysiological activities should change (i.e., visual processing and motor processing) in line with each category of doors with different handles, 2) perceived potential actions relevant to architectural affordances could be detected through neurophysiological activity (i.e., P100 ERP Wave Component) and 2.1) this activity should be detected on the contra-lateral hemisphere with handle position and 2.2) amplitude of the detected activity should vary accordingly with each category of doors with different handles.

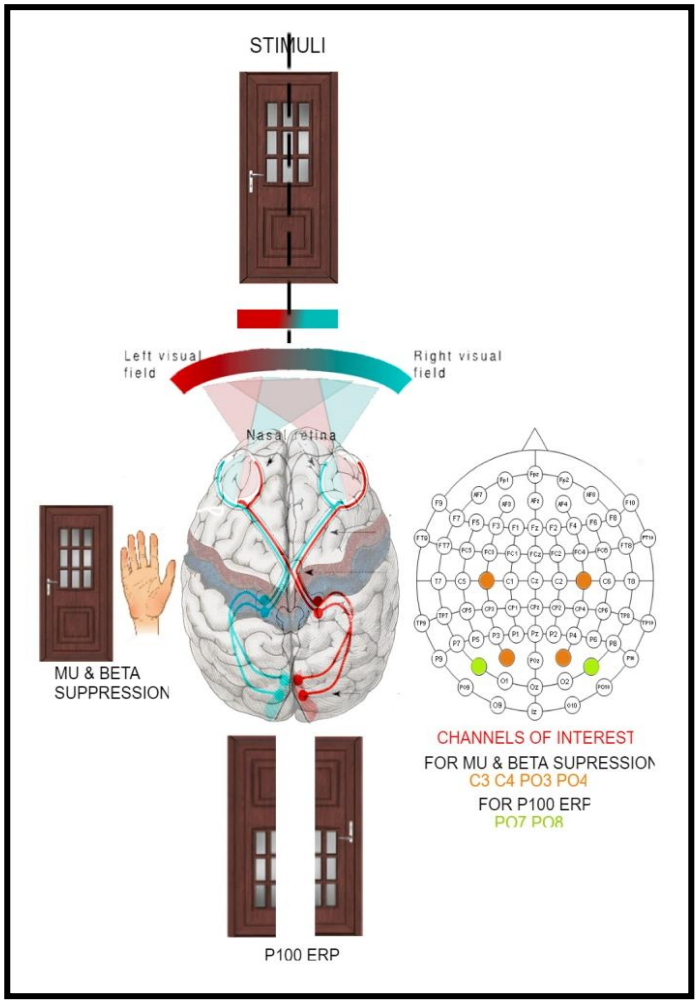

Figure-4.1 Region/Channels of Interests (PO7 and PO8 for ERP, green channels) of the Experiment and Visual & Motor and (Neural) Representation of Image of a Door with a Lever Handle
(Orange channels shows the channels of interests and control channels of Time-Frequency Analysis of ERD of mu oscillations across the experiments of the thesis, channels of interests are central electrodes; C3, C4; control channels are parieto-occipital electrodes; PO3, PO4)

4.2. METHODOLOGY

In this experiment, the EEG –electrophysiological monitoring to record brain activities-, has been used as the primary method. EEG has some advantages and disadvantages in terms of examining cognitive activities. The reason to use this method has been widely explained in the introduction chapter. Some of the reasons of preferring EEG as the method of this experiment can be listed as inexpensive use, easy applicability (i.e., less effort for implementation) and less specialisation demand (Light et al., 2010). Other benefits of this method are derived from its high-quality temporal resolution and ability to analyse the activities of cortical parts (Hari and Puce, 2017). EEG can detect neurophysiological activity ongoing on the regions of interest of the experiment (da Silva, 2009).

4.2.1. Participant Profile

Totally 38 participants were recruited for the experiment. Although there is no formal assessment for sufficient statistical power in terms of sample size (either participant number or trial number), sample size was considered by benefitting from comparable studies which has given in the table below **(see, Table-4.1).**

Literature Review for affordance+P100 ERP		
Study/Research	**Sample Size (Subjects)**	**Sample Size (Stimuli) for SNR**
Petit et al., 2006	**Thirteen** healthy university-level subjects	320 randomly intermixed trials, 2 x 2 x 4 conditions with **20 trials** in each condition
Sambo and Forster, 2009	**Fifteen** paid volunteers took part in the experiment	Each experiment consisted of 12 experimental blocks of 96 trials each (near and far sessions) (2 x 2 x 2, **n=144**) (far, near) (same, opposite) (left, right)
Proverbio et al., 2011	**Fifteen** healthy right-handed university students	300 pictures of familiar objects (half manipulable, half non-manipulable) **n=150**
Goslin et al., 2012	**Seventy volunteers** from the University of Plymouth	Eighty-four colour pictures of 42 common household objects (half kitchen utensil, half tool) 2 x 2 conditions, **n=21** (object category) (congruency)
Righi et al., 2014	**Fourteen** healthy right-handed Italian students	400 coloured pictures of everyday tools 2 x 2 conditions, **n = 100** (affordance) (attractiveness)
Wamain et al., 2014	**Twenty** adults participated in the experiment	420 trials, (3 sessions × 2 repetitions × 2 action types × 2 display types × 15 actions+24 trials without video presentation+36 trials in which the action "hammering [a nail]) for each condition (about **110 trials**)
Freeman et al., 2016	**Seventeen** right-handed, neurologically intact human volunteers	200 total trials, **40 total** trials per experimental condition
Decroix et al., 2020	The electrophysiological activity of **28 participants**	Twenty objects were selected, **n=20**
Ferguson et al., 2021	**Thirty three subjects** enrolled in psychology courses at the University of Vienna	Subjects completed two separate blocks of 112 trials (2 x 2 x 2) **n=28**

Table-4.1 Example Studies Used for Defining Sample Size for Sufficient Statistical Power

One participant could not attend the data acquisition process because of her long and thick hair. Thirty-seven participants attended the data acquisition process. However, two of these participants were excluded from any level of data analysis due to some problems related to technical applications-such as channels having no signal- emerging during the data acquisition process. Furthermore, three participants were excluded from the remaining 35 participants because their data were highly contaminated through artefacts and did not meet the criteria of the experiment. Therefore, 32 participants' data were used for both ERP and ERD/ERS analysis. All participants were right-handed and neurotypical (with no history of neurological or psychiatric problems) and no history of drug abuse (all by self-report). The experiment was approved by the ethics committee of the School of Psychology, University of Nottingham (Reference Number: "F978"). Before beginning the main experiment, participants signed the consent form confirmed by the ethics committee of the School of Psychology, University of Nottingham.

4.2.2. Stimuli, Design of Experiment and Experiment Procedure

Images of five different types of doors (i.e., doors with different forms of handles) that afford different forms of hand operation for opening the door were chosen as the stimuli of the experiment. Types of doors were categorised as doors with a horizontal bar, doors with a knob, doors with a push plate (swinging doors), doors with a lever handle, and doors with a vertical bar. For each door type category, two additional categories accordingly the lateralisation of the hand operation as doors that affords right or left-hand operation, was defined **(Figure-4.2)**.



Figure-4.2 Example Stimuli of the First Experiment

Therefore, ten stimuli categories (five-door types and two laterality categories) were defined, and each stimuli category included 25 images. An additional category (as the task category of the experiment) was designed in addition to the ten stimuli categories of the experiment. This category (task category) includes 25 images of doors (approximately %10 percentage of main experiment categories) that have a knob located in the middle of the door (Gaeta et al., 2003). The task of the experiment was based on an oddball paradigm which will be explained in the task section. Totally, 275 (250 stimuli of the experiment within ten door type x lateralisation categories and 25 stimuli of task category) images of doors **(Table-4.2)** that afford different hand

operations for opening the door were presented to participants during the data acquisition process. In addition to the design of the main experiment, a demo experiment was designed for the familiarisation of the participants to the main experiment. In the demo experiment, 33 images of doors were categorised and presented to the participants. They were the same as the main experiment (three door images for ten main categories and three additional doors images for the task category of the experiment).

All images of the doors for both the main experiment and demo version were chosen from different websites. It was done via Google Search with different words such as ‘door with horizontal bar’, ‘swinging doors’, ‘doors with knob’, etc. After finding several door images via Google Search, some door images of which handles could not be easily visually detected were eliminated from the potential stimuli set of the experiment. Additionally, some door images that cannot be seen directly from the front or are too distorted (i.e., seen from close to profile view) were also discharged from the stimuli set. The remaining chosen images of the doors were modified via free and online PIXLRPro Software. In the process of modification and preparation of the images, existing texts, numbers, human images, human reflections and shadows, furniture that affords hand operation were cleaned from the images to avoid any inference on the frequency of interest of the experiment (mu rhythm) (Cohen-Séat et al., 1954; Gastaut and Bert, 1954). The experiment was designed on PsychoPy 38 (Peirce, 2007; Peirce and MacAskill, 2018).

Door Category	Example Stimuli *Right Hand Operation*	Example Stimuli *Left Hand Operation*
HORIZONTAL		
KNOBBED		
SWINGING		
LEVER		
VERTICAL		
ODDBALL		

Table-4.2 Stimuli Categories of the Experiment (25 images of doors in each category, total 275 stimuli)

Stimuli were presented on a uniform gray background in pseudo-randomised order on the centre of the screen during the experiment's main and demo version. All stimuli were presented with fixed-width, which was 8 cm for the main experiment and was 7.57 cm for the demo version of the experiment. Stimuli height was changed from 6.8 cm to 22 cm in the main experiment and from 6.43 cm to 20.81 cm in the demo version of the experiment. Stimuli of the demo version of the experiment were presented on the screen of notebook of the experimenter (HP 250 G3 Intel Core, 1366 x 768 pixels, 15.6”, 60Hz refresh rate). Stimuli of the main experiment were presented on the screen of the computer (Samsung, ViewPixx3D, 1920×1080 pixels, 23.6”, 120Hz refresh rate, 1ms pixel response time) locating in Faraday Cabin (2.5 x 2.3 x 2.3 m), -a quiet room at ambient temperature-, in EEG Laboratory of University of Nottingham. During the data acquisition process, Faraday Cabin provides insulation from the contamination and interference of electromagnetic fields generated by different sources outside the Cabin. In the main experiment, the distance between participants and the screen was adjusted to 80 cm where the visual angle was 5° 43' on the horizontal axis and was between 4° 52' and 15° 39' in the vertical axis **(Table-4.3)**.

Stimuli Presentation Details of the Experiment	Main Experiment		Demo Experiment	
Technical Aspects of the Monitor	ViewPixx3D, 1920×1080 pixels, 23.6”, 120Hz refresh rate		HP 250 G3 Intel Core, 1366 x 768 pixels, 15.6”, 60Hz refresh rate	
Monitor Size (x, y)	51 cm x 28.5 cm		34.4 cm x 19.4 cm	
Distance from Monitor	~ 80cm		~ 60 cm	
Numbers of the Stimuli	275 (25 x 10 experiment category +25 task category/oddball)		33 (3 x 10 experiment category +3 task category/oddball)	
Stimuli Width (x-axis)	8 cm		7.57 cm	
Stimuli Height (y-axis)	Maximum	22 cm	Maximum	20.81 cm
	Minimum	6.8 cm	Minimum	6.43 cm
Visual Angle (Horizontal)	5° 43'		7° 13'	
Visual Angle (Vertical)	Maximum	15° 39'	Maximum	19° 40'
	Minimum	4° 52'	Minimum	6° 8'

Table-4.3 Stimuli Presentation Details of the Experiment (Main Experiment and its Demo Version)

For data pre-processing and analysis purposes, one trigger code is defined for each category of the door images. Thus, a total of eleven trigger codes which are multipliers of eight were defined.

4.2.3. Procedure and Task of the Experiment

Each stimulus (images of doors) was presented for two seconds during both the main and demo versions of the experiment. Between the images of the doors, a fixation cross that provides the fixation of the participant's gaze was presented between 1 to 2 seconds **(see, Figure-4.3.; Figure-4.4)**. The presentation of stimuli was divided into blocks in the design of both experiments (main experiment and demo version). Each block contains ten stimuli, and the main experiment includes 27 blocks and additional five images of doors (27x10+5=275 stimuli). The Demo version includes three blocks and three additional stimuli (3x10+3=33 stimuli). As the task of the experiment, participants were requested to count the number of oddball stimuli and report the number by shouting at the end of each block. In some experiment designs, participants can also be requested to press the key for oddball tasks; however, motor execution during task fulfilment (e.g., pressing a key) can shadow the effects of motor imagery/embodied perception on electrophysiological activity interest. Thus, participants were asked to shout the number of oddball stimuli to avoid motor execution when pressing any key. At the end of each block, a text informing participants to report the counted number of an oddball within the previous block was presented on the screen. As soon as the participants saw the text, they reported the total number they counted (oddball stimuli, images of doors with a knob in the middle of the door). The experimenter recorded reported numbers to examine the degree of attention of the participants throughout the experiment process. The accuracy rate was used to examine the degree of

attention of the participants. Most of the participants performed the task with 100 per cent accuracy. The main experiment approximately took 27 minutes.

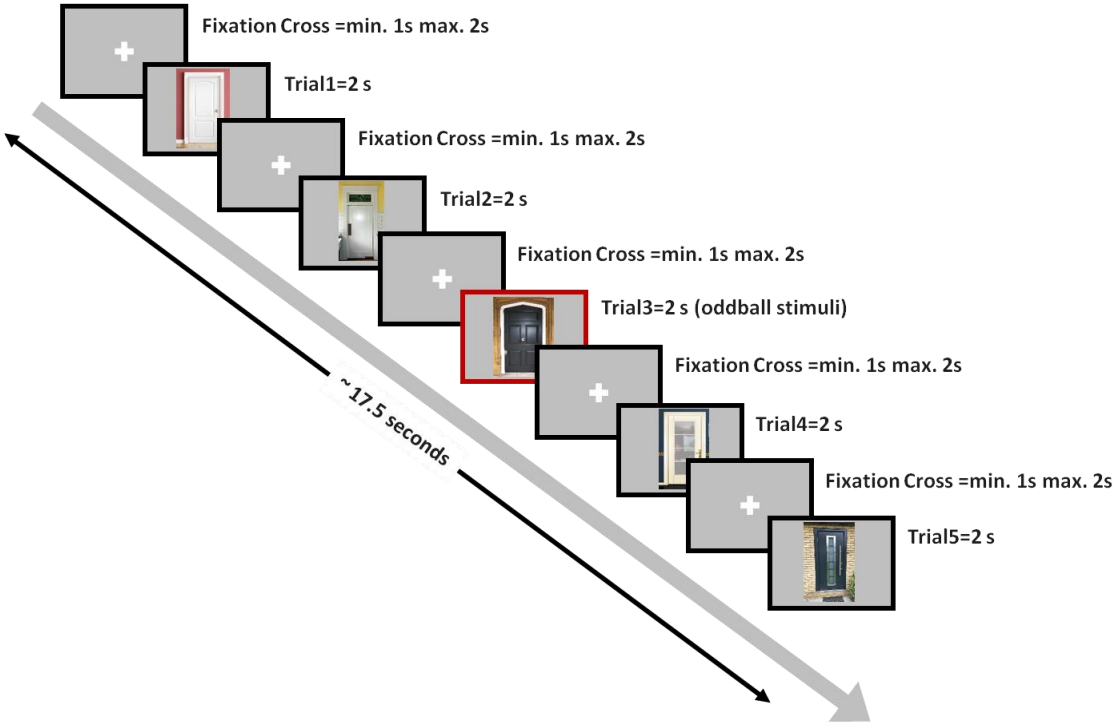

Figure-4.3 Flow of the Experiment (sequence of the stimulus presentation within half of the block) (red-framed sample is oddball stimulus)

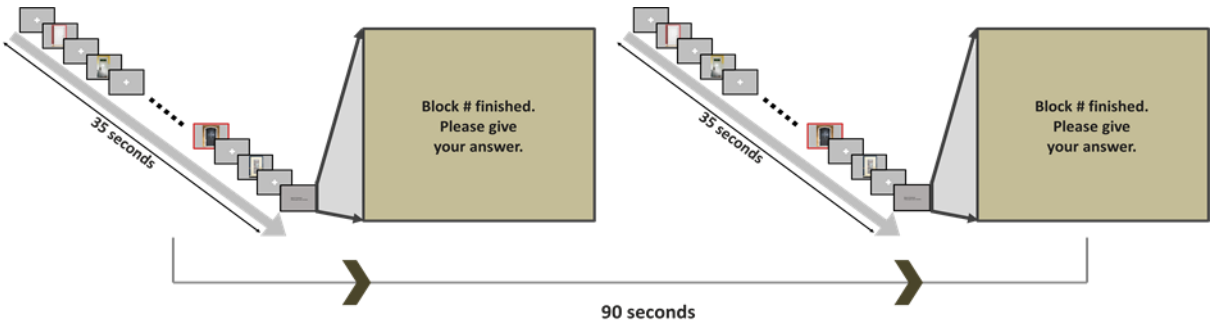

Figure-4.4 Flow of the Experiment (sequence of the Stimuli Presentation across two blocks)

4.2.4. Data Acquisition

Before the main experiment, participants were prepared for the experiment. In the preparation process, a BioSemi electrode cap was chosen according to the perimeter of the participants' heads and placed on the scalp to keep impedances below 20 kΩ (Headcaps. BioSemi.com, 2021). After placing the electrode cap, the electrolytic gel was applied to electrode locations for conductivity. After placing the electrode cap and implementing electrolytic gel to electrode areas on the cap, two pin-type electrode sets, including 32 pin type electrodes in each set, were placed

on the electrode cap. Additional six Ag/AgCl flat-type electrodes with Individual leads/connectors were placed on mastoids, temporal bone (i.e., lateral canthi) and sphenoid bones (M1, M2, F9, F10, T9, T10) to examine electrooculographic activity (EOG) and re-referencing for offline data pre-processing and analysis (Active electrodes. BioSemi.com, 2021). However, recorded activity from external electrodes was not analysed in offline signal processing because Independent Component Analysis (ICA was considered sufficient for rejecting artefacts resulting from electrooculographic activity (i.e., eye blinks, saccades, oscillatory potentials of the retina) (Delorme et al., 2007). After completing placement of electrodes, the normalised value of electrode offset of each electrode to the two reference electrodes as CMS (active, Common Mode Sense) and DRL (passive, Driven Right Leg) was checked (i.e., the average voltage between each electrode and active reference electrode). Below ±20mV was accepted as the indicator of a good electrode setup for the acquisition of raw EEG signals (Delorme and Makeig, 2004; Wamain et al., 2018).

After preparing participants for the experiment, Faraday Cabin's light was adjusted to a fixed position (same for all participants) which results the dim light in the cabin. For additional lighting within the Faraday Cabin, A Daffodil USB LED light (model: LEC150) was used. In darkness, strong and widespread posterior alpha oscillations (7.5–13 Hz) (Berger, 1929) can mask (Andrew and Pfurtscheller, 1997; Niedermeyer, 1997; Pfurtscheller et al., 2000; Benbadis, 2015; Yin et al., 2016; Thorpe et al., 2016) mu rhythm (8-12/13 Hz) (Pfurtscheller and Neuper, 1994; Pfurtscheller, 2000; Pfurtscheller, 2003; Neuper et al., 2006; Pfurtscheller and Neuper, 2009; Perry et al., 2011) and they also can interfere with signal averaging for ERPs (Basar and Stampfer, 1985; Jasiukaitis and Hakerem, 1988; Brandt and Jansen, 1991; Rahn and Basar, 1993a; Rahn and Basar, 1993b; Intriligator and Polich, 1995; Price, 1997; Haig and Gordon, 1999; Barry et al., 2000; Dockree et al., 2007; Hanslmayr et al., 2005; 2007; Min et al., 2007; De Blasio and Barry, 2013; Karamacoska et al., 2019; see also ERP masking ERD/ERS, Kalcher and Pfurtscheller, 1995; Pfurtscheller and da Silva, 1999). The above statement is related to the fact that alpha rhythm is associated with drowsiness, sleep and fatigue (see for review, Cantero et al., 2002; see also, Scammell et al., 2017; De Gennaro, 2001; Knaut et al., 2019; Tran et al., 2020). After completing required adjustments of experiment environment (e.g., the position of participant, task instructions, lighting level) and controls of devices used for data acquisition (e.g., electrode offsets, StimTracker device, ActiveTwo Biosemi Amplifier) (StimTracker.Cedrus.com, 2021; Products. BioSemi.com, 2021), experiment and data acquisition process began.

Raw EEG data were acquired using a 64-channel extended 10-20 Active-Two acquisition system (BioSemi, Amsterdam, Netherlands), sampled at 1024 Hz (which is well above the required

Nyquist rate for classical EEG bands delta to beta analysed in this study - higher sampling rates would have generated unnecessarily large data files, and digitised at 24-bits and recorded via ActiView 705 (version 8.6.1). Trigger codes of each door category were sent and synchronised with the acquired data via a Cedrus Stimtracker (StimTracker.Cedrus.com, 2021) and USB 2.0 Receiver (Receiver.BioSemi.com, 2021) during the process of the main experiment. Trigger codes are beneficial for segmenting and grouping/classifying the trials of defined stimuli categories of the experiment (i.e., different door categories) during offline data pre-processing and analysis.

4.3. DATA PRE-PROCESSING FOR TIME-FREQUENCY ANALYSIS OF ERD OF MU OSCILLATION

In terms of event-related brain dynamics of EEG, data analysis can be divided into two categories as Time-Domain Analysis) (Hjorth, 1970) (for Event-Related Potentials) (Handy, 2005) and Time-Frequency Analysis (Zhang, 2019) (for Event-Related (De-) Synchronization) (Pfurtscheller, 1997; Pfurtscheller and Da Silva, 1999). Thus, after completing the raw EEG data acquisition process, offline signal processing began. In offline signal processing, three steps were performed. These are; (1) data pre-processing & cleaning (for both Time-Frequency Analysis of Event-Related De-Synchronisations (ERD) of mu oscillation and Time-Lock/Time-Domain Analysis (Congedo, 2018) of Event-Related Potential of P100 wave component), (2) averaging amplitude of ERD of mu oscillation (8-12/13 Hz) within 200-500 ms after stimuli onset (Pineda, 2008; Pfurtscheller and Neuper, 2009; Urgen et al., 2013; Moreno et al., 2015) relative to pre-stimulus baseline (from 300 ms to ±0 ms before stimuli onset) at individual/subject level, (3) averaging amplitude change of ERPs within 90-120 ms after stimuli onset relative to pre-stimulus baseline at individual/subject level (Hamburger and vd Burgt, 1991; Eimer et al., 2003; Schubert et al., 2006; Schendan and Lucia, 2010; Gerdes et al., 2013; Li and Lu, 2014; Gherri and Forster, 2015). After completing data pre-processing, cleaning and individual-level analyses (both for ERDs and ERPs), (4) group-level statistical analysis of ERD of mu oscillations and (5) group-level statistical analysis of ERP of P100 wave component was performed via ANOVA (Analysis of Variance) on IBM SPSS (abbreviated from Statistical Package for the Social Sciences) to examine the statistical significance of parameters and interactions and means of relative amplitudes of statistically significant factors, and interactions were obtained as EMMs in SPSS Output.

4.3.1. The Offline Data Pre-processing

After the data acquisition process was completed, the data pre-processing step, which contains preparation and cleaning the data for analysis, began. In the preparation process, continuous raw data was *segmented* accordingly with trial definition, was *filtered* from some band range frequencies which are out of the range of frequency of interest of the experiment, was *re-*

referenced to the average value of potentials of 64 electrodes on the electrode cap, *corrected to baseline* to reduce the effects of temporal drifts within the data flow by the relativising signal of interest of the experiment to a control signal (defined accordingly chosen baseline correction method) (Rogasch et al., 2017; Hari and Puce, 2017, Peng, 2019). All data pre-processing steps were performed in Matlab (The MathWorks Inc., Natick, MA) using Fieldtrip routines (Oostenveld et al., 2011).

Trial Definition and Segmentation

The first step of data pre-processing is segmenting the data accordingly to the trial definition. For segmenting the data, information about the times of stimulus onset is needed. For this purpose, trigger codes (which were defined accordingly with stimuli categories) were synchronised with the onset of each relevant stimulus during data acquisition. Synchronised trigger codes were beneficial for detecting stimulus onset and defining the time window of trials accordingly for each stimulus onset. In the trial definition process, the time window should have enough time to capture the entire duration of the brain response to the stimulus and to include multiple cycles of the oscillations of frequency of the interest of the experiment (i.e., mu oscillation (8-12/13 Hz). Thus, the time window of trial definition was adjusted from 600 ms before stimulus onset to 1900 ms after stimulus onset. The Time window of trial definition cannot exceed 1000 ms before stimulus onset and 2000 ms after stimulus onset due to the design of the experiment (i.e., duration of fixation cross and each stimulus, **Figure-4.3)**. In the trial definition process, avoiding longer time window definitions and defining time window for sufficient duration is critical to cope with the noise within the signal because longer epochs potentially include more artefacts (Cohen, 2014, p.75-8; Zhang et al., 2020). Each segmented data should contain a pre-stimulus period (control signal for baseline correction) and a post-stimulus period which has sufficient duration to be able to highlight the particular activity of interest (Procházka et al., 2010; Sanei and Chambers, 2013, p.51-55; Cohen, 2014, p.75-8).

Bandpass Filtering (High Pass Filtering + Low Pass Filtering)

The second step of data pre-processing is bandpass filtering which includes high and low pass filtering. It is beneficial for decreasing the noise which is caused by physiological and non-physiological artefacts. The limits of bandpass filtering were chosen to include all classic EEG frequency bands where classic means excluding gamma frequency at 40Hz and above. In the bandpass filtering process, adjusting the filters to give some analysing flexibility chance of different frequency ranges is vital because different brain activity in different frequency ranges might be detected at the end of the analysing process. According to the frequency range of interest of the experiment (i.e., mu oscillation (8-13 Hz) and with some additional flexibility,

frequencies which are above 39 Hz *(low-pass filtering)* and are below 0.35 Hz *(high-pass filtering)* were filtered from the dataset. In addition to decreasing noise and jitters, bandpass filtering is crucial for avoiding aliasing problems before transforming analog signals to digital via data sampling (Rogasch et al., 2017; de Cheveigné and Nelken, 2019).

Re-referencing

The third step of data pre-processing was re-referencing. Each electrode's power spectrum of acquired data was referenced to the all-electrode average in the re-referencing process because the BioSemi system allows reference-free recordings. Common average re-referencing is beneficial, especially for multi-channel systems such as 64 channel or 128 channel systems, to avoid polarities and asymmetries caused by the spatial configuration of electrodes (i.e., different placements and distances of electrodes). In the re-referencing process, data were normalised to the mean of the total amplitude value of the acquired signal by all-electrode at each time point. This provides benefits for decreasing the noise arising from the ground electrode connected to the ground circuit of the amplifier. After data were re-referenced, power spectrum values belonging to each data gain new values accordingly the value of power spectrum of all-electrode average which is accepted as new 0 point. All-electrode average re-referencing (Common Average Referencing) is better to avoid polarisation, asymmetries and noise when compared with other channel-based re-referencing systems (e.g., re-referencing to a channel placed on mastoid, nose or earlobes). This is seen due to the non-equidistant location of chosen reference channel to other channels. The reason sits behind that any single reference channel cannot be equidistant from all other electrode locations (for example, the distance between mastoid and temporal electrode site is smaller than the distance between the mastoid and occipital electrode site) (Ludwig et al., 2009; Alhaddad, 2012; Tsuchimoto et al., 2021).

Baseline Correction

The last step of data pre-processing is baseline correction. Baseline correction is beneficial for comparing changes of EEG potentials between pre-and post-stimulus to examine oscillatory activity (i.e., synchronisations and de-synchronisations). Baseline correction avoids data from the effects of possible temporal drifts; direct current offsets caused by sweating and skin conductance, and other noise sources (Alday, 2019; Zhang et al., 2020). Baseline correction relativises or normalises the signal of interest of the brain following a control/baseline signal. The Time window of the control signal is mainly chosen from the pre-stimuli period (i.e., before stimulus onset, from 300 ms to ±0 ms before the stimulus onset) when event-related brain activity of interest has not yet emerged. Several ways of correcting the power of the signal of interest to a control signal (i.e., baseline) such as *subtracting* (*absolute* baseline correction;

subtracting control signal from signal of interest) or *dividing* (*relative* baseline correction; dividing signal of interest to control signal) or combinations of different basic mathematical operations (*relative change* baseline correction, *norm change* baseline correction) or logarithmic operations (*decibel* baseline correction) between signal of interest and control signal (see Methodology Chapter of the thesis for detailed explanation). In this experiment, the *norm change* type of baseline correction was performed for Time-Frequency Analysis (ERD/ERS Analysis).

4.3.2. Data Cleaning: Visual Inspection Based Cleaning and Independent Component Analysis

After completing all steps of data pre-processing, the data cleaning process began. Bad trials of which variance of amplitude was above 300 μV^2 was eliminated from the data set via visual inspection script of Fieldtrip routine. In this first pass of amplitude-based rejection, participants' datasets, including more than 10% of such trials, were excluded from general data analysis (i.e., 5 participants were excluded) (Tavakoli and Campbell, 2015; Cruz-Garza et al., 2017; Marini et al., 2019; Grosselin et al., 2019). Next, Independent Component Analysis (ICA) was performed to eliminate physiological artefacts, especially eye-blinks. For the ICA artefact rejection process, data acquired at a 1024/s sampling rate was downsampled to 300/s sampling rate, thereby reducing file size for speed of processing (Viola et al., 2010; Jenson et al., 2015; Rogasch et al., 2017). Analysis (ICA) allows certain physiological artefacts to be isolated as one component within EEG data thanks to its information-theoretic objective function (e.g., high order statistics, probability density function) and optimisation algorithm (e.g., conventional/standard gradient, stochastic gradient, the relative gradient or natural gradient algorithms) (Wei and Charoensak, 2005; Mi and Yang, 2012; Huang and Wang, 2013; Hsiao et al., 2016). In this experiment, ICA was performed using the Runica algorithm. Runica algorithm decomposes pre-processed EEG data by using the infomax ICA algorithm (Bell and Sejnowski, 1995) with the natural gradient learning algorithm (Amari et al., 1996) and Principal Component Analysis dimension reduction and/or spectrogram pre-processing (decomposition of complex Time-Frequency transform of data) (Zibulevsky and Pearlmutter, 2001; Zhen et al., 2016). Thanks to the Runica algorithm, the ICA components with scalp topography corresponding to eye blinks were removed from the primary data set (Makeig et al., 1997). After completing physiological artefact rejection through ICA, the second pass of amplitude-based rejection was performed, with analysis restricted to channels of interest (i.e., fronto-cental channels, (FC3, FC4), central channels (C3, C4), and parieto-occipital channels (PO3, PO4 (for ERD/ERS Analysis). In this step, trials exceeding an amplitude threshold of 100 µV were eliminated (Delorme et al., 2005; Zeman et al., 2007; McMenamin et al., 2010; Perry et al., 2011; Savelainen, 2010; Solé-Casals et al., 2010; Benito Núñez, 2011; Cong et al., 2011; Winkler et al., 2011; Plöchl et al., 2012; Cassani et al., 2014; Ghaderi et al., 2014; Sheoran et al., 2014; Borse,

2015; Kumar and Kareemullah, 2014; Tavakoli and Campbell, 2015; Hu et al., 2015; Paradeshi and Kolekar, 2017). After completing data cleaning steps, data became ready for analysing.

4.4. DATA ANALYSIS: TIME-FREQUENCY ANALYSIS OF ERD OF MU OSCILLATION

In Time-Frequency Analysis power spectrum of channels of interests as output configuration of the signal of interest was analysed (Blanco et al., 1995; Al-Fahoum and Al-Fraihat, 2014; DelPozo-Banos et al., 2015; Puranik et al., 2018; Zhang, 2019; FT_FREQANALYSIS. Fieldtriptoolbox.org, 2021; Time-frequency analysis. Fieldtriptoolbox.org, 2021) to examine duration and relative amplitude changes of Event-Related De-Synchronization (i.e., level of suppression of mu oscillation on the primary motor cortex (Brodmann Area 4)) (Tiihonen et al., 1989; Arroyo et al., 1993; Pfurtscheller and Neuper, 1994; Schnitzler et al., 1997; Penny et al., 1998; McFarland et al., 2000; Neuper and Pfurtscheller, 2001a; Hari, 2002; Muthukumaraswamy and Johnson, 2004a; MacKay, 2005; Hari, 2006; Pfurtscheller et al., 2006; Anderson and Ding, 2011; Kumar et al., 2013; Cannon et al., 2014; Hari et al., 2014; Fox et al., 2016; Coll et al., 2017; Debnath et al., 2019). In Time-Frequency Analysis, Time-Frequency spectrograms were formed with a sampling rate at 0.2 Hz in the frequency domain and at 5 ms in the time domain. Moreover, signals within each spectrogram that were truncated as segmentation results were recovered through Hanning windowing/tapering (FT_FREQANALYSIS. Fieldtriptoolbox.org, 2021; Percival and Walden, 1993; Mitra and Pesaran, 1999), and the spectral leak was minimised. To improve the efficiency of tapering in terms of minimising the data loss (Kaskarovska, 2005; van Vugt et al., 2007; Babadi and Brown, 2014; Cohen, 2014, p. 203-210; van Drongelen, 2018, p. 153-180; Zhang, 2019), the multitaper convolution was performed. Multitaper convolution uses multiplications in the frequency domain as the basis of multitaper frequency transformation (Cohen, 2014, p. 203-210; Karnik et al., 2021; mtmconvol method. Fieldtriptoolbox.org, 2021).

Differently from ERPs, Event-Related Synchronisations (ERS) and Event-Related De-synchronisations (ERD) are non-phase locked or induced responses (Da Silva, 2006; see also, Kalcher and Pfurtscheller, 1995; Pfurtscheller and Da Silva, 1999; Neuper and Pfurtscheller, 2001a; Penny et al., 2002; Makeig et al., 2004; Shah et al., 2004; Sauseng et al., 2007; Crone et al., 2008; Bastiaansen et al., 2011; Başar and Gölbaşı, 2014). In the context of this thesis, suppressions and enhancements of mu and alpha oscillations are associated with inhibitory and excitatory synaptic activities of different neural populations. These populations work with feedback mechanisms which form a loop between the thalamo-cortical relay (TCR) (inhibitory, hyperpolarised) and reticular nucleus (RN) (excitatory, depolarised) (Pfurtscheller and Da Silva, 1999; Suffczynski, 1999; Neuper and Pfurtscheller, 2001a; Suffczynski et al., 2001; Da Silva, 2006; Pfurtscheller, 2006; Klimesch et al., 2007; Takemi et al., 2013). These feedback mechanisms are

essential for gating of different cognitive processes (i.e., sensory/attention/perception/ information processing gating and so on) (MacKay, 1997; Pfurtscheller, 2003; Da Silva, 2006; Neuper et al., 2006; Anderson and Ding, 2011; Foxe and Snyder, 2011; Popov et al., 2011; Buchholz et al., 2014; Cheng et al., 2016; Dipoppa et al., 2016; Forschack et al., 2017; Hsiao et al., 2018; Fodor et al., 2020; Limanowski et al., 2020; Wiesman and Wilson, 2020).

In literature, mu suppression is mainly detected over the primary motor cortex, especially the parts which are associated with hand representation through central electrodes (C3, C4) (Pfurtscheller et al., 1994; Pfurtscheller et al., 1996; Pfurtscheller et al., 1997a; Pfurtscheller et al., 1997b; Pfurtscheller et al., 2000; Ramoser et al., 2000; Babiloni et al., 2002; Bai et al., 2005; Neuper et al., 2005; Pfurtscheller et al., 2006; Yeom and Sim, 2008; Neuper et al., 2009; Perry et al., 2011; McGarry et al., 2012; Yi et al., 2013; Nakayashiki et al., 2014; Yi et al., 2016; Hommelsen et al., 2017; Bartur et al., 2019). Therefore central electrodes (C3, C4) were chosen as the channels of interest of the experiment. Additionally, fronto-central (FC3, FC4), centro-parietal (CP3, CP4) and parieto-occipital (PO3, PO4) electrodes were chosen to understand how electrophysiological activity changes across head topography (i.e., suppression of mu and alpha oscillations) for comparison or control purposes. However, in group-level analysis, only channels located on the primary motor cortex (C3, C4) (as the typical location of ERD of central mu oscillation) and the ones located on the extrastriate visual cortex (PO3, PO4) (as the typical location of ERD of posterior alpha oscillation) were examined (Van Der Helden et al., 2010; ter Horst et al., 2013; Chaumon and Busch, 2014; Kourtis and Vingerhoets, 2015; Bouchra et al., 2016; Lim and Ku, 2018; Fabre et al., 2021). They are examined to understand cross-modal interaction between visual and motor cortex profoundly (Muthukumaraswamy and Johnson, 2004b; Muthukumaraswamy et al., 2004; Pineda, 2005; Hari, 2006; Oberman et al., 2007; Ulloa and Pineda, 2007; McGarry et al., 2012; Sabate et al., 2012; Umiltà et al., 2012; Kumar et al., 2013; Cannon et al., 2014; Heimann et al., 2014; Jenson et al., 2014; Rüther et al., 2014; Coll et al., 2017).

In Time-Frequency Analysis of ERD of mu oscillation, frequency of interest was chosen classical frequency band range of mu rhythm as 8 to 13 Hz Hz (Tiihonen et al., 1989; Nikouline et al., 2000; Bernier et al., 2014; Cannon et al., 2014; Muthukumaraswamy et al., 2004; Moore et al., 2012; Braadbaart et al., 2013; Cuellar et al., 2016; Fox et al., 2016; Hommelsen et al., 2017; Garakh et al., 2020; see also Pfurtscheller et al., 2000) and time window of ERD of mu oscillation was defined from 200 ms to 500 ms after stimuli onset by benefitting from Time-Frequency spectrograms. ERD of mu oscillation was examined relative to the pre-stimulus baseline, of which time window was defined from 300 ms before stimuli onset to stimuli onset (±0 ms). Mu

suppression levels (amplitude changes, ERD window compared to baseline window) were quantified and statistically analyzed using ANOVA. All ANOVA factors were within subjects: 5-level factor *door category* (i.e., doors with a horizontal bar, doors with a knob, doors with a push plate/swinging doors, doors with a lever handle, doors with a vertical bar), 2-level factor topography (i.e., central, parieto-occipital), 2-level factor *handedness* (i.e., left hand operation, right hand operation), 2-level factor *hemisphere* (i.e., left hemisphere, right hemisphere). All group-level statistical analysis was performed via SPSS by using General Linear Repeated Measures ANOVA *tests of within-subject effects* were performed.

4.5. RESULTS OF TIME-FREQUENCY ANALYSIS OF ERD OF MU OSCILLATION

In individual-level analysis, 5 participants were excluded from the data analysis because these participants could not satisfy the data cleaning criteria. In group-level statistical analysis, statistical analysis was performed for both of channel groups directly relevant to the research question (i.e., central electrodes) and control channels (i.e., parieto-occipital electrodes). In group-level statistical analysis, results of repeated measures ANOVA (5 x 2 x 2 x 2) was performed, and all these ANOVA results were demonstrated in **Table-4.4**. As the only significant result, there was a main effect of topography: suppression was weaker at central sites than at parieto-occipital sites, F (1, 31) = 86.813, p<0.001 and effect size was 0.737 partial eta squared. Estimated marginal means with standard errors relevant to main effect of topography is 85.5, (3.1) % for central electrodes and 52.4, (5.6) % for parieto-occipital electrodes.This difference reflects the known topography of ~10-Hz-reactivity but is not relevant to the research question.

Factor Names and Interactions	**Tests of Within-Subjects Effects**				
Source	DF_n	DF_d	F	Probability Value (p)	Partial Eta Squared
doorcat	4	124	0.428	0.776	0.014
topoC_PO_	1	31	86.813	<.001	0.737
hemiL3R4	1	31	0.8	0.378	0.025
handLR	1	31	0.379	0.542	0.012
doorcat * topoC_PO_	4	124	1.552	0.202	0.048
doorcat * hemiL3R4	4	124	0.615	0.636	0.019
topoC_PO_ * hemiL3R4	1	31	2.468	0.126	0.074
doorcat * topoC_PO_ * hemiL3R4	4	124	0.398	0.787	0.013
doorcat * handLR	4	124	0.741	0.559	0.023
topoC_PO_ * handLR	1	31	0.631	0.433	0.02
doorcat * topoC_PO_ * handLR	4	124	1.48	0.223	0.046
hemiL3R4 * handLR	1	31	1.093	0.304	0.034
doorcat * hemiL3R4 * handLR	4	124	0.138	0.956	0.004
topoC_PO_ * hemiL3R4 * handLR	1	31	0.595	0.446	0.019
doorcat * topoC_PO_ * hemiL3R4 * handLR	4	124	1.637	0.178	0.05

Table-4.4 Group Level Statistical Analysis Results of Time-Frequency Analysis for ERD of mu oscillation (5 x 2 x 2 x 2) through Repeated Measures ANOVA (for both central and parieto-occipital electrodes)

(Greenhouse-Geisser correction was applied where appropriate)
(DF_n = degrees of freedom numerator, DF_d = degrees of freedom denominator, p = probability value, Columns are round to 3 decimal places.)

4.6. DISCUSSION OF TIME-FREQUENCY ANALYSIS OF ERD OF MU OSCILLATION

Although there is only one statistically significant effect as the topography factor among factors or their two-way and three-way interactions however, this result is not relevant to the research question. Thus, the experiment design can be improved by choosing the proper stimuli with the handle, which is more conspicuous. Additionally, stimuli that show required interaction for opening the door can also be used to direct the participants' attention to opening the door. However, in this case, the spontaneity of affordance effect should be considered very well, and proper experiment design methods (e.g., counterbalancing, good control group selection) relevant to repeated measures should be taken into account following considerations of spontaneity. Furthermore, image size can be increased to make the participant feel closer to real situations in daily life (e.g., using virtual reality environments where doors are presented in their real sizes or close to the sizes within daily life).

4.7. DATA PRE-PROCESSING FOR TIME-DOMAIN/TIME-LOCK ANALYSIS OF P100 ERP COMPONENT

Time-domain analysis for P100 ERPs used the same ICA-processed data as described in section 4.3.2. The second pass of amplitude-based rejection, however, was performed for PO7 and PO8, the channels of interest for ERP analysis. In Time-Lock or Time-Domain Analysis for P100 ERP Component *absolute baseline* was used (i.e., subtracting control signal from signal of interest).

4.8. DATA ANALYSIS: TIME-DOMAIN/TIME-LOCK ANALYSIS OF P100 ERP COMPONENT

After completing data pre-processing and cleaning steps, Time-Domain Analysis (i.e., ERP Analysis for P100 ERP component) began. In Time-Domain Analysis, the maximal amplitude of the signal (in defined time window) serves to estimate the strength of the response to a stimulus (Hjorth, 1970; 1973; Van Drongelen, 2018). Channels of interest of ERP Analysis were parieto-occipital electrodes (PO7, PO8). Interaction between handle location (as one of the most conspicuous stimuli) on the doors and visual cortex hemisphere (i.e., left, right) was analysed through FieldTrip Routines and plots of topographic maps. For examining P100 ERP Component as one of the first positive ERP components in the visual cortex, changes of the amplitude of the signal of interest from 90 ms to 120 ms post-stimuli period were examined (i.e., P100 Time-Window).

In experiments with visual stimuli, activation/stimulation of the extrastriate cortex causes P100 ERP Component (Luck et al., 2000; Allison et al., 2002; Perdziak et al., 2014; Sass et al., 2014; Gupta et al., 2020, p.324) and this exogenous ERP component (Shevrin, 1996, p.65; Csibra et al.,

2008; Bott, 2010, p.195; Casanova et al., 2013, p.63; Miller, 2013, p.381; Sokhadze et al., 2013; Wauthia and Rossignol, 2016) appears before saccadic eye movements begin so, this sensory ERP component cannot be contaminated by potentials generated by saccadic eye movements. In general, P100 ERP Component is associated with visual perception and attention (Schubert et al., 2006), especially, visual perception of motion (Ding et al., 2006), faces (Hermann et al., 2005; Marzi and Viggiano, 2007; Dering et al., 2011; Colombatto and McCarthy, 2017; Boutet et al., 2021), body parts (Kovács et al., 2006; Sambo et al., 2009; Hogendoorn et al., 2015), scenes and objects (Schendan and Lucia, 2010; Proverbio et al., 2011; Bieniek et al., 2016; Negrini et al., 2017) also the perception of spatial context (Goffaux et al., 2002; Goffaux et al., 2003; Sambo et al., 2009; Ortiz et al., 2015; Kaiser et al., 2018), emotional content (Utama et al., 2009; Zhang et al., 2017; Gantiva et al., 2020) and semantic categorisation of visual stimuli (Khateb et al., 2002; Davis et al., 2014; Davis et al., 2019). In neuropsychological experiments on affordance, the P100 ERP component is associated with attention to visual features of objects during affordance perception and action processing (Petit et al., 2006; Sambo and Forster, 2009; Goslin et al., 2012; Righi et al., 2014; Wamain et al., 2014; Freeman et al., 2016; Djebbara et al., 2019; Decroix et al., 2020; Ferguson et al., 2021). After completing individual-level data analysis (calculating mean values of amplitudes for P100 ERP component) **(see, Figure-4.5)** and examining the Time-Domain and topographic map plots for contra-laterality between handle location and hemispheric laterality (in both individual-level and group-level analysis) through FieldTrip routines, statistical group-level analysis began.

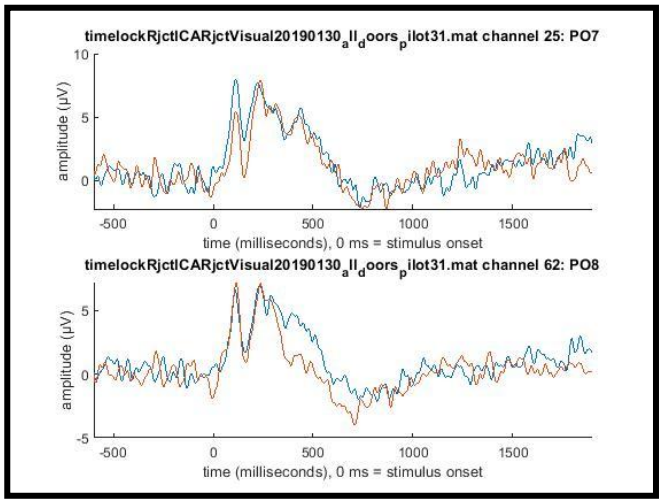

Figure-4.5 Non-(door) Category Specific (all categories lumped together) Timelock Analysis for P100 ERP Waveform (different colours refer for two channels of interest, PO7 and PO8, time of interest: from +90 to +120 ms)

In group-level statistical analysis, parieto-occipital channels (PO7, PO8) was chosen as channels of interest (i.e., channels locating on extrastriate cortex) (Goffaux et al., 2003; Minnebusch et al.,

2010; Soria Bauser et al., 2012; Soria Bauser et al., 2015; Fan et al., 2016). Although EEG is bad at source localisation of neuro-/electro-physiological activity, higher amplitudes of neuro-physiological potentials and activities of the primary visual cortex (V1, striate cortex) and secondary visual cortex (V2, extrastriate cortex) are expected on chosen channels of interest. For group-level statistical analysis, repeated-measures ANOVA was performed with three within-subject factors (i.e., doorcategory (5 levels, as horizontal, knobbed, swinging, lever and vertical), handedness (2 levels, as left and right-hand operation), and hemispheric laterality/channels (2 levels, as parieto-occipital PO7 and PO8)). General Linear Model 5 x 2 x 2 Repeated Measures ANOVA was performed.

4.9. RESULTS OF TIME-DOMAIN/TIME-LOCK ANALYSIS OF P100 ERP COMPONENT

Among the acquired data of 37 participants, the data of 5 participants were excluded because their data did not satisfy the data cleaning criteria. P100 ERP Component analysis was performed for 32 participants' data and amplitude changes within 90-120 ms after stimuli onset was examined. Statistical analysis was performed in two different steps. In the first step, all door categories were combined, and in the second step, each door category was analysed separately (i.e. in the category-specific way).

4.9.1. Analysis Including All Door Categories Combined

In the first step of analysis (i.e., all door categories combined), the significant probability value of two-way interactions between doorcategory and handedness (doorcategory x handedness) was F(4,124)=0.169, p=0.883 (not significant), partial eta squared 0.005; the significant probability value of two-way interactions between doorcategory and channels (PO7, PO8) (doorcategory x channels) was F(4,124)=2.736, p= 0.041 (which is significant), partial eta squared 0.081; and significant probability value of two-way interaction between handedness and channel (handedness x channels) was F(1,31)=29.160, p<0.001 (which is significant), partial eta squared 0.485 **(see, Table-4.5)**. In this regard, a significant contra-lateral effect was found between handle location (visual features of stimuli) and laterality of interest channels (i.e., PO7, PO8) which has already been hypothesized during the experiment design.

Factor Names and Interactions	Tests of Within-Subjects Effects				
Source	DF_n	DF_d	F	Probability Value (p)	Partial Eta Squared
DoorCat	4	124	2.650	0.041	0.079
DoorLHandRHand	1	31	0.151	0.701	0.005
ChanPO7PO8LR	1	31	0.017	0.898	0.001
DoorCat * DoorLHandRHand	4	124	0.169	0.883	0.005
DoorCat * ChanPO7PO8LR	4	124	2.736	0.041	0.081
DoorLHandRHand * ChanPO7PO8LR	1	31	29.160	<.001	0.485

DoorCat * DoorLHandRHand * ChanPO7PO8LR	4	124	3.466	0.016	0.101

Table-4.5 Results of Non-Category Specific Group-level Statistical Analysis (5 x 2 x 2) through General Linear Model Repeated Measures ANOVA
(Greenhouse-Geisser correction was applied where it is appropriated)
(DF_n = degrees of freedom numerator, DF_d = degrees of freedom denominator, p = probability value, Columns are round to 3 decimal places. Significant effects are in coloured.)

In three-way interaction analysis among all factors in non-category specific level, probability value was significant (F (4,124)=3,466, p=0.016, partial eta squared 0.101), which shows some door categories showed handedness x channel interaction and other categories did not. Thus, this result justifies category-specific analysis for the effect of contra-laterality.

After examining the significance within *Tests Within-Subjects Effects* analysis means for each factor and interaction (i.e., two-way and three-way interactions) were obtained as EMMs in SPSS output. Bar graphs of means for the two-way interactions between handedness x channels were plotted **(Figure-4.6)**.

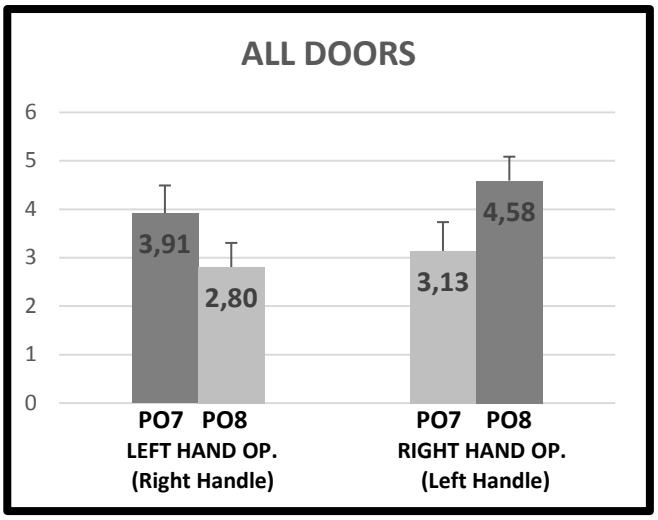

Figure-4.6 Means and SEM of Timelock Analysis for P100 ERP Component for 32 participants (for non-(door) category-specific, all doors combined, handedness x channels) (channels of interest: parieto-occipital PO7 & PO8, time of interest: from +90 to +120 ms)
(Means were obtained as EMMs in SPSS Output)

4.9.2. Separate Analysis for Each Door Category

Similar to non-category-specific analysis, in category-specific analysis, probability values and mean values of two-way interaction between handedness and channels were obtained as EMMs in SPSS output, and bar graphs were plotted. Results for probability values of two-way interaction between handedness (2) and channels (2) for each door category can be listed as; for doors with a horizontal bar was F(1,31)=7.612, p=0.010 (significant), partial eta squared 0.197 **(Table-4.6)**; for doors with a knob was F(1,31)=2.224, p=0.146 (not significant), partial eta squared 0.067 **(Table-**

4.7); for doors with a push plate (swinging doors) was F (1,31)=2.045, p=0.163 (not significant), partial eta squared 0.062 **(Table-4.8)**; for doors with a lever handle was F(1,31)=9.800, p=0.004 (significant), partial eta squared 0.240 **(Table-4.9)**; and for doors with a vertical handle is F=(1,31)=38.874, p<0.001 (significant), partial eta squared 0.556 **(Table-4.10)**.

Factor Names and Interaction	Tests of Within-Subjects Effects (Doors with a Horizontal Bar)				
Source	DFn	DFd	F	Probability Value (p)	Partial Eta Squared
LRHand	1	31	0.192	0.665	0.006
PO7PO8	1	31	1.417	0.243	0.044
LRHand * PO7PO8	1	31	7.612	0.010	0.197

Table-4.6 Results of Category Specific Group-level Statistical Analysis (2 x 2 x 2) through General Linear Model Repeated Measures ANOVA (for doors with a horizontal bar)
(DF_n = degrees of freedom numerator, DF_d = degrees of freedom denominator, p = probability value, Columns are round to 3 decimal places. Significant effects are in coloured.)

Factor Names and Interaction	Tests of Within-Subjects Effects (Doors with a Knob)				
Source	DFn	DFd	F	Probability Value (p)	Partial Eta Squared
LRHand	1	31	0.253	0.618	0.008
PO7PO8	1	31	0.053	0.819	0.002
LRHand * PO7PO8	1	31	2.224	0.146	0.067

Table-4.7 Same as Table-4.5 but for doors with a knob
(DF_n = degrees of freedom numerator, DF_d = degrees of freedom denominator, p = probability value, Columns are round to 3 decimal places.)

Factor Names and Interaction	Tests of Within-Subjects Effects (Doors with a Push Plate/Swinging Doors)				
Source	DFn	DFd	F	Probability Value (p)	Partial Eta Squared
LRHand	1	31	0.022	0.882	0.001
PO7PO8	1	31	0.396	0.534	0.013
LRHand * PO7PO8	1	31	2.045	0.163	0.062

Table-4.8 Same as Table-4.5 but for doors with a push plate/swinging doors
(DF_n = degrees of freedom numerator, DF_d = degrees of freedom denominator, p = probability value, Columns are round to 3 decimal places.)

Factor Names and Interaction	Tests of Within-Subjects Effects (Doors with a Lever Handle)				
Source	DFn	DFd	F	Probability Value (p)	Partial Eta Squared
LRHand	1	31	0.189	0.667	0.006
PO7PO8	1	31	0.068	0.796	0.002
LRHand * PO7PO8	1	31	9.800	0.004	0.240

Table-4.9 Same as Table-4.5 but for doors with a lever handle
(DF_n = degrees of freedom numerator, DF_d = degrees of freedom denominator, p = probability value, Columns are round to 3 decimal places. Significant effects are in coloured.)

Factor Names and Interaction	Tests of Within-Subjects Effects (Doors with a Vertical Bar)				
Source	DFn	DFd	F	Probability Value (p)	Partial Eta Squared
LRHand	1	31	0.220	0.643	0.007
PO7PO8	1	31	1.144	0.293	0.036
LRHand * PO7PO8	1	31	38.874	<.001	0.556

Table-4.10 Same as Table-4.5 but for doors with a lever handle
(DF_n = degrees of freedom numerator, DF_d = degrees of freedom denominator, p = probability value, Columns are round to 3 decimal places. Significant effects are in coloured.)

Thus, these results can be interpreted as; effect of contra-laterality between the conspicuous part of the visual stimuli (as the handle) and ERP P100 component on the channels of the interest was powerful for doors with a vertical bar and doors with a lever handle **(Figure-4.10; Figure-4.11)**, the effect was strong for doors with a horizontal bar **(Figure-4.7)**. The contra-laterality effect was far from significant for doors with a push plate (swinging doors) and doors with a knob **(Figure-4.8; Figure-4.9)**.

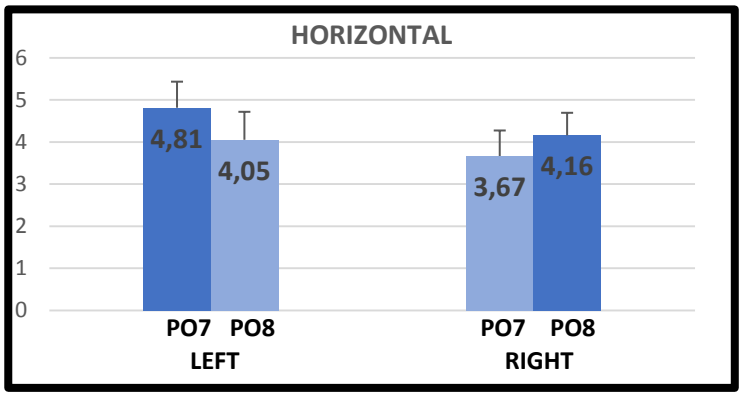

Figure-4.7 Means and SEM of Timelock Analysis for P100 ERP Component (only for doors with a horizontal bar, 32 participants, handedness x channels)
(channels of interest: parieto-occipital PO7 & PO8, time of interest: from +90 to +120 ms)
(Means were obtained as EMMs in SPSS Output)

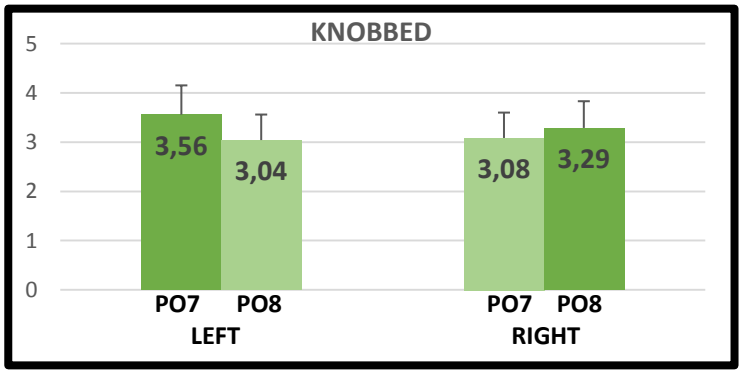

Figure-4.8 Same as Figure-4.6 but only for doors with a knob, (32 participants, handedness x channels)
(channels of interest: parieto-occipital PO7 & PO8, time of interest: from +90 to +120 ms)
(Means were obtained as EMMs in SPSS Output)

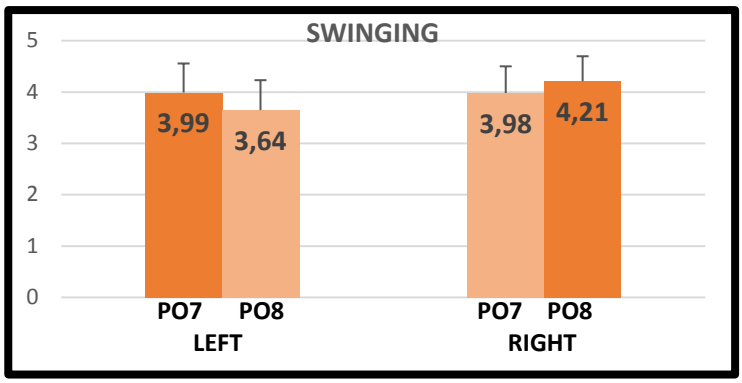

Figure-4.9 Same as Figure-4.6 but only for doors with a push plate/swinging doors, (32 participants, handedness x channels)
(channels of interest: parieto-occipital PO7 & PO8, time of interest: from +90 to +120 ms)
(Means were obtained as EMMs in SPSS Output)

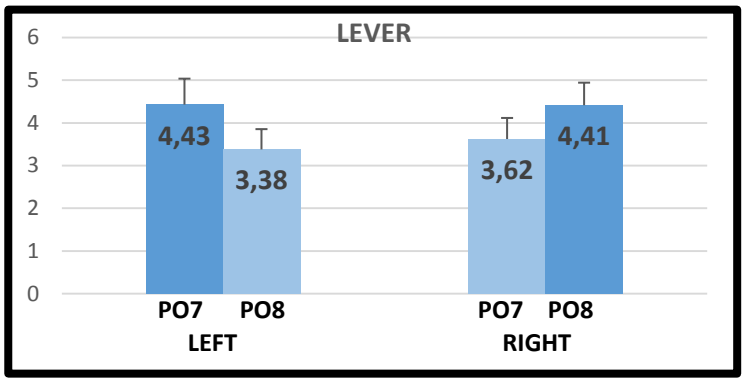

Figure-4.10 Same as Figure-4.6 but only for doors with a lever handle, (32 participants, handedness x channels)
(channels of interest: parieto-occipital PO7 & PO8, time of interest: from +90 to +120 ms)
(Means were obtained as EMMs in SPSS Output)

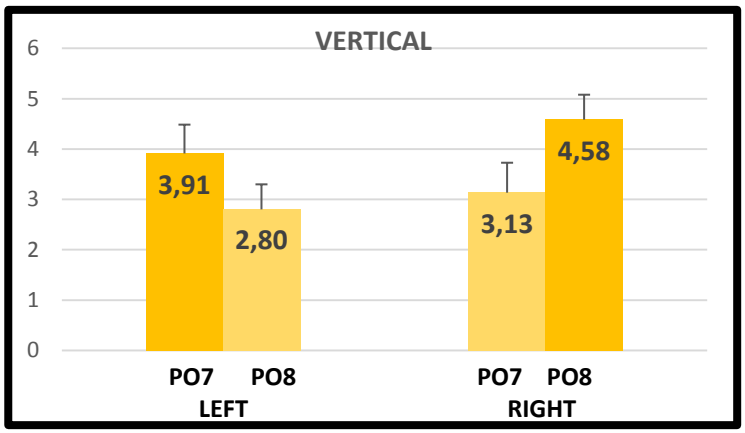

Figure-4.11 Same as Figure-4.6 but only for doors with a vertical bar, (32 participants, handedness x channels)
(channels of interest: parieto-occipital PO7 & PO8, time of interest: from +90 to +120 ms)
(Means were obtained as EMMs in SPSS Output)

4.10. DISCUSSION OF TIME-DOMAIN/TIME-LOCK ANALYSIS OF P100 ERP COMPONENT

Group-level Statistical Analysis for P100 ERP Component on channels of interest of parieto-occipital areas (i.e., PO7 and PO8) in non-category specific level (i.e., all doors combined) demonstrated that there is a significant effect of *contra-laterality* between handle location (visually conspicuous part) and neurophysiological responses (measured as P100 ERP from channels of interest). In other words, there is a critical influence of *ipsi-laterality* between hand operations afforded by door handles for opening the door and event-related neuro-physiological activity of interest (P100 ERP). In category-specific analysis, contra-laterality effect was very strong for doors with a vertical bar and strong enough to satisfy the statistical significance level for doors with a lever handle and doors with a horizontal bar. Statistical analysis of door category-specific laterality effect (handedness x channels) demonstrated that doors with a vertical handle/bar, doors with a lever handle and doors with a push plate (swinging doors) affording right-hand operation (i.e., which have left handle) causes the more vigorous neurophysiological activity of interest (P100 ERP Component). That is seen when compared with their equivalents affording left-hand operation (i.e., which have right handle). Adversely, doors with a horizontal bar and doors with a knob that afford left-hand operation (i.e., which have a right handle) cause the stronger neurophysiological activity of interest (P100 ERP Component) when compared with their equivalents which afford right-hand operation (i.e., which have left handle) in terms of laterality effect.

These results can be interpreted as laterality effect (handedness x channels) is dependent on the size (e.g., vertical bar vs. knob) or degree of conspicuousness (e.g., push plate vs. lever handle) of visual cue (i.e., handle), which changes accordingly with the door category. Additionally to visual features, the degree of familiarity of the participant to a visual cue (i.e., using the type of door in daily life commonly) can also impact the laterality effect. In this regard, even though doors with a knob were similar to doors with a lever handle in terms of their handles' visual features (i.e., size and degree of conspicuousness), the difference between lateralisation of visual perception can explain the effect of familiarity. Interestingly, although doors with a horizontal bar do not have strongly lateralised handles/bars, they have lateralised door lock areas (similar to knobs or lever handles in terms of size and degree of conspicuousness). And, the laterality effect was significant. Additionally, the event-related neurophysiological activity of interest was more substantial for the doors with a right horizontal bar (horizontal bar with right door lock) affording left-hand operation when compared with the equivalents with a left horizontal bar (horizontal bar with left door lock) affording right-hand operation. As expected, the minor laterality effect was detected on swinging doors (doors with a push plate) because there is no handle, and there is either only a

metal push plate or a non-existing cue in terms of hand operation. Additionally, hinges of swinging doors can have a contradicting impact on the laterality effect due to their degree of conspicuousness, and horizontal footplate on the bottom part of some of the swinging doors may have some impact that masks the laterality effect.

5. EXPERIMENT 2 (EEG)

5.1. LITERATURE REVIEW

Second Experiment and Predictions

In the second experiment, neurophysiological aspects of architectural affordance of doors with three different handle and embodied perception/implicit motor imagery will be investigated through ERD of mu oscillation. However, differently from the first experiment, in the second experiment, action observation relevant to (i.e., motor content = 1-grasping, 2-near) architectural affordance has also been examined as an additional category. Action observation or priming can provide additional benefits to cope with truthmaking and perspectivism problems relevant to dissociating visually spatial feature coding and motor program-related affordance grasping in addition to technical limits (e.g., static presentation, problem of realisticity). In addition to previous predictions, by benefitting from function-oriented unifying theories (e.g., common coding theory, event coding theory or embodied/motor simulation theory), action observation can have additional facilitation on perceived affordance relevant characteristics. Thus, additional mirror neuron firing (i.e. motor empathy) can increase this effect (see, Kumar et al., 2013; Wriessnegger et al., 2013; Coll et al., 2015; Drew et al., 2015; Kim and Kim, 2016; Hailperin-Lausch, 2017; Angelini et al., 2018; Bechtold et al., 2018; Sharma et al., 2018; de Vega et al., 2019). In this regard, the predictions relevant to the second experiment can be listed as; 1) in action observation condition (i.e., grasp) relative amplitude of de-synchronized mu oscillation should be less than no-affordance related action observation condition (i.e., near) due to mirror neuron effects (i.e., more powerful activation of cortical area) and additional direction of attention, 2) accordingly category of doors with different handles, there should be changes in the relative amplitude of de-synchronized mu oscillation, 3) laterality of de-synchronized posterior alpha oscillation (which is associated with visual processing) should be contra-lateral with the location of operating hand in images and handle of the door, 4) laterality of de-synchronized central mu oscillation (which is associated with visual processing) should be contra-lateral with the operating hand itself and ipsi-lateral with the location of the handle of the door.

5.2. METHODOLOGY AND EXPERIMENT DESIGN

Data of this experiment was acquired via EEG. EEG is (1) less expensive when compared with other data acquisition methods such as fMRI and MEG and other tomography methods (2) easily applicable (i.e. less requirement of technical expertise and specialization when compared with other neuroimaging methods) (Min et al., 2010; Daly et al., 2013; Reis et al., 2014; Koenig et al.,

2020) and (3) sufficient for studying regions of interest (i.e. the surface of cortical areas) of the experiment (Teplan, 2002; da Silva, 2009). Additionally, (4) good temporal resolution of EEG is also beneficial (Mulert and Lemieux, 2009; Burle, 2015; Beres, 2017) for examining the electrophysiological activity of interest (i.e., event-related de-synchronization of mu oscillation, -an indicator of embodied perception-) of the experiment (Pfurtscheller and Neuper, 1994; Pfurtscheller, 2000; Pineda, 2005; Hari, 2006; Pfurtscheller et al., 2006; Nam et al., 2011; Jeon et al., 2011; Proverbio, 2012; Coello and Iachini, 2015).

30 participants were recruited for data acquisition. However, 19 were used for data analysis because the remaining 11 participants' data could not satisfy data cleaning criteria (see, Chapter 5.3). All participants were right-handed and neurotypical (with no history of neurological or psychiatric problems) and with no history of drug abuse (all by self-report)). The experiment was approved by the ethics committee of the School of Psychology, University of Nottingham (Reference Number: "F978"). After each participant was recruited, Faraday Cage was demonstrated to familiarise them with the experiment environment for a short while. After familiarization with the environment, participants were asked whether they would like to continue or not. All participants gave written informed consent.

Images of doors with three different handles (i.e., lever handle, vertical bar and push plate) under two types of hand interactions as motor content (i.e., interacting for opening, interacting as if touching) were used for this experiment. For this experiment, photos of the doors of different buildings of the University of Nottingham (University Park Campus), all taken by experimenter H.K., were used as the stimuli of the experiment. Some of the door photos, which cannot be seen directly from to front or where the handle area of the door cannot be seen easily, were removed from the potential stimuli set. The remaining images of doors were modified for preparing them as the stimuli of the experiment. These modifications can be listed as; removing texts and numbers, adjusting the degree of brightness, changing the colour of the door or its surroundings, blurring any distracting elements located close to the door, blurring any human reflection or shadows, cleaning any additional graspable element except door handles. All images were modified via online PIXLRPro Software (Pixlr.com, 2021) **(see, Figure-5.1)**. Photos were taken from a wide range of doors over a number of days to exclude systematic variation in any other aspect than door handle location. However, there was no formal assessment of variability.



Figure-5.1 Example Stimuli of the Second Experiment

All stimuli were classified accordingly *three door handle* category (i.e., doors with a lever handle, doors with a vertical bar, doors with a push plate or swinging doors), *two motor content* category which refers to the interaction type (i.e., grasping/opening door-, near/as if touching with no interaction-) and two *laterality* category defines the laterality of handle location (i.e., right handle, left handle). In each three-way interaction among categories (3 door handle x 2 motor content x 2 laterality), 25 images of doors were used. Thus, 300 images of doors were used for the main stimuli of the experiment.

On top of the 300 stimuli, 32 further stimuli (~10% of 300) were used for the oddball task of the experiment (Friedman et al., 1998; Gaeta et al., 2003; Kiehl et al., 2005; Brown et al., 2009; Noyce and Sekuler, 2014; Sanger and Dorjee, 2016). Two categories of main stimuli (i.e., motor content and laterality) -except door category- were used to classify stimuli of the oddball task. Thus for each two-way interaction between categories (2 motor content x 2 laterality), 8 door images where the experimenter touched (or as if touch) the door's hinges were used. Like the main stimuli of the experiment, all images of doors were prepared by completing required modifications of taken photos of doors belonging to different buildings of the University of Nottingham. Totally 332 images of doors (300 as main stimuli, 32 oddball stimuli of the experiment) were presented to participants for data acquisition of this experiment **(Table-5.1).**

Interaction Category	Door Category	Laterality Category	Example Stimuli
GRASPING	LEVER	Right Hand Operation	
		Left Hand Operation	
	SWINGING	Right Hand Operation	
		Left Hand Operation	
	VERTICAL	Right Hand Operation	
		Left Hand Operation	
NOT APPROACHING	LEVER	Right Hand Operation	
		Left Hand Operation	
	SWINGING	Right Hand Operation	
		Left Hand Operation	
	VERTICAL	Right Hand Operation	
		Left Hand Operation	
ODDBALL	HINGES	-----(????)	

Table-5.1 Stimuli Categories of the Experiment (25 images of doors in each main stimuli category, 8 images of doors in each oddball stimuli category, total 332 stimuli)

In addition to main experiment, a demo experiment was designed for familiarization of the participants to the main experiment. For the demo version of the experiment, the three door images were used for each main stimuli category (3 door handle x 2 motor content x 2 laterality) and one door image for each task stimuli category (2 motor content x 2 laterality). Totally, 40 stimuli were used for designing the demo version of the experiment. All of the stimuli of the main experiment and the demo version of the experiment were different from each other for avoiding repetition suppression (repeating the presentation of the same stimuli can trigger some memory related processes which can potentially suppress EEG responses). None of the demo stimuli was

shown in the main experiment. (Schacter and Buckner, 1998; Grill-Spector et al., 2006; Summerfield et al., 2008; Horner and Henson, 2008; Garrido et al., 2009; Engell and McCarthy, 2014). Images were presented to the first fifteen participants to counterbalance visual differences of images according to the handle location (laterality category). Moreover, their flipped versions were presented to the remaining fifteen participants. Both the demo version and the main experiment were designed via PsychoPy 2 version 1.90.3 (Peirce et al., 2019).

In terms of experiment design, each stimulus (i.e., each door image) was presented for 2 s and between each stimulus. A fixation cross was presented for fixation of the participant's gaze to the centre of the monitor. Duration of fixation cross was varied from 0.5 s to 2 s randomly to avoid participants estimating the presentation time of the following stimuli of the main experiment. All stimuli and fixation cross were presented on the centre of a uniform grey background **(see, Figure-5.2)**. Stimuli were presented with fixed height, which were 15.83 cm for the main experiment and 10.68 cm for the demo version of the experiment. Stimuli width was changed from 3.24 cm to 10.25 cm in the main experiment and from 2.19 cm to 6.91 cm in the demo version of the experiment. For each category of the main experiment, one trigger code (totally 13 trigger codes) was defined, which would be multipliers of the eight to make trigger codes suitable for a parallel port system.

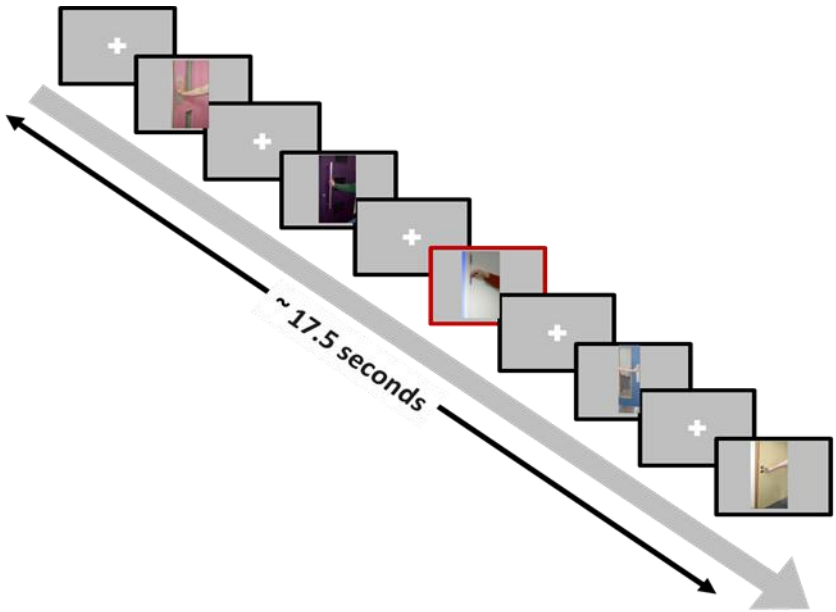

Figure-5.2 Flow of the Experiment (sequence of the Stimuli Presentation within half of the block)

Stimuli of the demo version of the experiment were presented on the laptop screen of the experimenter (HP 250 G3 Intel Core, 1366 x 768 pixels, 15.6”, 60 Hz refresh rate). Stimuli of the main experiment were presented on the computer’s screen (Samsung, ViewPixx3D, 1920×1080

pixels, 23.6”, 120Hz refresh rate, 1ms pixel response time) locating at Faraday Cabin (2.5 x 2.3 x 2.3 m), at a quiet room with an ambient temperature, in EEG Laboratory of the University of Nottingham. Faraday Cabin provides insulation from the contamination and interference of electromagnetic fields generated by different sources outside the Cabin during the data acquisition process. In the main experiment, the distance between participants and the screen was adjusted to 80 cm, where the visual angle was between 7° 19' and 2° 19' on the horizontal axis and was 11° 18' on the vertical axis **(Table-5.2)**.

Stimuli Presentation Details of the Experiment	**Main Experiment**		**Demo Experiment**	
Technical Aspects of the Monitor	ViewPixx3D, 1920×1080 pixels, 23.6”, 120Hz refresh rate		HP 250 G3 Intel Core, 1366 x 768 pixels, 15.6”, 60Hz refresh rate	
Monitor Size (x, y)	51 cm x 28.5 cm		34.4 cm x 19.4 cm	
Distance from Monitor	~ 80 cm		~ 60 cm	
Numbers of the Stimuli	332 (25x12 experiment category +8x4 task category/oddball)		40 (3x12 experiment category +1x4 task category/oddball)	
Stimuli Width (x-axis)	Maximum	10.25 cm	Maximum	6.91 cm
	Minimum	3.24 cm	Minimum	2.19 cm
Stimuli Height (y-axis)	15.83 cm		10.68 cm	
Visual Angle (Horizontal)	Maximum	7° 19'	Maximum	6° 35'
	Minimum	2° 19'	Minimum	2° 5'
Visual Angle (Vertical)	11° 18'		10° 10'	

Table-5.2 Stimuli Presentation Details of the Experiment (Main Experiment and its Demo Version)

In both the main and demo version of the experiment, the flow of the experiment was divided into blocks, and each block contained ten stimuli. All of the stimuli were presented in pseudo-randomized order. The main experiment contained 33 blocks and additional 2 stimuli. It took approximately 28 minutes. The task of the experiment was counting the numbers of doors where their hinges were grasped or as if grasped (oddball stimuli). At the end of each block, the text as “Block n finished. Please Report the Number” (n=ordinal number of each block) was presented on the screen for 10 seconds. As soon as the participants saw this text on the screen, they shouted the number of oddball stimuli which they counted in the ending block **(see, Figure-5.3)**. The experimenter recorded reported numbers to examine the degree of attention of the participants throughout the experiment process. Most of the participants performed the task with 100 percent accuracy.

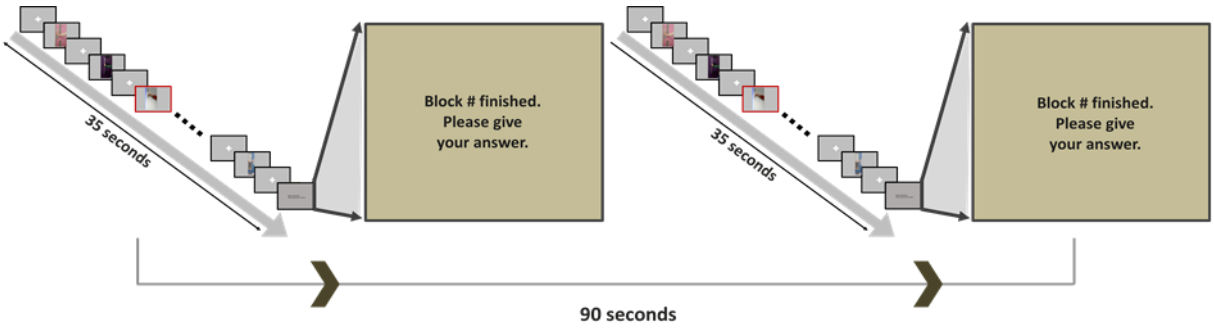

Figure-5.3 Flow of the Experiment (sequence of the Stimuli Presentation across two blocks)

5.3. DATA ACQUISITION, PRE-PROCESSING AND CLEANING

Before the main experiment began, participants were prepared for the experiment. The preparation process was as for Experiment 1. In the preparation process, 6 Ag/AgCl flat-type electrodes with individual lead connectors (FLAT Active electrodes. BioSemi.com, 2021) were placed on mastoids, temporal and sphenoid bones (M1, M2, F9, F10, T9, T10) to study electro-oculographic activity and re-referencing in offline data pre-processing step. After placing flat-type electrodes, a BioSemi electrode cap (Headcaps. BioSemi.com, 2021) was chosen according to the perimeter of the participants' head and placed on the scalp to keep impedances below 20 kΩ. Electrolyte gel was applied to electrode areas on the cap for conductivity. Then, two pin-type electrode sets, including 32 pin type electrodes (Pin-Type Active-electrodes. BioSemi.com, 2021) in each set, were placed on the BioSemi electrode cap for data acquisition. After completing the placement of the electrode cap and electrodes, the participant was requested to sit in the Faraday Cabin. The Cabin light was adjusted to a fixed position for all participants, resulting in the cabin's dim light. This aimed to prevent participants sleepiness and to prevent the widespread and powerful posterior alpha oscillations, typically associated with eyes open in darkness or eyes closed (Cantero et al., 2002; Scammell et al., 2017; De Gennaro, 2001; Knaut et al., 2019; Tran et al., 2020). Such oscillations can mask local and less powerful mu oscillation (i.e., frequency of interest of the experiment) (Andrew and Pfurtscheller, 1997; Niedermeyer, 1997; Pfurtscheller et al., 2000; Benbadis, 2015; Yin et al., 2016; Thorpe et al., 2016). The reason for preventing the masking of posterior alpha oscillation is that some components of Rolandic arc-shaped mu rhythm (8-12/13 Hz) (Cohen-Séat et al., 1954; Gastaut and Bert, 1954) have similar frequencies with alpha rhythm (7.5–13 Hz) (Berger, 1929). For additional lighting of Faraday Cabin, a Daffodil USB LED light (model: LEC150) was used.

After required adjustments of experiment environment (e.g., the position of participant, task instructions, lighting level), data acquisition devices were controlled (i.e., StimTracker device (StimTracker. Cedrus.com, 2021), ActiveTwo Biosemi Amplifier (ActiveTwo AD-box. BioSemi.com,

2021). As the last step of preparation, the normalized/referenced/relativized mean values of electrode offsets (which should be less than ±20 mV as the indicator of good electrode setup for data acquisition) (Zanto et al., 2010; Zanto et al., 2011; Muangjaroen and Wongsawat, 2012; Stewart et al., 2014; Albares et al. 2014; Saad et al., 2016; Kang et al., 2017; Jegadeeshwari and Nithya, 2019; Undurraga et al., 2021) and the monopolar display of Active View system (ActiView.BioSemi.com, 2021) were controlled to understand whether electrodes were working efficiently or not. And then, the data acquisition process began.

Raw EEG data were acquired using a 64-channel extended 10-20 Active-Two acquisition system (BioSemi, Amsterdam, Netherlands), sampled at 1024 Hz (which is well above than the required Nyquist rate to study classic EEG bands from delta to beta but prevents unnecessarily large data file sizes), and digitised at 24-bits and recorded via ActiView 705 (version 8.6.1) (ActiView. BioSemi.com, 2021). Trigger codes of each stimulus category were sent and synchronized with the acquired data via a Cedrus Stimtracker (StimTracker.Cedrus.com, 2021) and USB 2.0 Receiver (Receiver.BioSemi.com, 2021) during the process of the main experiment. Trigger codes are beneficial for segmenting and grouping/classifying the data of defined stimuli categories of the experiment during offline data pre-processing and analysis (Oostenveld et al., 2011; see also, Badier et al., 2016).

After completing data acquisition, offline signal processing began. Offline signal processing can be divided into two categories as (1) data pre-processing & cleaning and (2) ERS/ERD data analysis (both individual-level and group-level data analysis). All individual-level offline signal processing steps (i.e., data pre-processing & cleaning and data analysis) were performed in Matlab (The MathWorks Inc., Natick, MA) using Fieldtrip routines (Oostenveld et al., 2011). The group-level statistical analyses were performed via SPSS. General linear model repeated measures of ANOVA (Rutherford, 2011; Vik, 2013; Crowder and Hand, 2017) were performed for examining statistical significance (tests of within subjects) (Greenwald, 1976) and mean values of statistically significant factors and interactions were obtained as estimated marginal means (Searle et al., 1980).

In offline data pre-processing, the data was segmented according to the trial definition. Then, the data were filtered from frequencies that are out of interest and re-referenced to the average value of potentials of 64 electrodes on the electrode cap and corrected to baseline (normalization of the signal of interest to a defined control signal accordingly correction method) to reduce the effects of temporal drifts within continuous data (Cohen, 2014, p. 71-86; Bigdely-Shamlo et al., 2015; Rogasch et al., 2017; Hari and Puce, 2017, Kim, 2018; Peng, 2019). By benefitting from trigger codes (which defines time points of stimuli onset), the time window of trials was defined

from 600 ms before stimuli onset to 1900 ms after stimuli onset (for mechanisms of time window definition criteria, see Methodology Chapter and Experiment 1 Chapter). According to the time window definition of trials, data was segmented to examine the electrophysiological activity of interest (i.e. de-synchronization/suppression of mu oscillation) (Procházka et al., 2010; Cohen, 2014, p. 75-78; Clerc, 2016, p.105-106; Peng, 2019). After segmentation, frequencies of which band ranges were above than 39 Hz (low-pass filtering) and were below than 0.35 Hz (high-pass filtering) was filtered from the data (Kamp et al., 2005; Hari and Puce, 2017 p. 89-95; Rogasch et al., 2017; Baranowski and Piątek, 2017; de Cheveigné and Nelken, 2019; Peng, 2019).

Thanks to two electrodes (CMS & DRL) referencing data acquisition system, the BioSemi system allows reference-free recordings and after segmentation and filtering (Massar et al., 2014; Wessel and Aron, 2015; Derosiere et al., 2015; Balaban and Luria, 2016; Hartmann et al., 2016; Mahajan et al., 2017; Barham et al., 2017; Wisniewski et al., 2017; Ball et al., 2017; Fargier et al., 2018; Welcome and Trammel, 2018; Wisniewski et al., 2018; Dogge et al., 2019; Silas et al., 2019; Wilson and Foxe, 2020; Palluel et al., 2020; Pascucci et al., 2021), Common Average Referencing was performed. In this re-referencing method, the mean amplitude of electrophysiological data, which was acquired by each channel in each time point, was re-referenced/relativized/normalized to the average mean amplitude of electrophysiological data acquired by all channels (64 channels) in each time point (Offner, 1950; Osselton, 1965; McFarland et al., 1997; Essl and Rappelsberger, 1998; Teplan, 2002; Lakshmi et al., 2014; Kim and Im, 2018; Tsuchimoto et al., 2021). And then, normalization of activity of interest signal to control/baseline signal within each defined trial was performed accordingly chosen normalization method (i.e., baseline correction) (Maess et al., 2016) to avoid potential drifts emerging over time or direct current offsets (Bijma et al., 2003; Alday, 2019; Zhang et al., 2020). Time window width of baseline/control signal was defined from 300 ms in the pre-stimulus period to stimulus onset.

After these steps data was cleaned from physiological and non-physiological artefacts through Fieldtrip routines and independent component analysis (ICA). Amplitude-based rejection was performed. In each visual inspection cleaning, the amplitude-based rejection was performed as the part of visual inspection script of FieldTrip. In the first amplitude-based rejection step (Visual artifact rejection. Fieldtriptoolbox.org, 2021; FT_REJECTVISUAL. Fieldtriptoolbox.org, 2021), bad trials of which variance of average amplitude is above 300 μV^2 was rejected from the data set to eliminate heavily contaminated trials by EOG activity. Eliminating heavily contaminated trials is a crucial step for the efficient performance of ICA for artefact rejection (avoiding high amplitude artefacts which can cause difficulties on de-/re-composition processes of ICA and detection of more minor artefacts due to potential masking). Thus, 300 μV^2 was chosen as the upper limit

criterion for EOG artefacts before ICA (Delorme et al., 2005; Delorme et al., 2007; Eichele et al., 2010; Fung et al., 2012; Torppa et al., 2012; Law et al., 2013; Turnip and Junaidi, 2014; Tavakoli and Campbell, 2015; Bell et al., 2016; Lindström et al., 2016; Dube et al., 2016; Cruz-Garza et al., 2017; Affanni et al., 2019; Marini et al., 2019; Di Gregorio et al., 2019; Grosselin et al., 2019). In the same cleaning process, participants' datasets, including more than 10% of such trials, were excluded from general data analysis. Thus, among 30 participants, 11 ones were excluded. (Tavakoli and Campbell, 2015; Cruz-Garza et al., 2017; Marini et al., 2019; Grosselin et al., 2019).

ICA was performed for the remaining 19 participants, using data downsampled from 1024 Hz to 300 Hz to reduce file size and speed of processing (Van Dun et al., 2007; Maidhof et al., 2009; Viola et al., 2010; Bowers et al., 2014; Falco et al., 2014; Jenson et al., 2015; Duann and Chiou, 2016; Rogasch et al., 2017; Gallicchio and Ring, 2019; Issa et al., 2019; Zhang et al., 2021). Eye blinks were removed from data through the runica algorithm of ICA within FieldTrip routines. ICA allows certain physiological artefacts to be isolated as one component and corresponding topographic map (Makeig et al., 1997; Sanei and Chambers, 2013, p.83-103; Delorme et al., 2007; Cong, 2019). Runica algorithm (FT_COMPONENTANALYSIS. Fieldtriptoolbox.org, 2021) is sufficient to isolate artefacts as independent and isolated components through the infomax ICA algorithm (Bell and Sejnowski, 1995), the natural gradient learning algorithm (Amari et al., 1996) and the Principal Component Analysis dimension reduction and/or spectrogram pre-processing (Zibulevsky and Pearlmutter, 2001; Zhen et al., 2016).

After ICA, the second pass of amplitude-based rejection was performed, with analysis restricted to channels of interest (i.e., fronto-central channels, (FC3, FC4), central channels (C3, C4), centro-parietal (CP3, CP4) and parieto-occipital channels (PO3, PO4). In this cleaning process, trials exceeding a variance of relative amplitude threshold of 100 μV^2 were eliminated. Variance of recorded amplitude above 100 μV^2 would possibly be either heavily contaminated EEG, other electrophysiological activity (i.e., EOG, ECG or EMG), or any EEG activity that is out of this experiment's interest. (Delorme et al., 2005; Zeman et al., 2007; McMenamin et al., 2010; Perry et al., 2011; Savelainen, 2010; Solé-Casals et al., 2010; Benito Núñez, 2011; Cong et al., 2011; Winkler et al., 2011; Plöchl et al., 2012; Cassani et al., 2014; Ghaderi et al., 2014; Sheoran et al., 2014; Borse, 2015; Kumar and Kareemullah, 2014; Tavakoli and Campbell, 2015; Hu et al., 2015; Paradeshi and Kolekar, 2017). The remaining data were subject to ERD/ERS analysis.

5.4. DATA ANALYSIS: TIME-FREQUENCY ANALYSIS OF ERD OF MU OSCILLATION

In Time-Frequency Analysis for examining amplitude changes (i.e., level of suppression) of de-synchronization/ suppression of mu oscillation on the primary motor cortex (Brodmann Area 4)

(Tiihonen et al., 1989; Arroyo et al., 1993; Pfurtscheller and Neuper, 1994; Schnitzler et al., 1997; Penny et al., 1998; McFarland et al., 2000; Neuper and Pfurtscheller, 2001a; Hari, 2002; Muthukumaraswamy and Johnson, 2004a; MacKay, 2005; Hari, 2006; Pfurtscheller et al., 2006; Anderson and Ding, 2011; Kumar et al., 2013; Cannon et al., 2014; Hari et al., 2014; Fox et al., 2016; Coll et al., 2017; Debnath et al., 2019), power spectrum of channels of interests as output configuration of the signal of interest (channel x frequency x time) was computed to quantify the level of oscillation (Blanco et al., 1995; Al-Fahoum and Al-Fraihat, 2014; DelPozo-Banos et al., 2015; Puranik et al., 2018; Zhang, 2019; FT_FREQANALYSIS. Fieldtriptoolbox.org, 2021; Time-frequency analysis. Fieldtriptoolbox.org, 2021). For tapering the segmented data within each defined time-frequency spectrogram, Hanning windowing was used (FT_FREQANALYSIS. Fieldtriptoolbox.org, 2021; Percival and Walden, 1993; Mitra and Pesaran, 1999). In order to increase the efficiency in terms of decreasing the spectral leak and data loss, multitaper convolution was performed (Kaskarovska, 2005; van Vugt et al., 2007; Babadi and Brown, 2014; Cohen, 2014, p. 203-210; van Drongelen, 2018, p. 153-180; Zhang, 2019). Multitaper convolution implements multitaper frequency transformation based on multiplication in the frequency domain (Cohen, 2014, p. 203-210; Karnik et al., 2021; mtmconvol method. Fieldtriptoolbox.org, 2021). Time-Frequency spectrograms were sampled at a 0.2 Hz rate in the frequency domain and a 5 ms rate in the time domain.

Event-Related Synchronizations (ERS) and Event-Related De-synchronizations (ERD) are non-phase locked or induced responses (Da Silva, 2006; see also, Kalcher and Pfurtscheller, 1995; Pfurtscheller and Da Silva, 1999; Neuper and Pfurtscheller, 2001a; Penny et al., 2002; Makeig et al., 2004; Shah et al., 2004; Sauseng et al., 2007; Crone et al., 2008; Bastiaansen et al., 2011; Başar and Gölbaşı, 2014). Although underlying mechanisms of ERD/ERS have not been widely understood yet, mu and alpha band range synchronizations and de-synchronizations are associated with different neural populations' inhibitory and excitatory synaptic activities. These populations form a feedback loop between the thalamo-cortical relay (TCR) (inhibitory, hyperpolarized) and reticular nucleus (RN) (excitatory, depolarized) neurons (Pfurtscheller and Da Silva, 1999; Suffczynski, 1999; Neuper and Pfurtscheller, 2001a; Suffczynski et al., 2001; Da Silva, 2006; Pfurtscheller, 2006; Klimesch et al., 2007; Takemi et al., 2013). These feedback loops are crucial for gating function for several cognitive mechanisms (i.e., sensory/attention/perception/ information processing gating and so on) (MacKay, 1997; Pfurtscheller, 2003; Da Silva, 2006; Neuper et al., 2006; Anderson and Ding, 2011; Foxe and Snyder, 2011; Popov et al., 2011; Buchholz et al., 2014; Cheng et al., 2016; Dipoppa et al., 2016; Forschack et al., 2017; Hsiao et al., 2018; Fodor et al., 2020; Limanowski et al., 2020; Wiesman and Wilson, 2020).

Although the topographic definition of electrophysiological activity of interest (i.e., mu oscillation) is widespread over the primary motor cortex, it is typically detected on central electrodes (C3, C4), which are located on areas of the primary motor cortex associated with hand representation (Pfurtscheller et al., 1994; Pfurtscheller et al., 1996; Pfurtscheller et al., 1997a; Pfurtscheller et al., 1997b; Pfurtscheller et al., 2000; Ramoser et al., 2000; Babiloni et al., 2002; Bai et al., 2005; Neuper et al., 2005; Pfurtscheller et al., 2006; Yeom and Sim, 2008; Neuper et al., 2009; Perry et al., 2011; McGarry et al., 2012; Yi et al., 2013; Nakayashiki et al., 2014; Yi et al., 2016; Hommelsen et al., 2017; Bartur et al., 2019). Additionally, channels which are on the same anterior-posterior axis as central electrodes were included (i.e., C3, C4) on the head topography (from anterior to posterior) were also included to Time-Frequency analysis to examine cross-modal neural interactions (Muthukumaraswamy and Johnson, 2004b; Muthukumaraswamy et al., 2004; Pineda, 2005; Hari, 2006; Oberman et al., 2007; Ulloa and Pineda, 2007; McGarry et al., 2012; Sabate et al., 2012; Umiltà et al., 2012; Kumar et al., 2013; Cannon et al., 2014; Heimann et al., 2014; Jenson et al., 2014; Rüther et al., 2014; Coll et al., 2017) (especially between visual perception and motor imagery/embodied perception) (Pfurtscheller and Neuper, 1994; Pfurtscheller and Neuper, 1997; McFarland et al., 2000; Pfurtscheller et al., 2006; Xiaojing et al., 2008; Neuper et al., 2009; Neuper et al., 2010; Tangwiriyasakul et al., 2013; Li et al., 2015; Sivakami and Devi, 2015; Eaves et al., 2016; Bechtold et al., 2018; Toriyama et al., 2018) and to understand electro-physiological activity changes across head topography. Chosen channels are fronto-central (FC3, FC4), centro-parietal (CP3, CP4) and parieto-occipital (PO3, PO4) channels (see for cerebral locations of International 10-20 EEG system, Homan et al., 1987; Homan, 1988; Steinmetz et al., 1989; Towle et al., 1993; Silva et al., 2020). In this PhD project, statistical analysis was limited to channels locating on primary motor cortex (C3, C4) as the typical location of ERD of mu oscillation and the ones locating on extrastriate visual cortex (PO3, PO4) as the typical location of ERD of posterior alpha oscillation (Van Der Helden et al., 2010; ter Horst et al., 2013; Chaumon and Busch, 2014; Kourtis and Vingerhoets, 2015; Bouchra et al., 2016; Lim and Ku, 2018; Fabre et al., 2021).

Furthermore, the electrophysiological activity of interest (i.e., mu oscillation) have two different frequency band range components (i.e., similar frequency band ranges with alpha rhythm (7.5–13 Hz) and with beta rhythm (15-25 Hz)) and these two components synchronize and de-synchronize concomitantly (Pfurtscheller, 1981; Pfurtscheller et al., 1994; Pfurtscheller et al., 1996; Leocani et al., 1997; Pfurtscheller et al., 1997a; Schlögl et al., 1997; Crone et al., 1998; McFarland et al., 2000; Pfurtscheller, 2000; Pfurtscheller et al., 2000; Neuper and Pfurtscheller, 2001b; Babiloni et al., 2002; Pfurtscheller et al., 2006; Xiaojing et al., 2008; Neuper et al., 2009;

Pfurtscheller and Neuper, 2009; Nam et al., 2011; Moore et al., 2012; Cannon et al., 2014; Rüther et al., 2014; Li et al., 2015; Cuellar et al., 2016; Angelini et al., 2018; Tariq et al., 2018; Bartur et al., 2019; Démas et al., 2020; Jenson et al., 2020). However, components that have a similar frequency band range with alpha rhythm (7.5–13 Hz) showed de-synchronization. Thus, frequency of interest was defined 8 to 13.2 Hz (Tiihonen et al., 1989; Nikouline et al., 2000; Bernier et al., 2014; Cannon et al., 2014; Muthukumaraswamy et al., 2004; Moore et al., 2012; Braadbaart et al., 2013; Cuellar et al., 2016; Fox et al., 2016; Hommelsen et al., 2017; Garakh et al., 2020; see also Pfurtscheller et al., 2000) and time window of interest was defined from 200 ms to 500 ms after stimuli onset by benefitting from Time-Frequency spectrograms. The time window was defined for baseline correction from (-)300 ms to ±0 ms within pre-stimulus period. Norm change type normalization method (namely, baseline correction method) was performed for Time-Frequency Analysis (ERD/ERS Analysis) where absolute baseline correction (subtracting control signal from signal of interest) normalized by the total value of the whole signal's power within each defined trials (FT_FREQBASELINE. Fieldtriptoolbox.org, 2021, see also, Feige, 1999, p. 71-103; Cohen, 2014, p. 217-240; Dickter and Kieffaber, 2013; p. 116-137).

By benefitting from defined time windows (for both baseline and electrophysiological activity of interest) and frequency band ranges within each spectrogram of each trial belong to channels of interests of each participant, mean values of amplitude changes relative to pre-stimulus baseline (i.e., ERD Time Courses) was calculated statistically to examine suppression levels across participants and factors (i.e., (1)door categories, (2)motor content, (3)laterality of handle location/handness, (4)hemispheric laterality, (5)channels (central vs. parieto-occipital, for comparison)). For group-level statistical analysis, each participant's data was analyzed through SPSS. In group-level statistical analysis, General Linear Model Repeated Measures ANOVA was performed. P values within *tests of within-subject effects* (showing statistical significance) were examined to understand the effects of factors and their different way interactions, and mean values of statistically significant factors and interactions were obtained as estimated marginal means in SPSS output.

5.5. RESULTS OF TIME-FREQUENCY ANALYSIS OF ERD OF MU OSCILLATION

In group-level statistical analysis, channel-specific/channel by channel General Linear Model Repeated Measures ANOVA (3 x 2 x 2 x 2 x 2) was performed. Statistically significant factors and interactions were examined and their mean values were obtained as EMMs in SPSS output. In this group-level statistical analysis, factors were defined as 3-level *door category* factor (i.e., doors with a vertical bar, doors with a lever handle, doors with push plate/swinging door), 2-level *handle* factor (i.e., doors with a handle locating on the left side of the door, doors with a handle

locating on the right side of the door), 2-level *hemisphere* factor (i.e., channels on right hemisphere, channels on left hemisphere), 2-level *channel within hemisphere* factor (i.e., central(C) and parieto-occipital (PO)). In this ANOVA Analysis, a statistical significance within *tests of within-subject effects* was found in some factors and some of the interactions of factors. Among factors, door category (F (2, 36) = 5.811, p=0.011 and partial eta squared 0.244), handle (F (1, 18) = 7.252, p=0.015, partial eta squared 0.287) and channel within hemisphere (F (1, 18) = 18.876, p=0.000, partial eta squared 0.512) were statistically significant. Among two-way interactions, door category x channel within hemisphere (F (2, 36) = 2.78, p=0.089, partial eta squared 0.134) was statistically significant. Among three-way interactions, motor content x handle x hemisphere (F (1, 18) = 7.605, p=0.013, partial eta squared 0.297) and handle x hemisphere x channel within hemisphere (F (1, 18) = 3.252, p=0.088, partial eta squared 0.153) were statistically significant. All these ANOVA results were demonstrated in **Table-5.3**.

Factor Names and Interactions	**Tests of Within-Subjects Effects (For Two Channel Groups; C, PO)**				
Source	DF_n	DF_d	F	Probability Value (p)	Partial Eta Squared
doorcategory	2	36	5.811	0.011	0.244
motorcontent	1	18	1.391	0.254	0.072
handle	1	18	7.252	0.015	0.287
hemisphere	1	18	0.371	0.55	0.02
channelWithinHemi	1	18	18.876	<.001	0.512
doorcategory * motorcontent	2	36	0.201	0.779	0.011
doorcategory * handle	2	36	0.516	0.583	0.028
motorcontent * handle	1	18	2.453	0.135	0.12
doorcategory * motorcontent * handle	2	36	1.087	0.337	0.057
doorcategory * hemisphere	2	36	0.111	0.86	0.006
motorcontent * hemisphere	1	18	1.364	0.258	0.07
doorcategory * motorcontent * hemisphere	2	36	1.537	0.231	0.079
handle * hemisphere	1	18	0.575	0.458	0.031
doorcategory * handle * hemisphere	2	36	0.564	0.571	0.03
motorcontent * handle * hemisphere	1	18	7.605	0.013	0.297
doorcategory * motorcontent * handle * hemisphere	2	36	0.841	0.439	0.045
doorcategory * channelWithinHemi	2	36	2.78	0.089	0.134
motorcontent * channelWithinHemi	1	18	0.307	0.587	0.017
doorcategory * motorcontent * channelWithinHemi	2	36	0.754	0.473	0.04
handle * channelWithinHemi	1	18	0.004	0.949	<.001
doorcategory * handle * channelWithinHemi	2	36	0.567	0.562	0.031
motorcontent * handle * channelWithinHemi	1	18	0.041	0.841	0.002
doorcategory * motorcontent * handle * channelWithinHemi	2	36	0.752	0.473	0.04

hemisphere * channelWithinHemi	1	18	0.204	0.657	0.011
doorcategory * hemisphere * channelWithinHemi	2	36	1.182	0.313	0.062
motorcontent * hemisphere * channelWithinHemi	1	18	1.965	0.178	0.098
doorcategory * motorcontent * hemisphere * channelWithinHemi	2	36	0.289	0.709	0.016
handle * hemisphere * channelWithinHemi	1	18	3.252	0.088	0.153
doorcategory * handle * hemisphere * channelWithinHemi	2	36	1.234	0.3	0.064
motorcontent * handle * hemisphere * channelWithinHemi	1	18	0.235	0.634	0.013
doorcategory * motorcontent * handle * hemisphere * channelWithinHemi	2	36	0.885	0.42	0.047

Table-5.3 Results of Channel Specific Group-level Statistical Analysis (3 x 2 x 2 x 2 x 2) through General Linear Model Repeated Measures ANOVA
(Greenhouse-Geisser correction was applied where it is appropriated)
(DF_n = degrees of freedom numerator, DF_d = degrees of freedom denominator, p = probability value, Columns are round to 3 decimal places. Significant effects are in coloured.)

Regarding the significant main effect of door category (p=0.011), it is noteworthy that there is also a trend on the interaction between door category and channel within hemisphere (p=0.089). Therefore, follow-up ANOVAs were run, first for central electrodes C3 and C4 only (door category: F(2,36)=9.173, p=0.001), then for parieto-occipital electrodes PO3 and PO4 only (door category: F(2,36)=1.636, p=0.215). Therefore **Figure-5.4** (left panel) shows mean values and SEM for each door category for central electrodes only. For doors with a lever handle, mu oscillations were suppressed to 78.6%, for doors with a vertical bar were suppressed to 81.1%, and for doors with a push plate (swinging doors) were suppressed to 86.3%. The result shows an effect of door handle type on mu suppression that is topographically defined, observable at central electrodes without a corresponding effect on occipital ~10 Hz oscillations. The significant main effect of handle location (p=0.015) is illustrated in **Figure-5.4** (right panel) for parieto-occipital electrodes although it was comparably strong at central electrodes. At PO3 and PO4, doors with a handle locating on the left side of the door suppressed alpha oscillations to 61.9% and doors with a handle locating on the right side of the door to 58.8%.

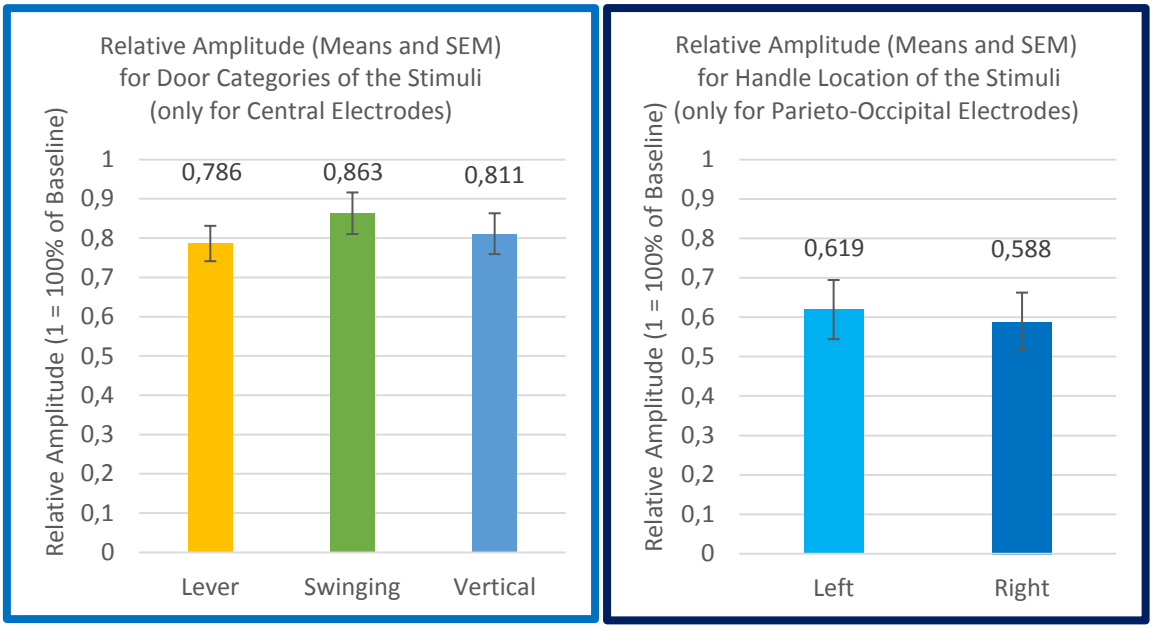

Figure-5.4 Relative amplitudes (mean and SEM) of mu and alpha oscillations

(Means were obtained as EMMs in SPSS Output)

Left, levels of the relative amplitude of mu oscillation (only for central electrodes) varying with door category (doors with a lever, doors with a push plate (swinging doors) and doors with a vertical bar)

Right, levels of the relative amplitude of alpha oscillation (only for parieto-occipital electrodes) vary with handle category (doors with a handle locating on the left side of the door, doors with a handle locating on the right side of the door)

Levels of de-synchronization/suppression of mu/alpha can be calculated by subtracting relative amplitudes from 1. Thus, lesser relative amplitude values show greater suppression/de-synchronization levels.

P value of 0.088 was found for the three-way interaction among Handle x Hemisphere X Channel within Hemisphere. Although this result is just a trend, not a significant outcome, the patterns of the results in the Figure-5.4 are noteworthy. For parieto-occipital electrodes, alpha suppression is stronger in the hemisphere contra-lateral to the handle location (dark orange bars are lower than bright orange bars in **Figure-5.5**). For central electrodes mu suppression is stronger in the hemisphere ipsi-lateral to the handle location (bright blue bars are lower than dark blue bars in **Figure-5.5**). The results for the central electrodes, although not significant, are in line with the prediction: for example door handle on the left half of the door affords right-hand action, corresponding left hemisphere mu suppression.

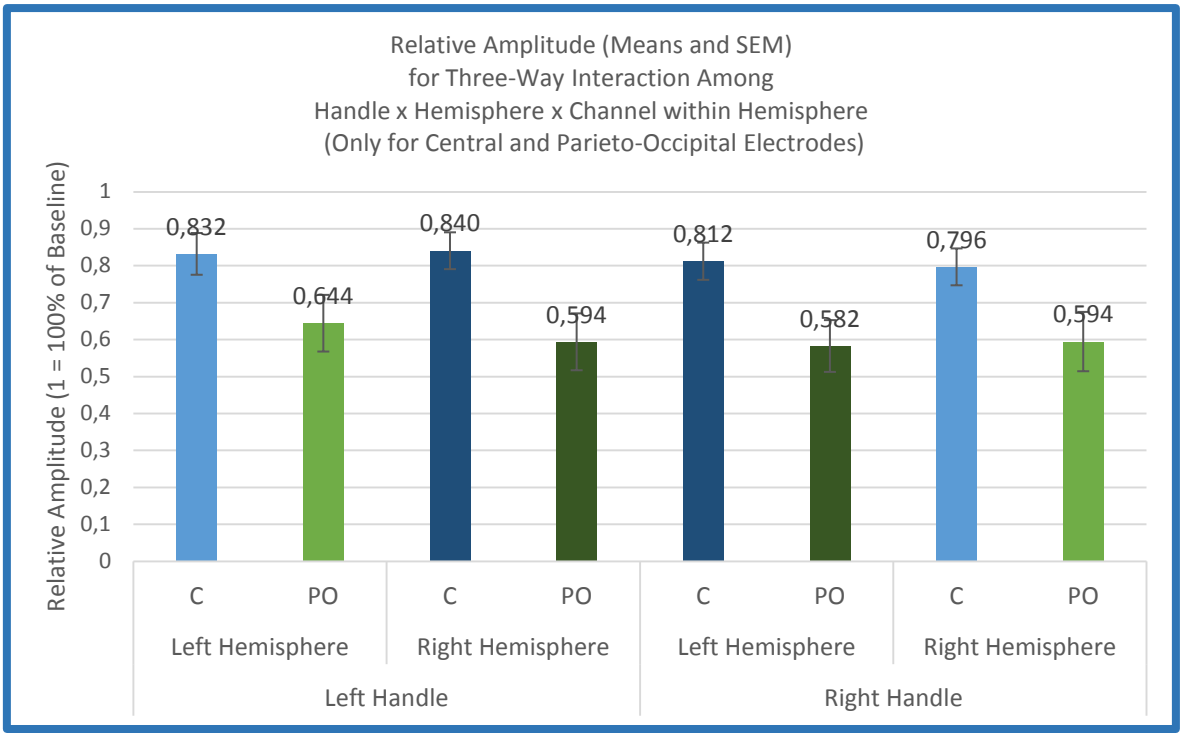

Figure-5.5 Relative amplitudes (mean and SEM) of mu oscillations on central electrodes and alpha oscillations on parieto-occipital electrodes for three-way interaction among Handle, Hemisphere and Channel within Hemisphere Factors
(Means were obtained as EMMs in SPSS Output)

5.6. DISCUSSION OF TIME-FREQUENCY ANALYSIS OF ERD OF MU OSCILLATION

In group-level statistical analysis, statistically significant results for handle factor can be associated with visual conspicuousness of handles and their effects on visual processing, which cause de-synchronization of alpha oscillation on the primary visual cortex. This result was already hypothesized before the experiment because posterior alpha oscillations of the visual cortex are more powerful and widespread when compared with central mu oscillations of the primary motor cortex, which are associated with motor empathy and embodied perception & motor imagery. Although there is no statistical significance, closeness to the statistical significance of two-way interaction between door category and channel within hemisphere ($p=0.089$) can be interpreted as the indicator of the strong difference between de-synchronization levels (or adversely relative amplitudes) of central mu and posterior alpha oscillations (namely significant difference between visual and motor processes) accordingly door category (at least for one of door category among the others). Although this result should not be over-interpreted, it can give us some evidence about cross-modal neural interaction between primary visual and motor cortex and also the existence of embodied perception/implicit motor imagery.

Furthermore, visual perception of images of doors with a lever handle cause more suppression/de-synchronization of mu oscillation (i.e., powerful motor imagery/embodied

perception) when compared with images of other door categories. This effect can be interpreted as familiarity's effect on affordance, which empowers the electrophysiological activity of interest. In comparing the other two door categories, visual perception of images of doors with a vertical bar causes more suppression/de-synchronization of mu oscillation (i.e., powerful motor imagery/embodied perception) when compared with images of doors with a push plate (swinging doors). This effect can easily be associated with the visual conspicuousness of the vertical handle due to its size and non-existence of any affordable element (except push plate) for interaction with swinging doors. Additionally, the opposite location of foot plates with push plates on swinging doors (or horizontal location of foot plate) can also play a role in the decrease of the affordance effect (i.e., contra-laterality between visual perception and motor imagery/embodied perception) for swinging doors.

Another statistically significant result was the handle factor for parieto-occipital areas. More significant suppression of doors with a right handle, when compared with door with a left one, can be associated with behavioural asymmetry of participants (i.e., right-handedness) and its habituation effects on visual perception. Although contra-lateral effect was hypothesized for visual perception of handle locations, ipsi-laterality can be associated with presentation sizes of images of doors. This matter may be related to the perception of images of doors as if daily hand-scale objects where the handle-hand interaction ipsi-lateral is in contrast to doors (where handle-hand interaction is contra-lateral). This result is one of the novelties of the experiment, which tries to understand the affordance effect of full-body scale architectural elements instead of hand-scale objects. However, due to technical limitations, full-body scale architectural elements were presented close to hand-scale during the data acquisition process.

6. EXPERIMENT 3 (EEG)

6.1. LITERATURE REVIEW

Third Experiment and Predictions

In the third experiment of the thesis, neurophysiological aspects of affordance of one of the hand-scale daily objects as cups/mugs with/without handle and embodied perception/implicit motor imagery will be examined through ERD of central mu oscillation (see, Proverbio et al., 2011; 2013; Goslin et al., 2012; Jardin et al., 2012; Proctor and Miles, 2014; Garrido-Vásquez et al., 2021). Additionally, cups/mugs with typical and non-typical handles have also been examined as an additional condition of the experiment to investigate the effect of manipulability (see, Proverbio et al., 2011; McNair and Harris, 2012; Proverbio et al., 2013) (i.e., easily graspable vs difficult to grasp) on visual perception and motor-related processes offered by the object (see, Cho and Proctor, 2010; Lopresti-Goodman et al., 2011; Suzuki et al., 2012; Lopresti-Goodman et al., 2013). Manipulability as one of the object properties can be used to cope with perspectivism and truthmaking relevant to dissociation of neurophysiological processes relevant to motor program in line with perceived affordances from coding spatial features visually. As previously mentioned, differently from architectural elements, hand-scale daily objects generally afford a potential action where the interaction between hand and handle is ipsi-lateral (e.g., right hand operation for right handle) except for some of the limited cases, such as opening a book page (contra-lateral).

In this regard, this experiment was designed as a control experiment to have an idea for examining ipsi-lateral interactions with hand-scale daily object affordances in comparison (to some degree) with contra-lateral architectural affordances, which have been presented in a smaller scale (similar to hand scale) (see, Warren, 1984; Ono et al., 2013; Brandl et al., 2015; Sollfrank et al., 2015; Alimardani et al., 2018; Kourtis et al., 2018; Ono et al., 2018; Choi et al., 2020; Carrere et al., 2021). Thus, we predicted 1) relative amplitude of de-synchronization of mu oscillation should be less for cups/mugs with handle in comparison with cups/mugs without handles; 2) relative amplitude of de-synchronization of mu oscillation should be less for cups/mugs with easily manipulable/typical handle in comparison with cups/mugs with difficult manipulable/atypical handle; 3) laterality of de-synchronized posterior alpha oscillation (which is associated with visual processing) and central mu oscillation (which is associated with motor processing) should be contra-lateral with the location of handle of the cups/mugs.

6.2. METHODOLOGY AND EXPERIMENT DESIGN

In this experiment, for data acquisition, EEG was used due to its several advantages. These advantages can be listed as; (1) economically affordable, (2) data acquisition may be simpler but interpretation needs expertise (when compared with other data acquisition methods such as fMRI and MEG and other tomography methods), (Min et al., 2010; Daly et al., 2013; Reis et al., 2014; Koenig et al., 2020) (3) adequate for studying cortical areas as the regions of the interest, (Teplan, 2002; da Silva, 2009) (4) good temporal resolution which is crucial for studying electrophysiological activity of interest of the experiment (Mulert and Lemieux, 2009; Burle, 2015; Beres, 2017) (i.e., de-synchronizations of alpha and mu oscillations, cross-modal neural interaction between primary visual and motor cortex) (Muthukumaraswamy and Johnson, 2004b; Muthukumaraswamy et al., 2004; Pineda, 2005; Hari, 2006; Oberman et al., 2007; Ulloa and Pineda, 2007; McGarry et al., 2012; Sabate et al., 2012; Umiltà et al., 2012; Kumar et al., 2013; Cannon et al., 2014; Heimann et al., 2014; Jenson et al., 2014; Rüther et al., 2014; Coll et al., 2017).

For data acquisition process, totally 26 participants were recruited. However, 2 participants' data were lost and could not be analysed. One further participant felt ill during the experiment and the data was also excluded from the study. Therefore, remaining 23 participants' data was analysed (14 males, aged 22 – 43 years where mean is 26.31 years and standard deviation is 4.78 years). All participants are right-handed, without a history of mental illness, neurological disorders, brain injury, drug/alcohol abuse within the previous 12 months, nor taking any mood-altering medication (by self-report). All participants were naïve to the research questions of the experiment, which was particularly important due to evidence indicating participants can consciously alter their own mu rhythm (Wolpaw et al., 1991). The experiment was approved by the ethics committee of the School of Psychology, University of Nottingham (Reference Number: "F978"). Before participants were recruited, each volunteer participant received an information sheet, and after recruitment, if they would like to continue, they signed the consent form before the experiment started.

In experiment design, images of different cups/mugs with different handles (typicality) and affordance effects (i.e., typical/familiar, atypical/strange) were used as the stimuli of the experiment. In addition to the handle-based affordance effect, chosen images of cups also varied in terms of grasping force requirements that conceptualized with the term 'semiotic properties'. Semiotic properties of the cups/mugs could be either in material level (i.e., material aspects of the cup/mug) and cultural/semantic level (e.g., ordinary everyday object vs invaluable unique museum piece). According to semiotic properties, cups/mugs were classified into two categories

as fragile cups and robust cups. Laterality of handle location was also another category for classifying the stimuli (i.e., left-handled cups/mugs, right handled cups/mugs, cups/mugs with no handle) **(see, Figure-6.1)**.



Figure-6.1 Example Stimuli of the Third Experiment

Thus stimuli categories can be listed as; handle direction (laterality), robustness (semiotic properties) and typicality (the form of handle). In terms of interactions of categories (e.g., *right typical* handled *robust* mug), there are totally ten different categories of stimuli, and in each category, and there are 20 stimuli. Thus, in the main experiment, 200 images of cups/mugs were used for experiment design. Additional 20 images of glass standard cups were used as task stimuli of the experiment (10% percentage of the main stimuli) (Friedman et al., 1998; Gaeta et al., 2003; Kiehl et al., 2005; Brown et al., 2009; Noyce and Sekuler, 2014; Sanger and Dorjee, 2016). Totally, 220 images of different cups/mugs were used for the main experiment. Although defining some of the categories (e.g., cultural/semantic semiotic properties) was rather subjective in comparison to the other categories, the inter-rater reliability score was found as 97% even for relatively subjective defined categories. Categorization of the stimuli can be seen in **Figure-6.2.**

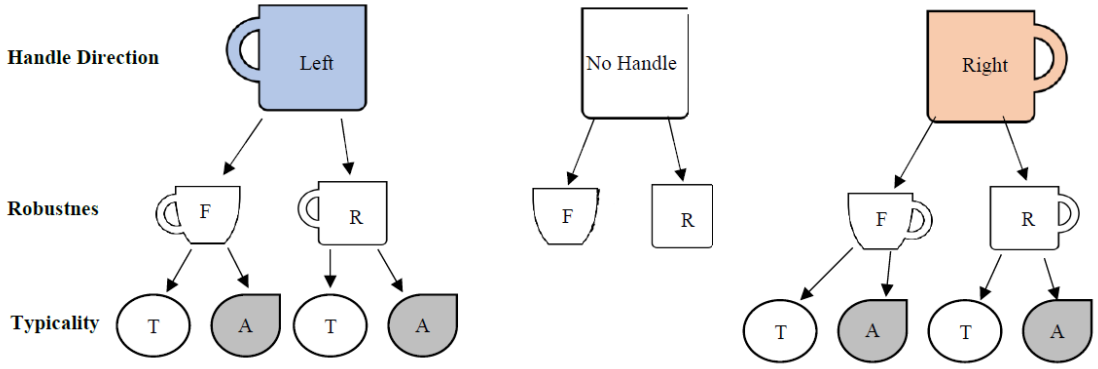

Figure-6.2 Categorization of the stimuli. From top to bottom, handle direction/existence of handle category (top), semiotic properties/grasping force (i.e. material and cultural level) category (middle), and formal features of handle (i.e., typicality/familiarity) category. Abbreviations can be listed as R=robust, F=fragile, T=typical/standard, A=atypical/strange (Graph prepared by Camilla Woodrow-Hill, C.W.-H.)

All images of cups/mugs were found through Google Search with different terms containing the word 'cup' or 'mug' (e.g., fragile cup/mug, weird handled cup/mug) and modified for the experiment (e.g., removing texts, numbers, shadows, reflections on the images of cups/mugs). Each stimulus was presented on gray-scale to avoid the distracting effects of colour on visual

perception, which can cause de-synchronization of alpha oscillation more powerfully (see for review, Cantero et al., 2002; see also, Scammell et al., 2017; De Gennaro, 2001; Knaut et al., 2019; Tran et al., 2020). This might mask the electrophysiological activity of interest of the experiment (i.e., de-synchronization of mu oscillation) (Andrew and Pfurtscheller, 1997; Niedermeyer, 1997; Pfurtscheller et al., 2000; Benbadis, 2015; Yin et al., 2016; Thorpe et al., 2016). All images of cups/mugs were presented to participants in similar size to their original size. All stimuli were presented approximately within a rectangular area of which measures are about 9 cm X 12 cm (height X width) to increase participants' sense of presence (see for sense of presence, Clark, 2007; in virtual reality; Slater et al., 1994; Witmer and Singer, 1998; Schultze, 2010; Kilteni et al., 2012; Leonardis et al., 2014; Fribourg et al., 2018; Wong, 2018; Alchalabi et al., 2019; motor imagery/embodiment & sense of presence; Baños et al., 2004; Costa et al., 2013; Invitto et al., 2016; Iachini et al., 2019; Choi et al., 2020) during the data acquisition process.

For familiarization of the participants with the main experiment and letting them understand the task of the experiment, a demo version of the experiment was prepared. For the demo version of the experiment, additional 20 images of cups were used (approximately 10% of the total stimuli of the main experiment) and none of these 20 stimuli appeared in the main experiment to avoid repeated presentation of stimuli which will trigger memory processes and potentially also suppress EEG responses (Schacter and Buckner, 1998; Grill-Spector et al., 2006; Summerfield et al., 2008; Horner and Henson, 2008; Garrido et al., 2009; Engell and McCarthy, 2014). At least one stimulus (i.e. the image of cup/mug) belonging to each category of the main experiment was presented to participants in the demo version of the experiment. In the demo experiment, two stimuli were presented in task category stimuli (i.e., glass standard mug/cup). The Demo version contains two blocks, and each block contains 10 stimuli. A demo experiment was presented to participants on the experimenter's computer outside the Faraday Cabin. The experimenter checked whether the participant understood the task of the experiment or not.

Demo and main experiments were designed and presented to participants through PsychoPy version 1.90.3 (Peirce, 2007), which provides adjustments of duration and order of presentation of stimuli, fixation crosses, and instructions relevant to the experiment. The duration of each stimulus was defined as 2.5 s, and between each stimulus, a white fixation cross was presented to fix participants' gaze to the centre of the screen. The size of the fixation cross was 3 cm x 3 cm, and both experiments (i.e., demo and main version) were presented block by block to participants. Each block contains ten stimuli, and all stimuli were presented in pseudo-randomized order. At the end of each block, an instruction text informing the participants about

the end of the block and task of the experiment was presented. All of the experiment was presented on the centre of a full-screen grey background **(Figure-6.3)**.

The main experiment was presented to participants on a Samsung Monitor (model: S23T00D, 1920×1080 pixels, 23.6", 120Hz refresh rate, 1ms pixel response time), and dimensions of the monitor was 28.5 cm height X 51 cm width located in the Faraday Cabin (2.5 x 2.3 x 2.3 m), -a quiet room at ambient temperature-, in EEG Laboratory of University of Nottingham. The monitor centre was adjusted to direct the participant's visual field, and the monitor height from the surface of the table was 50 cm to avoid vertical eye movements of the participant, which can add additional artefacts to acquired EEG data. After completing data acquisition of the first 12 participants, for counterbalancing the laterality category (i.e., left and right handled cups/mugs), images of cups/mugs were flipped 180 degrees around the y-axis. Flipped stimuli were presented to further remaining participants.

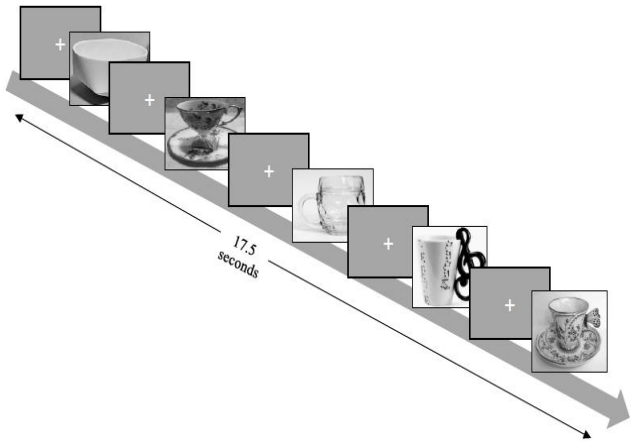

Figure-6.3 Sequence of the stimuli within a half block-full block includes 10 stimuli- shown to participants during the experiment (graph prepared by C.W.-H.)
This figure omits the grey background surrounding the 9cm X 12cm stimulus images for display purposes.

The task of the experiment was the oddball paradigm, where the stimuli sequence was interrupted by a deviant stimulus as an oddball stimulus (García-Larrea et al., 1992; Debener et al., 2005; Sochurková et al., 2006; Verleger and Śmigasiewicz, 2016; Schlossmacher et al., 2020). In this experiment, standard glass mugs/cups were chosen as an oddball stimulus. As the task of the experiment, the participants were requested to count the oddball stimuli within each block of the experiments (in both main and demo versions), and they were requested to indicate the total number of oddball stimuli at the end of each block. The end of the block was informed to participants via an instruction text ("Block n finished. Please Report the Number" (n=ordinal number of each block)) **(see, Figure-6.4)**. As soon as they saw the instruction text, they shouted the total number of oddball stimuli within the ending block. In the main experiment, the

experimenter recorded the shouted numbers at the end of each block to check the level of attention of the participant during the experiment flow. Participants' performance accuracy level was approximately 97% and with Standard Error 0.01%. Total duration of the main experiment was approximately 25 minutes.

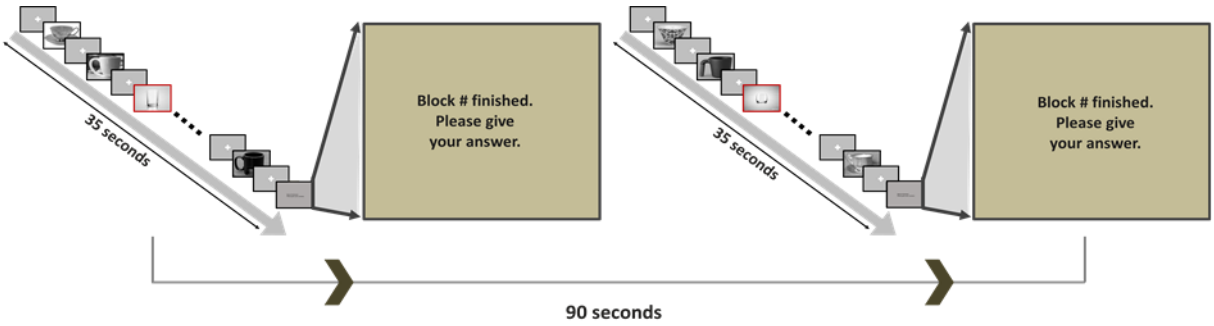

Figure-6.4 Block sequence within the experiment (graph prepared by Hasan Kartal)

Two example blocks of ten stimuli each, red frames show oddball stimuli. Last image of block, showing instruction text, enlarged for readability.

6.3. DATA ACQUISITION, PRE-PROCESSING AND CLEANING

For data acquisition, extended 10-20 Active-Two System (BioSemi, Amsterdam, Netherlands), 64-channel EEG was used with a sampling rate of 1024 Hz, digitized at 24-bits. For the preparation of participants for data acquisition, 6 external Ag/AgCl flat-type electrodes with Individual leads/connectors (FLAT Active electrodes. BioSemi.com, 2021) were placed on mastoids, temporal bones (i.e., lateral canthi) and sphenoid bones (M1, M2, F9, F10, T9, T10) for examining electrooculographic activity and re-referencing purposes. And then, a BioSemi electrode cap (Headcaps. BioSemi.com, 2021) in suitable size with the perimeter of the participant's head was chosen to keep scalp impedances below 20 kΩ, which is essential for good quality data acquisition. Choosing an electrode cap as tight as possible is very important to keep impedances below. However, the electrode cap should not be too tight, disturbing the participant during the data acquisition process. Thus, to define proper size, head perimeters were measured from nasion to inion and from right to the left tragus, and their intersection point was marked as the vertex point for placing the cap accurately. Cz electrode was placed on marked vertex point, and other electrode areas on the cap were placed according to this reference electrode area (Cz) (Echallier et al., 1992; Kouri and Lukas, 2001; Atcherson et al., 2007; Schalk and Mellinger, 2010, p.9-36; Estepp and Christensen, 2015; Kam and Handy, 2015; Seeck et al., 2017; Hari and Puce, 2017, p.51-2; Newman, 2019, p. 81-2; Rich and Gillick, 2019; Benevides et al., 2020; Müller-Putz et al., 2020; Shahriari et al., 2020; Müller-Putz and Wriessnegger, 2021).

After electrolytic gel application to electrode areas on the electrode cap, electrodes of two pin-type electrode sets, including 32 pin type electrodes in each set, were placed into a BioSemi electrode cap (Pin-Type Active-electrodes. BioSemi.com, 2021). After placing all electrodes, monopolar display (ActiView.BioSemi.com, 2021) and normalized/referenced mean values of electrode offsets of Active View system to two reference electrodes of BioSemi Active Two System (CMS & DRL) were checked (Massar et al., 2014; Wessel and Aron, 2015; Derosiere et al., 2015; Balaban and Luria, 2016; Hartmann et al., 2016; Mahajan et al., 2017; Barham et al., 2017; Wisniewski et al., 2017; Ball et al., 2017; Fargier et al., 2018; Welcome and Trammel, 2018; Wisniewski et al., 2018; Dogge et al., 2019; Silas et al., 2019; Wilson and Foxe, 2020; Palluel et al., 2020; Pascucci et al., 2021) and if the electrode offsets were less than ±40 mV (as an indicator of good electrode setup for data acquisition) (Xu et al., 2011; Heisz, and McIntosh, 2013; Liang et al.; 2018; Xu et al., 2018; Van Rinsveld et al., 2020) and if the electrodes were working efficiently (i.e., good monopolar display), data acquisition began.

After the preparation process was completed, participants sat in Faraday Cabin in a relaxed position, and their distance from the monitor was 65 cm; thus, stimuli would be presented to participants in their peripersonal space (as if daily observations of the cups/mug for increasing realisticity effect) (Warren, 1984; Ono et al., 2013; Brandl et al., 2015; Sollfrank et al., 2015; Alimardani et al., 2018; Kourtis et al., 2018; Ono et al., 2018; Choi et al., 2020; Carrere et al., 2021). Before the data acquisition process began, participants were instructed to avoid any motor activities such as clenching hands, crossing legs or arms or any grasping movements because of avoiding contaminations of EEG data via additional powerful motor artefacts (Jung et al., 2000; Whitham et al., 2008; Shackman et al., 2009; Deville et al., 2010; McMenamin et al., 2010; McMenamin et al., 2011; Olbrich et al., 2011; Ma et al., 2012). The participants were requested to keep their hands on the table in a flat position to avoid motor execution effects of grasped position hand, which can potentially mask the electrophysiological activity of interest that emerged from motor imagery/embodied perception instead of motor execution.

In order to avoid powerful and widespread posterior alpha suppression (Cantero et al., 2002; Scammell et al., 2017; De Gennaro, 2001; Knaut et al., 2019; Tran et al., 2020), which can potentially mask the electrophysiological activity of interest (i.e. local and less powerful mu oscillation) (Cohen-Séat et al., 1954; Gastaut and Bert, 1954; Andrew and Pfurtscheller, 1997; Niedermeyer, 1997; Pfurtscheller et al., 2000; Benbadis, 2015; Yin et al., 2016; Thorpe et al., 2016), Faraday Cabin was illuminated via A Daffodil USB LED light (model: LEC150) for additional lighting. After checking environmental participant related conditions (i.e., degree of lighting, sitting position of participant), data acquisition devices were controlled (i.e., StimTracker device

(StimTracker. Cedrus.com, 2021), ActiveTwo Biosemi Amplifier (ActiveTwo AD-box. BioSemi.com, 2021)). Each trigger code defined for each category of the stimuli was sent to the data acquisition computer via Cedrus StimTracker and synchronized with stimuli onset via Optical receiver / USB 2.0 interface (Receiver.BioSemi.com, 2021). Raw EEG data were acquired via ActiView 705 (version 8.6.1) (ActiView.BioSemi.com, 2021) system, and after completing data acquisition, the offline signal processing began.

In offline signal processing steps, data pre-processing, cleaning and individual level Time-Frequency Analysis for Event-Related De-synchronization of mu oscillation were performed through FieldTrip routines (Oostenveld et al., 2011) in MATLAB R2018a (The MathWorks Inc., Natick, MA). For group-level statistical analysis, R statistical Software was used. After completing the group-level, statistical analysis through General Linear Model repeated measures ANOVA (Rutherford, 2011; Vik, 2013; Crowder and Hand, 2017), statistical significance within *tests of within-subject effects* (Greenwald, 1976) and estimated marginal means of statistically significant factors and interactions were examined (Searle et al., 1980).

In the data pre-processing step, the data were segmented according to the trial definition and filtered from the frequencies out of the experiment's interest to avoid additional noises. For relativization/normalization to avoid masking effects of noise sources and to emphasize the electrophysiological activity of interest, the data were re-referenced and corrected to baseline (Cohen, 2014, p. 71-86; Bigdely-Shamlo et al., 2015; Rogasch et al., 2017; Hari and Puce, 2017, chapter 7; Kim, 2018; Peng, 2019). For segmenting the data according to stimuli onset, which was synchronized with trigger codes, the time window of the trial was defined from 600 ms before stimuli onset to 1900 ms after stimuli onset. Time window length should be long enough to examine the electrophysiological activity of interest (i.e., de-synchronization of mu oscillation). It should have a long enough pre-stimuli period for baseline correction, but it should not be too long, which can cause additional noise) (Procházka et al., 2010; Cohen, 2014, p. 75-78; Clerc, 2016, p.105-106; Peng, 2019).

After segmenting data according to trial definition, the out-of-interest frequencies were filtered via band-pass filtering. Frequencies above 39 Hz were filtered via low pass filtering, and frequencies below 0.35 Hz were filtered via high pass filtering to avoid additional noise (Kamp et al., 2005; Hari and Puce, 2017 p. 89-95; Rogasch et al., 2017; Baranowski and Piątek, 2017; de Cheveigné and Nelken, 2019; Peng, 2019). After filtering the out-of-interest frequencies, thanks to reference-free data acquisition of BioSemi (online two reference system based data acquisition, CMS & DRL) (Massar et al., 2014; Wessel and Aron, 2015; Derosiere et al., 2015; Balaban and Luria, 2016; Hartmann et al., 2016; Mahajan et al., 2017; Barham et al., 2017;

Wisniewski et al., 2017; Ball et al., 2017; Fargier et al., 2018; Welcome and Trammel, 2018; Wisniewski et al., 2018; Dogge et al., 2019; Silas et al., 2019; Wilson and Foxe, 2020; Palluel et al., 2020; Pascucci et al., 2021), acquired data (i.e., amplitude) by each channel in each time point re-referenced/relativized/normalized to the average value of data (i.e., amplitude) acquired by all of the channels in each time point. Common Average Referencing is very beneficial for multi-channel EEG systems to avoid the noise from the ground electrode connected to the ground circuit of the amplifier and polarization of the data because scalp topography is not an ideal sphere (especially when compared with other referencing systems) (Offner, 1950; Osselton, 1965; McFarland et al., 1997; Essl and Rappelsberger, 1998; Teplan, 2002; Lakshmi et al., 2014; Kim and Im, 2018; Tsuchimoto et al., 2021).

As the last step of data pre-processing, the data within each trial were corrected to control signal for the relativizing electrophysiological activity of the interest to baseline (Maess et al., 2016). Control signal/baseline is chosen from the pre-stimuli period within the defined trials/epochs, from 300 ms before stimuli onset to stimuli onset. The Time window of electrophysiological activity of interest was defined from 300 ms to 750 ms after stimuli onset (within the post-stimuli period of the defined trials/epochs) and corrected to baseline (from 300 ms to ±0 ms before stimuli onset). The baseline correction is crucial for examining the electrophysiological activity of interest (i.e., de-synchronization of mu oscillation) to cope with drifts and direct current offsets (Beisteiner et al., 1995; Bijma et al., 2003; Alday, 2019; Zhang et al., 2020). The normchange baseline correction was chosen due to its common use for Time-Frequency Analysis (Lehr, 2020; Blohm et al., 2021). The normchange baseline correction is the normalization of absolute baseline correction (subtracting control signal from signal of interest) to total value of the power of the whole signal within each defined trials/epochs (FT_REJECTVISUAL. Fieldtriptoolbox.org, 2021, see also, Feige, 1999, p. 71-103; Cohen, 2014, p. 217-240; Dickter and Kieffaber, 2013; p. 116-137).

6.3.1. Data Cleaning: Visual Inspection Based Cleaning and Independent Component Analysis

After data was pre-processed, data was cleaned from physiological and non-physiological artefacts before data analysis. In the data cleaning process, the data were first cleaned via amplitude-based rejection as the part of visual inspection script of FieldTrip Routines and MATLAB (Visual artifact rejection. Fieldtriptoolbox.org, 2021; FT_REJECTVISUAL. Fieldtriptoolbox.org, 2021). In this data cleaning step, heavily contaminated trials by EOG and EMG of which variance of amplitude was above than 300 μV^2 was rejected (Delorme et al., 2005; Delorme et al., 2007; Eichele et al., 2010; Fung et al., 2012; Torppa et al., 2012; Law et al., 2013; Turnip and Junaidi, 2014; Tavakoli and Campbell, 2015; Bell et al., 2016; Lindström et al., 2016; Dube et al., 2016; Cruz-Garza et al., 2017; Affanni et al., 2019; Marini et al., 2019; Di Gregorio et

al., 2019; Grosselin et al., 2019). Eliminating heavily contaminated trials by EOG and EMG is crucial for the efficiency of Independent Component Analysis. In the same cleaning process, some participants' datasets, including more than 20% of such trials, were excluded from general data analysis. Hence, four participants' data could not satisfy the criteria and these participants were excluded.

For Independent Component Analysis (ICA), eliminating high-level EOG and EMG artefacts and implementing ICA to data including only artefacts of which amplitudes are close to pure EEG amplitudes is beneficial. After rejecting high contaminated data and exclusion of participants that could not satisfy the criteria and down sampling the data to reduce file size for speed of processing (Van Dun et al., 2007; Maidhof et al., 2009; Viola et al., 2010; Bowers et al., 2014; Falco et al., 2014; Jenson et al., 2015; Duann and Chiou, 2016; Rogasch et al., 2017; Gallicchio and Ring, 2019; Issa et al., 2019; Zhang et al., 2021), ICA was applied to data of other participants for removing eye blinks. Other artefacts, especially artefacts which do not have Gaussian distribution across the recorded signal (i.e., non-rhythmic artefacts) could not be eliminated (Vigário et al., 2000; Hamaneh et al., 2013).

ICA give the opportunity to isolate artefacts to different components thanks to its objective function and optimization algorithm, and isolated artefacts from pure EEG data can easily be eliminated from data set via corresponding topographic maps of artefact including components (Kobayashi et al., 1999; James and Lowe, 2000; Delsanto et al., 2003; Delorme et al., 2005; Jann et al., 2008; Mantini et al., 2007; Abbaas, 2014; Calcagno et al., 2014; Ghaderi et al., 2014; Snyder et al., 2015; Xue et al., 2016). By benefitting from objective function, the ICA de-compose and re-compose the acquired data and optimization algorithm optimize and provide to isolate artefacts within new re-composed components of ICA (Hyvärinen, 1998; 1999; 2013; Hyvarinen et al., 2002; Comon and Jutten, 2006; Van Drongelen, 2018, p.579-617). In this experiment, ICA was performed using the Runica algorithm (FT_COMPONENTANALYSIS. Fieldtriptoolbox.org, 2021) within FieldTrip Routines. Runica algorithm benefits from the infomax ICA algorithm (Bell and Sejnowski, 1995), the natural gradient learning algorithm (Amari et al., 1996), Principal Component Analysis dimension reduction and/or spectrogram pre-processing (Zibulevsky and Pearlmutter, 2001; Zhen et al., 2016) and isolate artefacts as independent components.

After ICA based artefact rejection step was completed, the second pass of amplitude-based rejection was performed. In this cleaning step, the cleaning process was only applied to channels of interest. Channels of interest were chosen from typical recording areas of electrophysiological activity of interest. Central electrodes placed on the primary motor cortex (i.e., C3 and C4) and parieto-occipital electrodes placed on the primary visual cortex (i.e., PO7 and PO8) were chosen

(Van Der Helden et al., 2010; ter Horst et al., 2013; Chaumon and Busch, 2014; Kourtis and Vingerhoets, 2015; Bouchra et al., 2016; Lim and Ku, 2018; Fabre et al., 2021) to examine cross-modal neural interaction between visual and motor processes (i.e., motor imagery/embodied perception). On channels of interest, the trials of which variance of amplitudes were above than 100 μV^2 were excluded (Delorme et al., 2005; Zeman et al., 2007; McMenamin et al., 2010; Perry et al., 2011; Savelainen, 2010; Solé-Casals et al., 2010; Benito Núñez, 2011; Cong et al., 2011; Winkler et al., 2011; Plöchl et al., 2012; Cassani et al., 2014; Ghaderi et al., 2014; Sheoran et al., 2014; Borse, 2015; Kumar and Kareemullah, 2014; Tavakoli and Campbell, 2015; Hu et al., 2015; Paradeshi and Kolekar, 2017) because amplitude range of typical pure EEG activity is generally from 1 to 100 µV. So, any recorded amplitude above this range will be possible either heavily contaminated EEG or other electrophysiological activity arising from different physiological sources such as (EOG, ECG, EGG or EMG) (Nagel, 2000; Klemm et al., 2009; Mou et al., 2009; Reilly and Lee, 2010; Clancy et al., 2011; Dubey et al., 2014; Song et al., 2015; Alhammadi et al., 2016; Spinelli and Guerrero, 2017; Kassanos et al., 2018; Ha et al., 2021). After the data were cleaned from artefacts, data were subjected to Time-Frequency Analysis for ERD of mu oscillation.

6.4. DATA ANALYSIS: TIME-FREQUENCY ANALYSIS FOR ERD OF MU OSCILLATION

Time-Frequency Analysis was performed by FieldTrip routines in MATLAB for ERD of mu oscillation, and plotted spectrograms for each category of stimuli for each channel of interest were examined to understand the characteristics (e.g., time window, frequency band range of mu oscillation) electrophysiological activity of interest (Tiihonen et al., 1989; Arroyo et al., 1993; Pfurtscheller and Neuper, 1994; Schnitzler et al., 1997; Penny et al., 1998; McFarland et al., 2000; Neuper and Pfurtscheller, 2001a; Hari, 2002; Muthukumaraswamy and Johnson, 2004a; MacKay, 2005; Hari, 2006; Pfurtscheller et al., 2006; Anderson and Ding, 2011; Kumar et al., 2013; Cannon et al., 2014; Hari et al., 2014; Fox et al., 2016; Coll et al., 2017; Debnath et al., 2019). 10 Hz was chosen as representative frequency band range for examining de-synchronization of mu oscillation (Pfurtscheller and Neuper, 1992; Rappelsberger et al., 1994; Stančák Jr, 2000; Leocani et al., 2001; Pfurtscheller, 2001; Cheyne et al., 2003; Pfurtscheller, 2003; Chéron et al., 2006; Neuper et al., 2006; Anderson and Ding, 2011; Yin et al., 2016; Démas et al., 2020).

As it is known, during the motor imagery (e.g., action observation, action imaging, and referential action observation such as marking) and motor execution (e.g., transitive action, intransitive action, tool use action), mu oscillation is de-synchronized because of the non-phase locked and induced responses (Da Silva, 2006; see also, Kalcher and Pfurtscheller, 1995; Pfurtscheller and Da Silva, 1999; Neuper and Pfurtscheller, 2001a; Penny et al., 2002; Makeig et al., 2004; Shah et al., 2004; Sauseng et al., 2007; Crone et al., 2008; Bastiaansen et al., 2011; Başar and Gölbaşı, 2014).

These responses are widely associated with electrophysiological activities of inhibitory and excitatory post-synaptic potentials of different neuron populations. The activities organized by feedback loops between thalamo-cortical relay (TCR) (inhibitory, hyperpolarized) and reticular nucleus (RN) (excitatory, depolarized) neurons (Pfurtscheller and Da Silva, 1999; Suffczynski, 1999; Neuper and Pfurtscheller, 2001a; Suffczynski et al., 2001; Da Silva, 2006; Pfurtscheller, 2006; Klimesch et al., 2007; Takemi et al., 2013) and play a crucial role on gating functions (MacKay, 1997; Pfurtscheller, 2003; Da Silva, 2006; Neuper et al., 2006; Anderson and Ding, 2011; Foxe and Snyder, 2011; Popov et al., 2011; Buchholz et al., 2014; Cheng et al., 2016; Dipoppa et al., 2016; Forschack et al., 2017; Hsiao et al., 2018; Fodor et al., 2020; Limanowski et al., 2020; Wiesman and Wilson, 2020).

For Time-Frequency Analysis, the power spectrum of data was used and to remedy the truncated signals (as a result of segmentation and transformation from Continuous to Short Time Fourier Transform), Hanning windowing was performed (FT_FREQANALYSIS. Fieldtriptoolbox.org, 2021; Time-frequency analysis. Fieldtriptoolbox.org, 2021; Percival and Walden, 1993; Mitra and Pesaran, 1999). By benefitting from the power spectrum, spectrograms were formed where the frequency range of the spectrogram was defined from 2 Hz to 10 Hz. The time-domain of the spectrogram was defined from 300 ms before stimuli onset to 1800 ms after stimuli onset. The sampling rate of the frequency domain was defined as 0.2 Hz, and the sampling rate of the time-domain was defined as 5 ms. Multitaper convolution method was performed for generating spectrograms (Time-frequency analysis. Fieldtriptoolbox.org, 2021; Kaskarovska, 2005; van Vugt et al., 2007; Babadi and Brown, 2014; Cohen, 2014, p. 203-210; van Drongelen, 2018, p. 153-180; Zhang, 2019). Multitaper convolution applies multitaper frequency transformation based on multiplication in the frequency domain (Cohen, 2014, p. 203-210; Karnik et al., 2021; mtmconvol method. Fieldtriptoolbox.org, 2021). For Time-Frequency Analysis of ERD of mu oscillation, the time window of electrophysiological activity of interest was detected from 300 ms to 750 ms after stimuli onset in the post-stimuli period. And then, the electrophysiological activity of interest was corrected to the baseline, of which time window was defined from 300 ms before stimuli onset to stimuli onset (±0 ms) in the pre-stimuli period.

6.5. RESULTS OF TIME-FREQUENCY ANALYSIS FOR ERD OF MU OSCILLATION

After completing individual level Time-Frequency Analysis for ERD of mu oscillation, for group-level statistical analysis, factors were defined. Defined factors can be listed as; handle direction, 3-level = (left, right, no handle), robustness, 2-level = (robust, fragile), hemisphere, 2-level = (right, left), topography, 2-level = (central, occipital). All group-level statistical analyses were performed via R programming language and RStudio, and statistical graphs were plotted using the

same software. Statistical significance (p values) within *tests of within-subject effects* and *estimated marginal means* of statistically significant factors and interactions were calculated via R Programming Language (version 1.2.1335) (R Core Team, 2019) and R Studio. 19 participants' data were checked via a pre-analysis step where package 'car' (**C**ompanion to **A**pplied **R**egression) (Fox et al., 2012) were performed. In this analysis, 2 participants were removed from data analysis because they were not within the limits of probability distribution which was tested via QQ-plots (Jayasheela, 2002; Kohler and Kreuter, 2005, p. 170-174; Dodge, 2008, p.437-439; Dihar et al., 2014; Christian and Michael Schomaker, 2016, p.44-45). Only these two participants' relative amplitude values were above 200%. After completing pre-analysis and checking all individual-level data before proceeding to group-level analysis, General Linear Model repeated measures ANOVA was performed for defined factors (i.e., 3 handle direction X 2 robustness X 2 hemisphere X 2 topography). The statistical tests were applied to data with Type III sums of squares (Tanguma and Speed, 2000; Boyacioglu and Baskan, 2007; Choi, 2014; Hershberger, 2014; Roy LaMotte, 2020).

After performing the ANOVA test, statistical significance was found for the hemisphere factor (p=.002), and greater mu suppression was detected for the right hemisphere factor (Mean value=72.70%, Standard Error=4.37%) when compared with left (Mean value=82.50%, Standard Error=4.73%). Statistically significant another factor was topography (p<.001), and greater suppression was found in occipital areas (Mean value=63.80%, Standard Error=6.37%) when compared with central electrodes (Mean value=91.4%, Standard Error=3.24%). In the two-way interaction level, handle x topography (p=.015) had a trend to statistical significance **(Figure-6.5)**. Data from central and occipital electrodes were analysed separately to examine further the trend to the significance of two-way interaction (handle x topography, p=.015). In this analysis, statistical significance could not be found for central electrodes; for factor handle, there was no significant main effect but a trend to statistical significance (F(2,32)=2.62, p=0.092) (Grieve, 1984; von Ende, 2001; Bathke et al., 2009; Abdi, 2010; Time et al., 2012; Field, 2015; Lee, 2015; Armstrong, 2017; Brunner, 2019; Denis, 2021, p.316-332). For occipital electrodes, there was no significant main effect (F (F2,32)=2.05, p=0.159).

Predictor	df_{Num}	df_{Den}	ε	MSe	F	p	η_{2p}
(Intercept)	**1.00**	**16.00**			**316.04**	**<.001****	**.95**
Robustness	1.00	16.00		690.20	1.57	.228	.09
Hemisphere	**1.00**	**16.00**		**701.64**	**14.01**	**.002***	**.47**
Topography	**1.00**	**16.00**		**2650.56**	**29.34**	**<.001****	**.65**
Robustness x Hemisphere	1.00	16.00		401.01	0.05	.822	.00
Robustness x Topography	1.00	16.00		518.84	3.37	.085	.17
Hemisphere x Topography	1.00	16.00		1153.02	1.79	.200	.10
Robustness x Hemisphere x Topography	1.00	16.00		342.90	0.93	.350	.05
Handle	1.96	31.40	0.98	647.04	0.60	.552	.04
Handle x Robustness	1.78	28.47	0.89	355.54	0.61	.534	.04
Handle x Hemisphere	1.69	26.98	0.84	400.30	0.03	.953	.00
Handle x Topography	**1.86**	**29.82**	**0.93**	**525.26**	**4.98**	**.015***	**.24**
Handle x Robustness x Hemisphere	1.78	28.52	0.89	201.14	0.39	.658	.02
Handle x Robustness x Topography	1.80	28.80	0.90	524.59	1.67	.207	.09
Handle x Hemisphere x Topography	1.00	25.13	0.79	205.43	0.00	.989	.00
Handle x Robustness x Hemisphere x Topography	1.82	29.06	0.91	332.45	1.44	.252	.08

Table-6.1 Statistical Results of Group-level ERD Analysis General Linear Model Repeated Measures ANOVA (3 x 2 x 2 x 2 factors)

(df_{Num}= degrees of freedom numerator, df_{Den}= degrees of freedom denominator, ε= Greenhouse-Geisser multiplier for degrees of freedom- where Mauchly's Test indicated sphericity had been violated-, *MSe*= mean Standard Error, η_{2p}= partial eta squared as a measure of effect size, *p*= probability value, except p values, all other values were presented with two decimal units, and only p-value were presented with three values in order to examine statistical significance, *significant 0.01<p<0.05, ** significant p<=0.01)

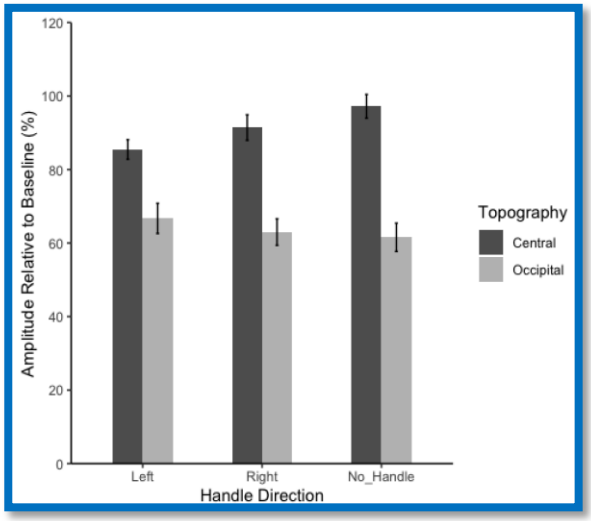

Figure-6.5 Descriptive Statistics of the Handle x Topography interaction (p=.015) from the 3 x 2 x 2 x 2 ANOVA (with error bars representing one Standard Error of the mean and the *y* axis representing the mean relative amplitude across all participants. The main effect of Topography (p<.001) can also be seen across Handle levels. Values <100% indicate suppression, with lower values indicating stronger suppression.) Graph prepared by C, W.-H

In addition to GLM Repeated Measures ANOVA for 3 x 2 x 2 x 2 factors, another GLM Repeated Measures ANOVA where the no-handle category was excluded and handle typicality was added as a new factor were performed (i.e., two handle x 2 robustness x 2 typicality x 2 hemisphere x 2

topography). Images of cups/mugs were excluded from the analysis because they do not have any handle, classified as typical or atypical. For avoiding Type I Error inflation which may possibly be resulted from conducting two separate ANOVA (Starr and McKnight, 2000; Austin and Brunner, 2003; Brunner and Austin, 2009; Feng, 2016), neither main effects of factors (i.e., Hemisphere, Topography, and Handle) nor any interactions with these three factors should be interpreted via second ANOVA results. Results of the second GLM Repeated Measures ANOVA can be seen in **Table-6.2.** According to results, the main effect of Typicality was found (p=0.023), and mu suppression level for images of cups/mugs with an atypical handle was (Mean 75.2%, Standard Error=4.42%) and mu suppression level for images of cups/mugs with a typical one was (Mean = 77.8%, Standard Error = 4.33%).

Among interactions, statistically, significant ones can be listed as; three-way interaction among Robustness X Typicality X Hemisphere (p=0.017) **(Figure-6.6)**, four-way interactions among Handle X Robustness X Typicality X Hemisphere (p=0.006) **(Figure-6.7)**, among Handle X Robustness X Typicality X Topography (p=0.010); and among Handle X Typicality X Hemisphere X Topography (p=0.038). After completing two GML Repeated Measures ANOVAs, Tukey-corrected post hoc tests (Andy, 2000, p.323-340; Homack, 2001; Cramer and Howitt, 2004, p.172-175; Richardson, 2009; Abdi, 2010; Kim, 2015) were performed to understand the effects of robustness and typicality on de-synchronization of mu oscillation in terms of hemispheric laterality. As a result of Tukey Correction Tests, greater de-synchronization of mu oscillation was found in the right hemisphere for images of robust cups/mugs with a typical handle (Mean = 72.2%, Standard Error= 4.62%) when compared with the left hemisphere (Mean= 83.5%, Standard Error= 47.9%, p<.001) **(Figure-6.6)**. For images of fragile cups/mugs, greater de-synchronization of mu oscillation was found in right hemisphere for fragile cups/mugs with atypical left handle (Mean = 65.9%, Standard Error = 5.23%) when compared with right hemisphere (Mean= 79.8%, Standard Error = 5.44%, p=.030) **(Figure-6.7)**.

Predictor	df_{Num}	df_{Den}	*MSe*	*F*	*p*	η_{2g}
(Intercept)	**1**	**16**		**310.11**	**<.001****	**.95**
Handle	1	16	551.26	1.48	.242	.08
Robustness	1	16	507.25	0.15	.702	.01
Typicality	**1**	**16**	**137.19**	**6.35**	**.023***	**.28**
Hemisphere	1	16	815.62	11.52	.004*	.41
Topography	1	16	2582.27	40.18	<.001**	.72
Handle x Robustness	1	16	428.47	3.46	.081	.18
Handle x Typicality	**1**	**16**	**730.15**	**0.06**	**.809**	**.00**
Robustness x Typicality	**1**	**16**	**912.60**	**0.04**	**.839**	**.00**
Handle x Hemisphere	1	16	459.76	0.46	.506	.02
Robustness x Hemisphere	1	16	150.75	0.02	.879	.00
Typicality x Hemisphere	**1**	**16**	**150.75**	**0.13**	**.727**	**.01**
Handle x Topography	1	16	632.46	0.00	.951	.00
Robustness x Topography	1	16	388.58	0.77	.394	.05
Typicality x Topography	**1**	**16**	**321.96**	**0.55**	**.470**	**.03**
Hemisphere x Topography	1	16	868.12	3.61	.076	.18
Handle x Robustness x Typicality	**1**	**16**	**914.06**	**2.17**	**.160**	**.12**
Handle x Robustness x Hemisphere	1	16	203.96	0.89	.360	.05
Handle x Typicality x Hemisphere	**1**	**16**	**212.90**	**0.23**	**.641**	**.01**
Robustness x Typicality x Hemisphere	**1**	**16**	**178.93**	**7.07**	**.017***	**.31**
Handle x Robustness x Topography	1	16	643.82	0.28	.606	.02
Handle x Typicality x Topography	**1**	**16**	**290.80**	**1.09**	**.313**	**.06**
Robustness x Typicality x Topography	1	16	451.29	2.18	.160	.12
Handle x Hemisphere x Topography	1	16	254.17	0.11	.747	.01
Robustness x Hemisphere x Topography	1	16	261.63	1.65	.217	.09
Typicality x Hemisphere x Topography	**1**	**16**	**133.97**	**0.11**	**.748**	**.01**
Handle x Robustness x Typicality x Hemisphere	**1**	**16**	**205.66**	**9.98**	**.006***	**.38**
Handle x Robustness x Typicality x Topography	**1**	**16**	**630.68**	**8.58**	**.010***	**.35**
Handle x Robustness x Hemisphere x Topography	1	16	300.43	0.42	.527	.03
Handle x Typicality x Hemisphere x Topography	**1**	**16**	**210.19**	**5.12**	**.038***	**.24**
Robustness x Typicality x Hemisphere x Topography	1	16	270.37	0.68	.422	.04
Handle x Robustness x Typicality x Hemisphere x Topography	1	16	230.63	0.49	.494	.03

Table-6.2 Statistical Results of Group-level ERD Analysis based on 2 x 2 x 2 x 2 x 2 ANOVA Test

(df_{Num}= degrees of freedom numerator, df_{Den}= degrees of freedom denominator, *MSe*= mean Standard Error, η_{2p}= partial eta squared as a measure of effect size, *p*= probability value, except p values, all other values were presented with two decimal units and only *p* value were presented with three values in order to examine statistical significance, *significant 0.01<p<0.05, **significant p<=0.001. Greyed-out lines: factors and interactions which replicate analysis in Table-6.1, ignored here to avoid type I error inflation.

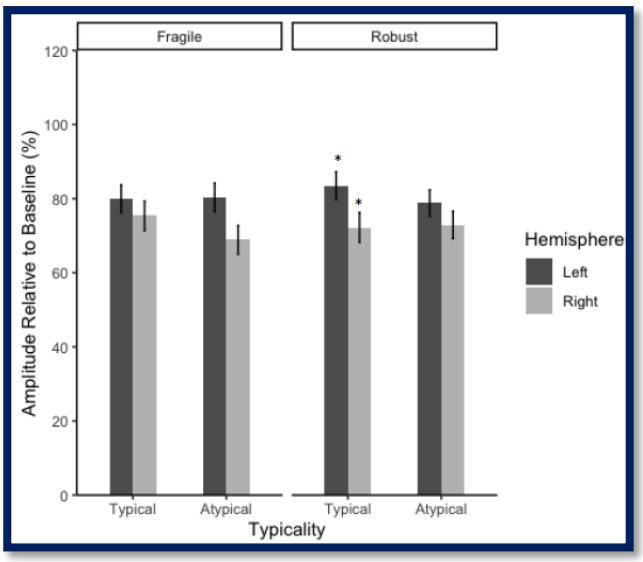

Figure-6.6 Descriptive statistics of the Robustness X Typicality X Hemisphere interaction

(In this graph, error bars depict one standard error of the mean, and the y-axis depicts the mean relative amplitude of mu suppression Values <100% indicate suppression, lower values represents greater suppressions. The significant difference between left and right hemisphere suppression for typical robust stimuli is represented by *(p<.001)) Graph prepared by C, W.-H

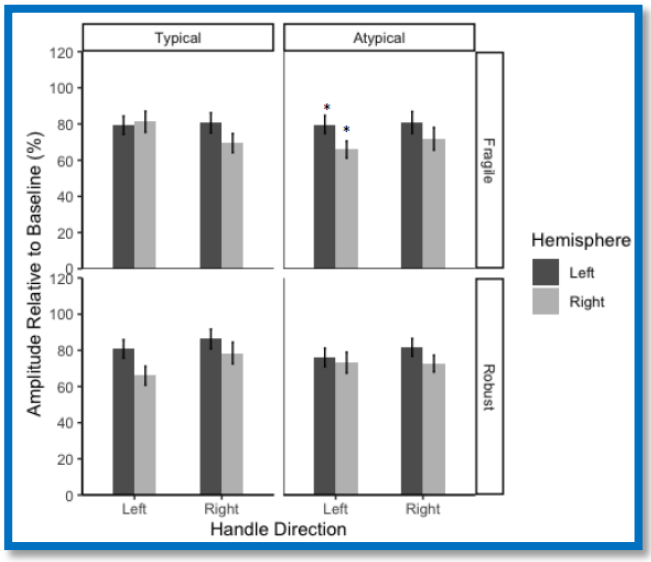

Figure-6.7 Descriptive statistics of the Handle X Robustness X Typicality X Hemisphere interaction

(In this graph, error bars depict one standard error of the mean and the y-axis depicts the mean relative amplitude of mu suppression Values <100% indicate suppression, lower values represents greater suppressions. The significant difference of fragile atypical stimuli with left handles between the right and left hemispheres is represented by * (p=.030).) Graph prepared by C, W.-H.

6.6. DISCUSSION OF TIME-FREQUENCY ANALYSIS OF ERD OF MU OSCILLATION

The main effect of Topography (central vs. occipital areas) is in line with the typical topographical distribution of de-synchronization of mu oscillation (i.e.,~10-Hz EEG) over primary motor cortex (Brodmann area 4) and topographical distribution of de-synchronization of alpha oscillation

(i.e.,~10-Hz EEG) over occipital cortex is less clear. Also, the main effect of the hemisphere between left and right hemispheres is less clear. However, neither the main effect of Topography, nor the main effect of Hemisphere is directly relevant to the research question of the experiment. Statistical significance of two-way interaction between hemispheric laterality and topography **(Figure-6.5)** can be associated with the influence of location of the handle on de-synchronization of mu oscillation specific to central electrodes. One of the interesting results is greater de-synchronization of mu oscillation for images of cups/mugs with a left handle (i.e., affordance is for left-hand operation), although participants were right-handed by self-report. The contradiction between right-handedness of participants and greater de-synchronization of mu oscillation for left-hand operation affording cup/mug images can be associated with the effect of less familiarity. As is expected, the weakest de-synchronization of mu oscillation was found for images of cups/mugs without a handle **(Figure-6.5)**.

Regarding lateralization of representation of the electrophysiological activity of interest, images of fragile cups/images with left atypical handled show statistically significant hemispheric difference **(Figure-6.7)**. This strong lateralization effect can be associated with handling sensitivity due to the fragility of cups/mugs and handling difficulty because of the atypicality of handle forms which increase the representation of the electrophysiological activity of interest. In this context, stronger lateralization on the left hemisphere can also be associated with contradiction with the right-handedness of participants and the unfamiliarity effect of left-hand operation. However, the lateralization effect could not be seen separately for central areas (de-synchronization of central mu oscillation) and occipital areas (de-synchronization of anterior alpha oscillation). In this regard, semiotic properties of both handle form (typicality) and material properties/cultural context of the cup/mug as a whole object and novelty/unfamiliarity of afforded imagery hand operation have an influential role on motor imagery/embodied perception.

7. EXPERIMENT 4 (BEHAVIOURAL)

7.1. LITERATURE REVIEW

Fourth Experiment and Predictions

In the fourth experiment, cognitive aspects beyond the interaction between architectural affordance of presented images of doors with five different handle types (i.e., stimuli of the first experiment) and effects of embodied perception/implicit motor imagery will be investigated through reaction times relevant to the given tasks within the designed behavioural experiment (see, Tipper et al., 2006; Loach et al., 2008; Cho and Proctor, 2011; 2013). This experiment will expand the neurophysiological findings of the first experiment and support a deeper understanding of perception-action relationships within the context of architectural affordance. Cognitive aspects reflected reaction times can also help dissociate spatial account of stimulus-response compatibility effect from affordance account of object-based correspondence effects. Although images of doors will be presented close to the hand-scale, we expected the reaction times would vary in line with the effect of architectural affordance. Due to contra-lateral interactions between door handles and hand of the user within architectural affordance context, we predicted 1) reaction times should be faster if the participant's hand on the keyboard and handle location of the presented door image is contra-lateral due to the affordance effect; 2) reaction times should vary in line with the category of door with different handles which offers a different way of hand interaction or familiarity; 3) unrelated to the research question, we predicted that reaction time where the response hand is right should be faster than left response hand used condition due to right-handedness of participants.

7.2. METHODOLOGY, EXPERIMENT DESIGN AND DATA ACQUISITION

The method of this experiment is a performance-based behavioural experiment which gives a task to participants (i.e., pressing a response key relevant to task instruction) to measure their response times and error rates (Harris, 2008; Sani and Todman, 2008; Abdi et al., 2009; McBride, 2018; MacLin, 2020). The experiment is designed by benefitting from repeated measures experiment design (Leik, 1997; Ellis, 1999; Sullivan, 2008; Salkind, 2010; Verma, 2015) where participants experience all defined independent components (e.g., stimuli categories, task types) of the experiment. All participants were recruited through either poster advertisement & e-mail or the university's research participation scheme (RPS). Voluntary participants have received either inconvenience allowance or points in the SONA system because the experiment took approximately 45 minutes. In this experiment, participants were requested to sit in front of a

computer/laptop and fulfil the task accordingly given instructions written on the screen during the flow of the experiment. At the end of the experiment, the participants' reaction times were analyzed statistically to understand the effects of cross-modality on the decision times of participants for responding (i.e., fulfilling the task).

Totally 48 participants were recruited, and the first 14 of them were recruited by one of the experimenters, Hasan Kartal (H.K.) and the remaining 34 ones were recruited by another experimenter, Kenneth Tong (K.T.). All recruited participants were right-handed by self-report (they were informed that right-handedness is necessary before recruitment). Their age, gender information was recorded before the experiment and also some brief notes relevant to the observation of experiment flow (e.g., problems, difficulties, level of attention of participant) were also taken by the experimenters in a daily experiment log. The experiment was approved by the ethics committee of the School of Psychology, the University of Nottingham, with reference number “F978”. Potential participants who paid attention to the experiment received an information sheet. After reading the information sheet, if the participants were still volunteers, the available time slots would be sent to potential participants and participants were recruited at a convenient time. No more than one participant participated in the experiment at a time.

In this experiment, the same stimuli as the stimuli of the first EEG experiment were used. Five different door categories affording different hand operations for opening the door were used. These door categories can be listed as (1) doors with a horizontal bar, (2) doors with a vertical bar, (3) doors with a knob, (4) doors with a lever handle, (5) doors with a push plate (i.e., swinging doors). Laterality of handle location of the door was also taken into account for defining stimuli categories. Thus, two additional laterality category was defined as (1) doors with a handle located on the left side of the door (shortly, left or left-handed) and as (2) doors with a handle located on the right side of the door (shortly, right or right-handled). Totally ten (i.e., 5 door category x 2 laterality category) stimuli categories were defined. In each category (door category x laterality), 24 images of doors were used, and each stimulus was presented to participants twice in pseudo-randomized order. Thus, a totally 480 stimuli were presented to participants (2 presentation times x 24 images of doors in each category x 5 door category x 2 laterality = 480).

Door Category	Example Stimuli *Right Hand Operation*	Example Stimuli *Left Hand Operation*
HORIZONTAL		
KNOBBED		
SWINGING		
LEVER		
VERTICAL		

Table-7.1 Stimuli Categories of the Experiment
(24 images of doors in each category, total 2 x 240 = 480 stimuli)

The stimuli sequences were presented to participants block by block in pseudo-randomized order where each block contains 20 stimuli (i.e., images of the doors). Thus, the experiment includes 24 blocks (20 x 24 = 480). At the end of each sixth block (after every 120 stimuli were presented), the experiment design allows participants to rest and adjust their beginning time to present further the stimuli within the other blocks of the experiment. After each sixth block, either only the response key of the keyboard for fulfilling the task (i.e., response for relevant superimposed circle) or both response key and response hand position were changed for counterbalancing response key for task and response hand position across the experiment flow. All requested changes for fulfilling the task (i.e., response key and response hand information) were instructed to participants via the text presented at the end of each sixth block. Experimental conditions differ in terms of response key on the keyboard (i & m keys) x superimposed circle (red and blue circles) and response hand (RL, right and left hand of the participant). Thus, there are four experimental conditions which can be listed as (iLRed, mRBlue), (iLBlue, mRRed), (iRRed, mLBlue) and (iRBlue, mLRed). All these conditions were counterbalanced to balance the lateralization effect of handle location **(Figure-7.1)**.

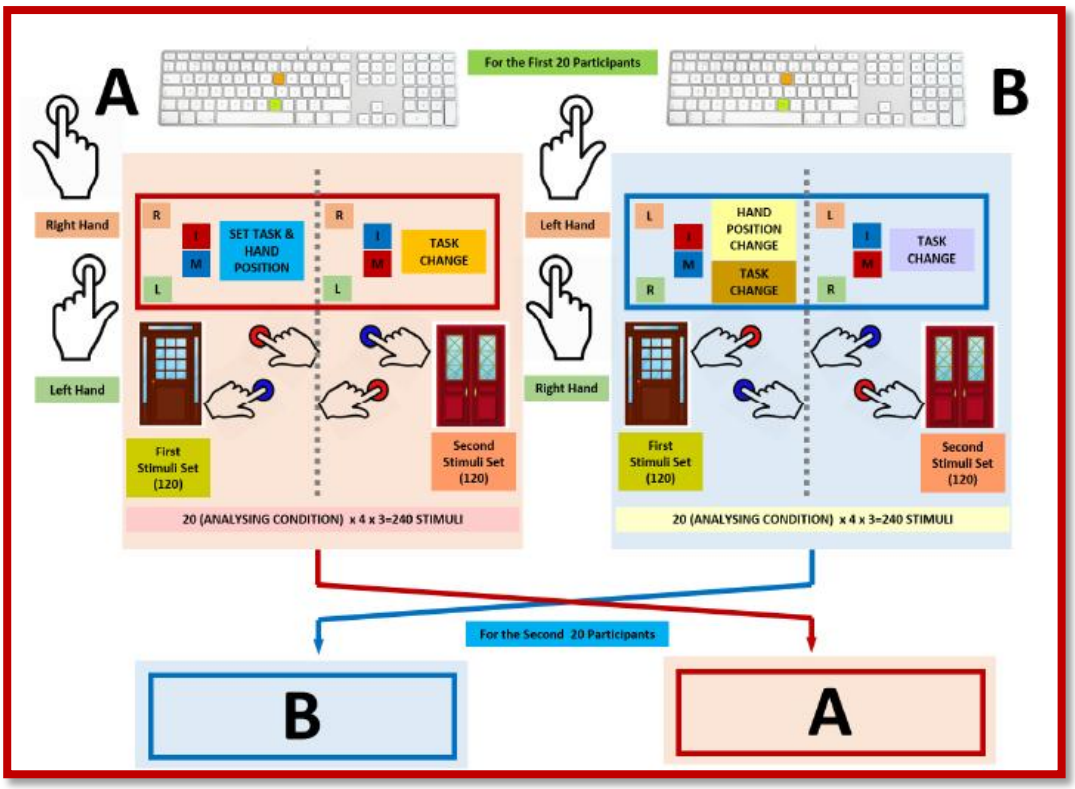

Figure-7.1 A Diagram depicting four experimental conditions & how they are counterbalanced (within and between subjects/participants)

Response keys as i and m were chosen due to their central location on the keyboard, which facilitate to avoid spatial-compatibility effects (e.g., Simon effect) (Simon and Wolf, 1963; Simon and Rudell, 1967; Hasbroucq and Guiard, 1991; Hommel, 1993; 1995; Zorzi and Umiltá, 1995; Hommel and Prinz, 1997; Hommel, 2000; Ansorge and Wühr, 2004; Vallesi et al. 2005; Wühr and Ansorge, 2005; Hommel, 2011; Leuthold, 2011; Dittrich et al., 2013; Dolk et al., 2014). Stimulus compatibility effects (their laterality effect) can mask object based compatibility effects (e.g., Affordance effect) (for object based compatibility effects, Tucker and Ellis, 1998; Shomstein and Yantis, 2002; Tipper et al., 2006; Sevos et al., 2013; Thill et al., 2013; Osiurak and Badets, 2016; Azaad et al., 2019; Gordon et al., 2019; Azaad and Laham, 2020; see for spatial vs./and object based compatibility effects, Proctor et al., 1993; Michaels, 1993; Proctor et al., 1994; Symes et al., 2005; Cho and Proctor, 2010; Pellicano et al., 2010; Borghi et al., 2011; Galpin et al., 2011; Iani et al., 2011; Caligiore et al., 2013; Wilf et al., 2013; Couth et al., 2014; Pappas, 2014; Proctor and Miles, 2014; Song et al., 2014; Kostov and Janyan, 2015; Ambrosecchia et al., 2015; Kume et al., 2016; Saccone et al., 2016). In addition to counterbalancing experiment condition within each participant's acquired data, for counterbalancing the stimuli properties, participants were split into two groups (see for counterbalancing, Gaito, 1961; Pollatsek, and Well, 1995; Reese, 1997; Krauth, 2000, p. 58-65; Harrington, 2010, p.92; Alferes, 2012, p.192-214; Brooks, 2012; DePuy and Berger, 2014; Beins, and McCarthy, 2018, p.238; Schweigert, 2021, p.124-128). The original

images of doors were presented to the first group of participants. The second group of participants were given by a horizontally flipped version of the same stimuli.

The experiment was designed on PsychoPy v.3.0.4, and 1.90.3 (Peirce et al., 2019) by Hasan Kartal and stimuli were presented to participants on a uniform gray background. In addition to the main experiment, two additional experiments as demo experiments were also designed to familiarise the participant to the experiment environment (and to explain the task and check the participants' performance in terms of fulfilment of the task). Each stimulus has a different resolution, but stimuli widths were fixed to 300 pixels (x-axis), and the heights of stimuli were changing (y-axis) in both main experiment and two demo versions. All experiments were presented to participants via either Hasan Kartal's laptop (15.6-inch HP 250 G3 Intel Core with a 60Hz refresh rate) or via classroom computers (21.5-inch iMac running macOS Mojave version 10.14.6 on a 4096 x 2304-pixel screen with 60 Hz refresh rate with Radeon Pro 560X 4gb graphics) by Kenneth Tong. Stimuli were presented from 60 cm distance and stimuli width was 7.57 cm for laptop presentation and width was 7.37 cm for classroom computer presentations. Stimuli heights were changing from minimum 6.43 cm to maximum 20.81 cm for laptop presentation and from minimum 6.44 cm to maximum 20.84 cm for classroom computer presentation. Visual angle was 7° 13' for laptop presentation and 7° 1' for classroom computer presentation in horizontal axis. In vertical axis, visual angles were changing from minimum 6° 8' to maximum 19° 40' for laptop presentation and from minimum 6° 8' to maximum 19° 42' for classroom computer presentation **(Table-7.2)**. All experiments were conducted either in Computer Labs or EEG Lab of School of Psychology, University of Nottingham.

Stimuli Presentation Details of the Experiment	**Phase 1: Laptop (Experimenter: Hasan Kartal, H. K.) (14 Participants)**		**Phase 2: Computers in Computer Classrooms of School of Psychology (Experimenter: Kenneth Tong, K. T.) (34 Participants)**	
Technical Aspects of the Monitor	15.6-inch HP 250 G3 Intel Core with a 60Hz refresh rate		21.5-inch iMac running macOS Mojave version 10.14.6 on a 4096 x 2304-pixel screen with 60Hz refresh rate with Radeon Pro 560X 4gb graphics	
Monitor Size (x, y)	34.4 cm x 19.4 cm		47 cm x 27 cm	
Distance from Monitor	~ 60cm		~ 60 cm	
Numbers of the Stimuli	480 stimuli (2 presentation times x 24 images of doors in each category x 5 door category x 2 laterality)		480 stimuli (2 presentation times x 24 images of doors in each category x 5 door category x 2 laterality)	
Stimuli Width (x-axis)	7.57 cm		7.37 cm	
Stimuli Height (y-axis)	Maximum	20.81 cm	Maximum	20.84 cm
	Minimum	6.43 cm	Minimum	6.44 cm
Visual Angle	7° 13'		7° 1'	

(Horizontal)				
Visual Angle (Vertical)	Maximum	19° 40'	Maximum	19° 42'
	Minimum	6° 8'	Minimum	6° 8'

Table-7.2 Stimuli Presentation Details (from both Laptop and School Computers)

In each trial, images of different doors were presented for 2 s and 800 ms after each stimulus onset, either a red or a blue superimposed circle with 50% opacity were displayed for 800 ms. Accordingly, the colour of the circle (either red or blue), the participants fulfil the task by pressing a response key accordingly instruction text which was presented at the beginning of each six blocks. After the superimposed circle (blue/red) display, the presented circle (i.e., blue/red circle) were replaced by either a light or a dark gray circle for maximally 400 ms to avoid any priming effects of red/blue coloured circles on task performance **(Figure-7.2)**. All pairs of superimposed circles (either blue/red circles or dark/light gray circles) were presented in pseudo-randomized order in each trial. All superimposed circles were the same size and presented to participants within 100 x 100 pixel imaginary square area at the centre of the screen. A fixation cross was presented within randomized duration (any duration from at least one second to the most two seconds).

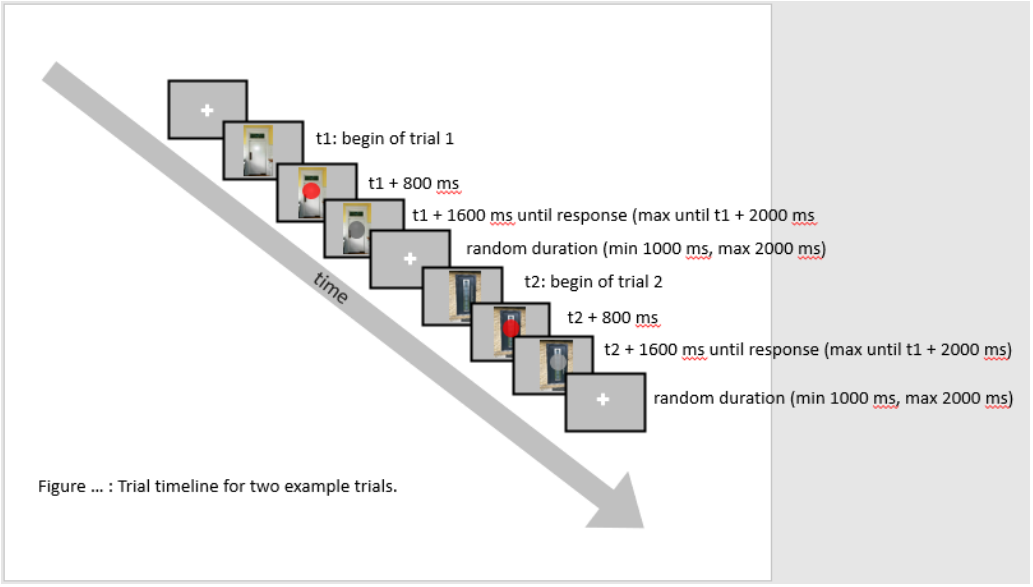

Figure-7.2 Timeline of stimuli presentation (for two example trials)

During the experiment, participants were requested to put their index fingers on “I” and “m” response keys due to their positions on the keyboard (central position to avoid spatial laterality effect of response). After each sixth block of the experiment, participants were requested to change either their response key (i & m) to respond appearing superimposed circle (blue/red circle) or response hand (left/right hand) position (top/down on the keyboard) for counterbalancing experimental conditions. Therefore, during the experiment flow, participants

received a task instruction (for example, respond i to blue circle, m to red circle). After each sixth block, the instructions changed (i for red, m for blue). After block twelve, participants were instructed to change hand position: one index finger from "i" (top of keyboard) now on "m" (bottom of keyboard), the other index finger vice versa **(Figure-7.3)**.

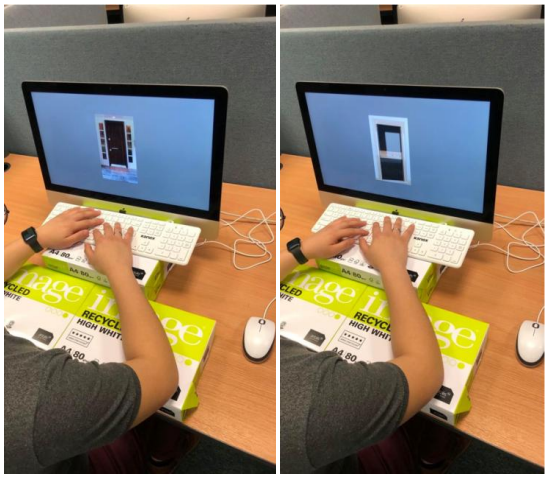

Figure-7.3 The left/right response hand position changes (top/down position on the keyboard) and desk setup across the experiment (prepared by Kenneth Tong)

In addition to the main experiment, two demo versions were designed to familiarize the participants with the task and experiment environment. The same stimuli were used for both of the demo versions of the main experiment, and all of the stimuli of the demo versions were different from the stimuli of the main experiment to avoid repeated presentation of stimuli which will trigger memory processes and potentially also suppress EEG responses (Schacter and Buckner, 1998; Grill-Spector et al., 2006; Summerfield et al., 2008; Horner and Henson, 2008; Garrido et al., 2009; Engell and McCarthy, 2014). The first demo experiment was very slow to let participants understand the response key and response hand changes accordingly given instructions presented on the screen. The first demo was designed for habituation (Thompson and Spencer, 1966; Groves and Thompson, 1970; Rankin et al., 2009; Thompson, 2009) of the participants to task and experiment environment. The second demo experiment was designed at the same speed as the main experiment, where participants could practice the actual experiment environment and the task of the main experiment with different stimuli.

In the slow demo experiment, images of doors/stimuli were presented for 5.5 s and 1.6 s after stimulus onset, superimposed red or blue circles were presented for 2.5 s and then superimposed red or blue circle was replaced by light or dark gray circle automatically and presented for 1.4 s. All superimposed circles were the same size and presented to participants within 100 x 100 pixel imaginary square area at the centre of the screen in pseudo-randomized order. Between each trial, a fixation cross was presented to participants in randomized duration (any duration from at

least two seconds to the most four seconds). In demo versions of the main experiment, 80 stimuli were used, and experiments were split into four blocks. Each block contained 20 stimuli, and at the end of each block, the participants were requested to change either their response key accordingly superimposed blue/red circle or both response key and response hand, similar to the main experiment. For requested changes, participants were informed with the same instructions of the main experiment presented on the screen at the end of each block.

During the demonstration of demo versions of the experiment, participants were not closely monitored to avoid creating any stressful environment on participants, but the experimenter was readily accessible for any question during the experiment. At the end of the main experiment, some self-report questions such as 'how did you find the study? and what do you think about the aim of the experiment?' were asked to examine whether each participant could guess the aim of the experiment or not. And then, they received a debrief form that explained the aim of the study and privacy notice which gave information about data protection and preservation policy.

Differently from previous EEG experiments, there is no specific preparation process for data acquisition in this computer-based behavioural experiment. For data acquisition, participants were requested to sit in a relaxed position in front of the experimenter's computer and requested to fulfil the tasks in both demo experiments and the main experiment. Data containing response times of each participant was automatically generated and saved in comma-separated values (.csv file) format by PsychoPy software. All individual-level data were addressed to R programming language for data analysis and IBM SPSS (Gray and Kinnear, 2012; Field, 2013; Ho, 2013; Meyers et al., 2013; Stehlik-Barry and Babinec, 2017; Morgan, 2019) for group-level statistical analysis. Ten different stimuli categories were defined in group-level data analysis for categorization of the data accordingly stimuli categories (i.e., 5 door categories and 2 laterality categories).

7.3. DATA ANALYSIS: RESPONSE TIME ANALYSIS

Differently from EEG experiments, in the computer-based behavioural experiment, there was no data pre-processing step. Before data analysis, only data cleaning step for mistrials (e.g., wrong task performance such as wrong response hand or response key use) and outlier responses (longer response times than 1 s) were performed independently from data analysis (see for the outlier in statistics, Hodge and Austin, 2004; Ben-Gal, 2005; Rousseeuw and Leroy, 2005; Chandola et al., 2007; Kriegel et al., 2010; Rousseeuw and Hubert, 2011; Aggarwal, 2017; Wang et al., 2019). After eliminating outliers and mistrials, group-level statistical analysis for mean response times was performed. For individual-level analysis, data were addressed to R

Programming Language. For group-level statistical data analysis of mean response time, four different factors were defined as (1) *response hand* (Left/Right), (2) *response key* (“i” and “m”), (3) *colour of superimposed circle* responded for task performance (Red/Blue) and (4) *laterality* which refers to response hand’s interaction with afforded hand operation by presented door handles of different door types (Contra-lateral/İpsi-lateral) **(Table-7.3)**.

After completing individual-level repeated measures within subjects’ factors analysis (Roger et al., 1979; Girden, 1992; Keselman et al., 1999; Keselman, 2001; Loerts, 2008; Park et al., 2009; Lawal, 2014; Lee, 2015; Galilei, 2018; Lix and Keselman, 2018) for mean response time, a Microsoft Excel File was generated. Moreover, data within each generated excel file were addressed to IBM SPSS Statistics 26 (George and Mallery, 2019) to examine the effect of laterality (Contra-lateral/İpsi-lateral) more comprehensively through General Linear Model Repeated Measures ANOVA (Weinfurt, 2000; Keselman et al., 2001; von Ende, 2001; Davis, 2002; Haase and Haase, 2011; Rutherford. 2011; Heson, 2015; Vik, 2015; Cleophas and Zwinderman, 2018, p.147-180; Sharma, 2020). After group-level statistical analysis for GLM Repeated Measures 2 x 2 x 2 x 2 x 2 ANOVA were performed with between-subjects factor as 2 level *experiment phase* factor (i.e., Phase 1 (H.K.), Phase 2 (K.T.)) (tests between subjects effect, Maxwell et al., 1991; Edwards, 1993, p.114-126; Algina and Olejnik, 2003; Gonzalez, 2009, p.165-190; Privitera, 2011, p.229-252; Leroy, 2011; Young et al., 2012; Leong et al., 2019) and within subjects factors which can be listed as; 2 level *response key* factor (i.e., Key I, Key M), 2 level *response hand* factor (i.e., left hand, right hand), 2 level *colour of superimposed circle* (task) (i.e., red, blue) and 2 level *laterality* factor (i.e., *contra-laterality*, -response hand contra-lateral to door handle-, *ipsi-laterality*, -response hand ipsi-lateral to door handle) (Lyons and Thomas, 1967; Greenwald, 1976; Keselman and Keselman, 1990; Bakeman, 2005; Lambdin, 2009; Cotton, 2013; Lane, 2019; see for tests within & between subjects effect/design, Keren and Raaijmakers, 1988; Gleason, 1999; Lamb, 2003; Thompson and Campbell, 2004; Keren, 2014; Mullet and Chasseigne, 2018). And then, statistical significance among the main effect of factors or interactions was examined. Next, mean values of statistically significant factors and interactions were obtained as estimated marginal means in SPSS output (Searle et al., 1979; Searle et al., 1980).

Defined Factors for Tests of Between Subjects Effects and Tests of Within Subjects Effects				
Between Subjects Effect	**Response Key**	**Response Hand**	**Colour of Superimposed Circle (Task)**	**Laterality**
Phase 1 (H.K., 14 participants)	Key I	Left Hand	Red	Contra-Laterality
				Ipsi-Laterality
			Blue	Contra-Laterality
				Ipsi-Laterality

		Right Hand	Red	Contra-Laterality
				Ipsi-Laterality
			Blue	Contra-Laterality
				Ipsi-Laterality
	Key M	Left Hand	Red	Contra-Laterality
				Ipsi-Laterality
			Blue	Contra-Laterality
				Ipsi-Laterality
		Right Hand	Red	Contra-Laterality
				Ipsi-Laterality
			Blue	Contra-Laterality
				Ipsi-Laterality
Phase 2 (K.T., 34 Participants)	Key I	Left Hand	Red	Contra-Laterality
				Ipsi-Laterality
			Blue	Contra-Laterality
				Ipsi-Laterality
		Right Hand	Red	Contra-Laterality
				Ipsi-Laterality
			Blue	Contra-Laterality
				Ipsi-Laterality
	Key M	Left Hand	Red	Contra-Laterality
				Ipsi-Laterality
			Blue	Contra-Laterality
				Ipsi-Laterality
		Right Hand	Red	Contra-Laterality
				Ipsi-Laterality
			Blue	Contra-Laterality
				Ipsi-Laterality

Table-7.3 Defined factors for group-level data analysis in IBM SPSS Statistics 26

7.4. RESULTS OF RESPONSE TIME ANALYSIS

There was a significant between subjects effect between Phase 1 vs. Phase 2 of the experiment. Mean of response time in Phase 2 (K.T.) were 453 ms, 43 ms faster than mean of response time of Phase 1 (H.K.) of the experiment which were 496 ms and main effect of between subjects factor was $F(1,46)=9.892$, $p=0.003$, partial eta squared 0.177. However, the interaction between the between-subjects factor and the factor contra-laterality was not significant (ContraIpsi X Phase 1_Phase 2; $F(1,46)=1.986$, $p=0.165$, partial eta squared 0.041). The main research question of the experiment was about contra-laterality between response hand and afforded hand operation by the handle of the door images. However, statistical significance could not be found in this factor (main effect), $F(1,46)=0.226$, $p=0.637$, partial eta squared 0.005, and there were no statistically significant interactions with this factor **(Table-7.4)**.

Factor Names and Interactions	Tests of Between Subjects Effects				
Source	DF_n	ANOVA DF_d	F	Probability Value (p)	Partial Eta Squared
HK_1_KT_2	1	46	9.892	0.003	0.177

Table-7.4 Results of Group-level Statistical Analysis of Main Effect of Between-Subjects through General Linear Model Repeated Measures ANOVA

(DF_n = degrees of freedom numerator, DF_d = degrees of freedom denominator, p = probability value, Columns are round to 3 decimal places. Significant effects are in coloured in blue.)

Factor Names and Interactions	Tests of Within-Subjects Effects (Combined with Between Subjects Effect)				
	DF_n	ANOVA DF_d	F	Probability Value (p)	Partial Eta Squared
KeyI_KeyM	1	46	0.013	0.911	<.001
KeyI_KeyM * HK_1_KT_2	1	46	1.005	0.321	0.021
LHandRHand	1	46	10.396	0.002	0.184
LHandRHand * HK_1_KT_2	1	46	0.182	0.672	0.004
RedBlue	1	46	6.075	0.018	0.117
RedBlue * HK_1_KT_2	1	46	0.41	0.525	0.009
ContraIpsi	1	46	0.226	**0.637**	0.005
ContraIpsi * HK_1_KT_2	1	46	1.986	**0.165**	0.041
KeyI_KeyM * LHandRHand	1	46	24.273	<0.001	0.345
KeyI_KeyM * LHandRHand * HK_1_KT_2	1	46	2.771	0.103	0.057
KeyI_KeyM * RedBlue	1	46	3.901	0.054	0.078
KeyI_KeyM * RedBlue * HK_1_KT_2	1	46	5.322	0.026	0.104
LHandRHand * RedBlue	1	46	0.725	0.399	0.016
LHandRHand * RedBlue * HK_1_KT_2	1	46	0.017	0.898	<.001
KeyI_KeyM * LHandRHand * RedBlue	1	46	3.528	0.067	0.071
KeyI_KeyM * LHandRHand * RedBlue * HK_1_KT_2	1	46	2.706	0.107	0.056
KeyI_KeyM * ContraIpsi	1	46	0.99	0.325	0.021
KeyI_KeyM * ContraIpsi * HK_1_KT_2	1	46	2.121	0.152	0.044
LHandRHand * ContraIpsi	1	46	0.024	0.877	0.001
LHandRHand * ContraIpsi * HK_1_KT_2	1	46	2.363	0.131	0.049
KeyI_KeyM * LHandRHand * ContraIpsi	1	46	0.002	0.967	<.001
KeyI_KeyM * LHandRHand * ContraIpsi * HK_1_KT_2	1	46	0.067	0.796	0.001
RedBlue * ContraIpsi	1	46	0.704	0.406	0.015
RedBlue * ContraIpsi * HK_1_KT_2	1	46	0.004	0.952	<.001
KeyI_KeyM * RedBlue * ContraIpsi	1	46	0.058	0.811	0.001
KeyI_KeyM * RedBlue * ContraIpsi * HK_1_KT_2	1	46	1.471	0.231	0.031
LHandRHand * RedBlue * ContraIpsi	1	46	0.131	0.719	0.003
LHandRHand * RedBlue * ContraIpsi * HK_1_KT_2	1	46	0.141	0.709	0.003
KeyI_KeyM * LHandRHand * RedBlue * ContraIpsi	1	46	4.616	0.037	0.091
KeyI_KeyM * LHandRHand * RedBlue * ContraIpsi * HK_1_KT_2	1	46	1.622	0.209	0.034

Table-7.5 Results of Group-level Tests of Within-Subjects Effects (Combined with Between Subjects Effect) Statistical Analysis (2 x 2 x 2 x 2 x 2) through General Linear Model Repeated Measures ANOVA
(Greenhouse-Geisser correction was applied where it is appropriated)

(DF_n = degrees of freedom numerator, DF_d = degrees of freedom denominator, p = probability value, Columns are round to 3 decimal places. Significant effects are coloured in blue, and values relevant to the research question are coloured in orange.)

In terms of mean response time relevant to laterality effect, contra-lateral trials (i.e., affordance effect) were 475 ms and 1 ms faster than ipsi-lateral trials, which were 476 ms (i.e., spatial-compatibility effect) **(Figure-7.4)**.

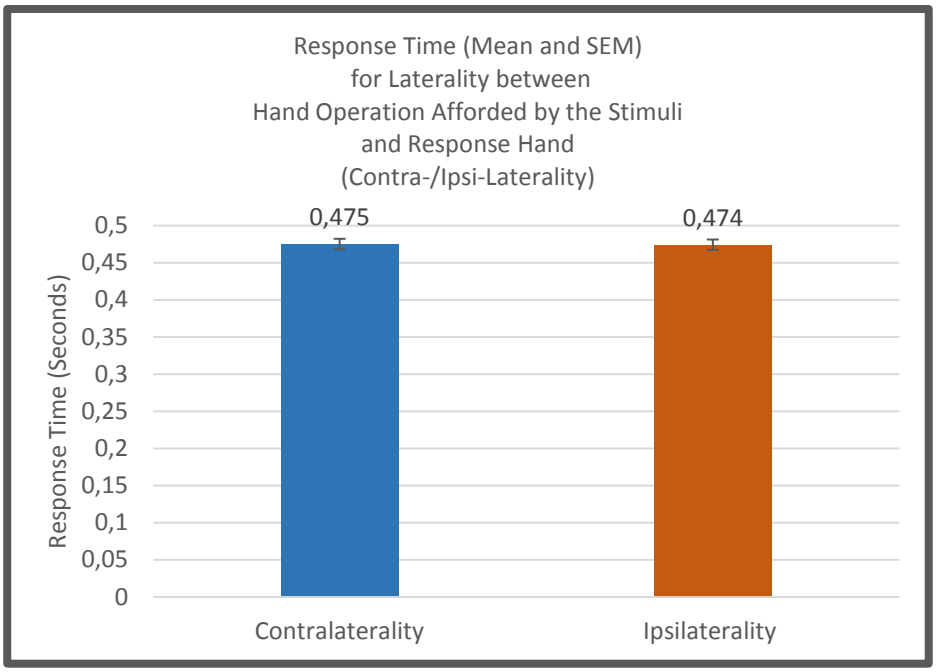

Figure-7.4 Mean Response Times for Laterality Factor (Contra-/Ipsi-Laterality between response hand of the participant and afforded hand operation by door handle of presented door images) (Means were obtained as EMMs in SPSS Output)

Although there was no significant effect of laterality, many significant effects were unrelated to the research question. Mean response times for response hands (i.e., right, left) were also calculated. The right-hand responses were 469 ms, 11 ms faster than left-hand responses, which were 480 ms, and the main effect of response hand factor (i.e., left hand and right hand) was $F(1,46)=10.396$, $p=0.002$, partial eta squared 0.184. Faster right-hand responses can be explained by right-handedness of the recruited participants (by self-report). Additionally, the mean response time for the superimposed red circle was found 471 ms, 7 ms faster than the superimposed blue one, which was 478 ms. The main effect of the colour of the superimposed circle on the main stimuli (i.e., red and blue circles) was $F(1,46)=6.075$, $p=0.018$; partial eta squared 0.117. This effect can be associated with visual luminance, and the colour of red is associated with the warning, danger, action (Eliot et al., 2009; Elliot and Aarts, 2011; Elliot and Maier, 2014; Meier et al., 2015; Nichols, 2015; Wiedemann, 2016) and may stimulate the participants more powerfully than superimposed blue ones.

In terms of the mean response time of two-way interactions between response key (i/m) and response hands of the participants (right(R)/left(L)), m (key) x R (hand) and i (key) x L (left) both of which share the same hand conditions show the slowest reaction times. In terms of conditions of the experiments in the different session of the experiment flow, the mean response time of iLmR was 463.5 ms and 22.5 ms faster than iRmL condition, which was 486 ms and interaction between response key (i.e., key I and key m) and response hand (i.e., left hand and right hand) was $F(1,46)=24.273$, $p=0.000$, partial eta squared 0.345. Although the reason beyond this effect is ambiguous, it can be associated with practising effects (Thompson and Spencer, 1966; Groves and Thompson, 1970; Schacter and Buckner, 1998; Grill-Spector et al., 2006; Summerfield et al., 2008; Horner and Henson, 2008; Garrido et al., 2009; Rankin et al., 2009; Thompson, 2009; Engell and McCarthy, 2014) because iLmR condition of the experiment was performed in only one sessions - in later blocks of the experiment. This explanation, however, does not account for the fatigue effect.

7.5. DISCUSSION OF RESPONSE TIME ANALYSIS

Although the experiment aimed to find the affordance effect relevant to images of doors presented to participants, we could not find any statistical significance in faster mean response time of contra-lateral interaction (the contra-lateral interaction should be between response hand and afforded hand operation by the handle of presented door images). This result can be associated with the presentation size of images of doors and handles instead of their realistic size (Warren, 1984; Ono et al., 2013; Brandl et al., 2015; Sollfrank et al., 2015; Alimardani et al., 2018; Kourtis et al., 2018; Ono et al., 2018; Choi et al., 2020; Carrere et al., 2021). One of the main problems of affordance studies is to dissociate spatial compatibility effect, which mainly focuses on visual perception oriented spatial matching (same laterality) between response and target (e.g., Simon effect) from object-based compatibility effects (e.g., affordance effect) (Proctor et al., 1993; Michaels, 1993; Proctor et al., 1994; Symes et al., 2005; Cho and Proctor, 2010; Pellicano et al., 2010; Borghi et al., 2011; Galpin et al., 2011; Iani et al., 2011; Caligiore et al., 2013; Wilf et al., 2013; Couth et al., 2014; Pappas, 2014; Proctor and Miles, 2014; Song et al., 2014; Kostov and Janyan, 2015; Ambrosecchia et al., 2015; Kume et al., 2016; Saccone et al., 2016).

And for daily hand-scale objects (e.g., mugs, cups), these two effects were overlapping due to grasping action fulfilled where response hand and response target are spatially the same in terms of body's bilateral symmetry (Enticott et al., 2010; Humphreys et al., 2010; Vainio et al., 2011; Bozzacchi et al., 2012; Piotr and Edward, 2012; Wykowska and Schubö, 2012; Boutonnet et al., 2013; Cardellicchio et al., 2013; Vainio et al., 2014; Freeman et al., 2016; Hailperin-Lausch, 2017; Rounis et al., 2018; Hailperin-Lausch and Bertenthal, 2019; Scerrati et al., 2020; Federico et al.,

2021; Kumar et al., 2021, see for other daily hand-scale objects, Cardellicchio et al., 2011; Roberts and Humphreys, 2011; McBride et al., 2012; Lien et al., 2013; Makris et al., 2013; Natraj et al., 2013; Rüther et al., 2014; Flumini et al., 2015; Natraj et al., 2015; Invitto et al., 2016; Saccone et al., 2016; Skiba and Snow, 2016; Wamain et al., 2016; Wulff et al., 2016; Dagaev et al., 2017; McNair et al., 2017; Vastano et al., 2017; Schulz et al., 2018; Wamain et al., 2018; Federico and Brandimonte, 2019; Kim and Lee, 2020; Ferguson et al., 2021; Mustile et al., 2021).

However, dissociating these effects is easy for full-body scale objects such as doors, cupboards. Opening these objects/architectural elements can be achieved when the response hand and response target are contra-lateral (Tipper et al., 2006; Loach et al., 2008; Cho and Proctor, 2011; Cho and Proctor, 2013; Lien et al., 2014; Vecchiato et al., 2015; Jelić et al., 2016; Banaei et al., 2017; Rietveld and Brouwers, 2017; Djebbara, 2018; Djebbara et al., 2019; Djebbara et al., 2020a; Djebbara et al., 2020b; Florescu and Nistor, 2020; Jelić, 2020; Djebbara et al., 2021; Djebbara, 2021; Jelić, 2021). In this regard, the non-significant contra-laterality effect can be associated with the size of the images where the participant may experience these images as if they are hand-scale daily objects. Thus, they may spontaneously concentrate visual properties of the image instead of experiencing implicit motor imagery (mental agency) for opening the door. However, if the size does not have any impact on the experience of motor imagery for affordance effect, lack of expected statistical result can also be associated with lack of motor properties presented mere visual images (Humphrey et al., 1994; DeLoache et al., 1998; Friedman and Johnson, 2000; Chainay and Humphreys, 2001; Schendan and Kutas, 2003; Bonfiglioli et al., 2004; Symes et al., 2005; Rugg and Curran, 2007; Harris and Wilcox, 2009; Cisek and Kalaska, 2010; Snow et al., 2011; Heft, 2013a; Pappas, 2014; Proctor and Miles, 2014; Snow et al., 2014; Squires et al., 2016; Proctor et al., 2017; Gomez et al., 2018; Pegna et al., 2018; Marini et al., 2019; Bhargava et al., 2020; Xiong et al., 2021.

Thus, the cross-modal interaction beyond affordance effect, between visual processes and motor imagery/embodied perception, is addressed in several studies in neuro- and cognitive psychology (Goodale et al., 1991; Goodale and Milner, 1992; Milner and Goodale, 1993; Goodale et al., 2004; Milner and Goodale, 2006; Milner and Goodale, 2008; Proverbio et al., 2011; Ambrosini et al., 2012; Goslin et al., 2012; Kumar et al., 2013; Volcic et al., 2013; Cañal-Bruland and Van Der Kamp, 2015; Vecchiato et al., 2015; Thermos et al., 2017; Rounis et al., 2018; Job, 2019; Freud et al., 2020; Wagman and Blau, 2020; Ferretti, 2021). Another reason can also be associated with the size of the superimposed circle and their presentation position (on the centre), which may create difficulty to focus on the handle of doors (relatively small) during the fulfilment of the task. Although the task aimed to direct the participants' attention to the centre of the door images,

close to the handle, their performance concerns may mask their attention to handle. This may diminish the affordance effect in statistical results.

Regarding future alternatives, the issues related to the size, realisticity/volumetricity, non-masking task design should be considered. In terms of response target as superimposed red/blue circles, faster response time for superimposed red can be associated with its luminance and bio-semiotic and signalling values (Eliot et al., 2009; Elliot and Aarts, 2011; Elliot and Maier, 2014; Meier et al., 2015; Nichols, 2015; Wiedemann, 2016). However, in terms of future designs, chosen colours should also be counterbalanced. Although the response target for task fulfilment (superimposed blue/red circle) may not directly affect the expected result, it has the potential to mask the expected result. Additionally, duration of experiment and timings of trials and level of complexity of task should also be considered for further studies to avoid the effects of fatigue which can potentially mask the affordance effect (Lorist et al., 2000; Lorist et al., 2002; Van der Linden et al., 2003; Boksem et al., 2005; Boksem et al., 2006; Csathó et al., 2012; Faber et al., 2012; Hopstaken et al., 2015; Hopstaken et al., 2016; Natraj et al., 2018; Feltmate et al., 2020). Furthermore, experiment conditions (response hand x hand position on keyboard x response target x response key) can also be counterbalanced between subjects in addition to the within-subjects to avoid the effects of timing of practising these conditions in demo presentation.

In literature, the affordance effect was found in several studies focussing on daily hand scale objects such as mugs and cups or tools where additional action planning relevant to the function of the tool is needed (Proverbio et al., 2011; Proverbio, 2012; Mizelle et al., 2013; Natraj et al., 2013; Proverbio et al., 2013; McNair and Harris, 2014; Rüther et al., 2014; Borghi and Riggio, 2015; Kourtis and Vingerhoets, 2015; Natraj et al., 2015; Kalénine et al., 2016; Skiba and Snow, 2016; Osiurak et al., 2017; Federico and Brandimonte, 2019; Foerster and Goslin, 2021). However, the affordance effect could not be detected at a statistically significant level due to either effect of size or lack of volumetricity, with further modifications listed above or just improving the quality of existing stimuli.

CHAPTER 8: THE GENERAL DISCUSSION OF THE THESIS

8.1 THE CONCLUSION DEBATE ON THE RESEARCH

One of the main aims of architectural design is to understand humans (with the biological, cognitive and socio-cultural dimensions) and improve the design quality to create better buildings in terms of their compatibility with human biology, cognition, and socio-cultural nature. In this regard, an exemplary designing process should benefit from the contributions of biological sciences (e.g., evolutionary biology, ecology, anatomy and physiology), cognitive sciences (e.g., psychology, neuroscience) and socio-cultural disciplines (e.g., architectural history and theory, sociology, anthropology). In addition to these disciplines, technical considerations (and engineering) relevant to physics and chemistry (e.g., energy engineering, material science) and limits of advanced technology (e.g., computer science, human-computer interaction) should be taken into account. By starting from this consideration, this thesis attempted to understand the 'architectural agency' (with the emphasis on embodied account of post-cognitivism and affordance within ecological psychology and enactivism) from the perspective of neuropsychology through four different experiments. In addition to the methodological contributions of the research, the conceptual framework of this thesis has made original contributions to three different pieces of literature. The first one has been architectural neuroscience (a newly emerging interdisciplinary area), the second area has been architectural agency within neuropsychology, and the third one has been architectural agency within the architectural theory (original contributions to these three literature reviews have already been mentioned within the introduction of the thesis.)

Although there are several originalities in terms of the research's contributions to the three literature pieces, it is crucial to emphasise 1) horizon and problematics (general), 2) strength and weaknesses (thesis-specific) relevant to characteristics of the research to justify its position and value. In terms of horizon and problematics of this research, three issues have been considered as; 1) alternative ways of researching and experimenting (horizon), 2) philosophical and conceptual problematics, 3) methodological and technical problematics. In terms of thesis specific characteristics, three issues can be considered; 1) special features (distinguished characteristics of the thesis), 2) thesis-specific implementation of the problematics, 3) strength and weaknesses. The close horizon of the thesis can be defined in line with either its conceptual position or the distinguishing characteristics relevant to experiments. Close conceptual horizon can be defined by benefitting from three pieces of literature in which the thesis is directly linked and made original contributions. Close experiment horizon can be considered by benefitting from

the distinguishing characteristics of the research's experiments with their alternatives. Additionally, the far conceptual horizon of the research can be determined through the disciplines listed in the previous paragraph, such as biological, cognitive and socio-cultural disciplines.

The conceptual horizon of architectural neuroscience can be considered as one of the conceptual horizons of this research. Thus, this thesis is one of the early attempts to understand the neurophysiological and cognitive aspects relevant to architectural features (i.e., architectural affordance) in terms of architectural agency in the immediate time scale. The alternatives forming the research's horizon in terms of relationships of agents with the architectural domain can be considered as the order of reciprocal interaction with the architectural domain, the ontology of the architectural domain, and the epistemology of architectural research. In terms of the order, two types of order can be mentioned as temporal order and hierarchical order. Temporal order in terms of effects of reciprocal interaction within the architectural agency (e.g., immediate, learning, skill-acquisition, developmental, evolutionary) can be regarded as one of the axes of the horizon to form alternatives within epistemic space. The hierarchical order in terms of the prioritisation of research interest (e.g., brain/cognition domain is prioritised, the architectural domain is prioritised) is another axis within epistemic space, including the close conceptual horizon. Additionally, in terms of the ontology of the architectural domain, designing (pre-existence of the architectural environment) and using/experiencing (existing architectural environment) architectural domain can also be considered as another axis forming the close horizon of alternatives. Regarding epistemology of architectural research, research on potentials of architectural neuroscience and practical implementation areas relevant to potentials (e.g., architectural education, scientific organisations and institutions) can also be considered different discussion axes defining horizon of alternatives.

Examining architecture-specific characteristics in addition to ongoing neurophysiological and cognitive investigations on agency in different modes can form the axis of alternatives within the close conceptual horizon. In this regard, the scale (close to body scale or larger, at least larder than daily objects) and the specific details relevant to architectural environments (such as door handles) give the architecture-specific characteristics to agency and form architectural agency. Therefore, taking into account scale and architecture-specific details and manipulating either one of them or a combination of them can be used diversification of the research and form the close conceptual horizon. Similarly, diversification of methodological and technical/practical dimensions relevant to ways of researching/experimenting can form axes of alternatives in the conceptual horizon of architectural agency discussions within architectural theory literature.

Additionally, benefitting from ways of theoretizations relevant to architectural experience (especially in the context of the ecological dimension of agency) within architectural theory can also define the direction of expansion of close conceptual horizon relevant to the thesis. In order to widen the conceptual horizon, specific characteristics of each discipline (i.e., architecture, cognitive or neuropsychology) such as research attitudes, methodological considerations, practical implementations, technical limits need to be regarded. The tensions relevant to integrating characteristics (e.g., methodology, research design strategies, contribution policy) of the two disciplines (i.e., architecture and neuropsychology) can provide prolific discussions to widen the close conceptual horizon.

In addition to the close conceptual horizon of the thesis, the problematics of different branches of philosophy and different disciplines (besides the sub-branches of the cognitive sciences) demonstrate the far conceptual horizon of the thesis and possible future studies. Philosophical problematics can arise from either general branches of philosophy (e.g., ontology, logic, epistemology) or philosophies dealing with biology and mind/cognition (e.g., philosophy of mind, neurophilosophy) or philosophy/philosophication of science/research characteristics. Possible problematics within the three types of philosophy (general, mind/cognition specific, research/ science-specific) can be addressed to the thesis's central theme and discussions to form a far conceptual horizon by widening the close horizon (the philosophical problematics relevant to the thesis, which can be within the far conceptual horizon, have already been mentioned within general literature review of the experiment chapter.) Furthermore, the research attitudes, methodologies, and technical or practical implementations of sub-branches of cognitive science such as anthropology and artificial intelligence can be considered as the good performance area for creating alternative ways of researching architectural agency. For instance, in evolutionary anthropology, the architectural agency can be examined with its evolutionary and cultural dimensions, and in artificial intelligence, findings of neuropsychology and cognitive science can be implemented to software relevant to artificial intelligence. The examples (either philosophication or benefitting from other sub-branches of cognitive science) which have the potentials for forming a far conceptual horizon can be extended, but further examples of potentials of extending the study will not be given within this part.

Besides far or close conceptual considerations relevant to the thesis, technical and practical limits and potentials can also be considered to define the horizon of alternatives. Integrating two complex domains as architecture and brain/mind creates practical or technical limits and problematics relevant to limits (e. g., prioritisation problem, balancing the complexity of domains, isolation from noise). Strategies relevant to forming testable scenarios for experimenting provide

prolific cogitations such as considering limits of existing technological devices, alternative existing technological devices, alternative future technological advancements relevant to devices and practical limits of experimenting (e.g., time, cost). In this regard, preferring different technologies (e.g., fMRI, TMS) or combining them with used technology (e.g. fMRI+EEG, TMS+EEG) can add an additional dimension to our understanding of architectural agency. Additionally, pushing the limits of used technology (e.g., Mobile Brain-Body Imaging) or attempts for advancing current technology and visionary assessments relevant to the future of tools of neuropsychology can be used as alternatives for examining architectural agency. In terms of practical limits, allocating more funds and appointing a longer time for examining architectural agency with a bigger sample size (i.e., participants, stimuli) with different dimensions can enrich our understanding and form another dimension of the horizon of alternatives.

By considering these three different horizontal dimensions and problematics (i.e., close conceptual, far conceptual and technical/practical horizon), characteristics of the thesis (especially experiments and original contributions), its position and value can be described. In addition to the original contributions of this thesis to three different pieces of literature (i.e., architectural neuroscience, architectural agency in architectural theory, architectural agency in neuropsychology), this thesis criticises and problematises several issues relevant to research. In this regard, several issues relevant to the optimisation of research, such as stimuli selection and method optimisation have been discussed by benefitting from previous research. Additionally, several philosophical problematics arising from different branches of philosophies (i.e., general, mind/cognition specific, research/ science-specific) were also considered within the context of this thesis. Furthermore, experiments of the thesis made unique contributions to the different pieces of literature and theoretical discussions of the thesis.

Among four opportunities in terms of ways of experimenting (i.e., direct vs indirect architectural experience and comparable vs non-statistically comparable), experiments of this thesis consider statistical comparison during the indirect architectural experience (i.e., images instead of the real environment). Additionally, to cope with prioritisation problems relevant to the primary research interests of two disciplines (i.e., brain vs architectural environment), this thesis pays attention to the architectural agency where the brain and architectural environment meets. Furthermore, the chosen ontological ground where this meeting appears is doors with handles which are the unique feature of human architecture and one of the limited architectural elements facilitating communication with the architectural medium. Moreover, our communication differs from architectural elements (e.g., doors, windows) where handle location and used hand for communication/interaction is contra-lateral in contrast to ipsi-lateral communication/interaction

with daily hand-scale objects. Thus, architecture-specific characteristics of architectural elements can be considered with two dimensions without separation as scale (close to the body or larger) and architecture-specific detail (e.g., door handle). Lack of architecture-specific detail may make the neurophysiological or cognitive effects architectural elements close to a natural correspondent element such as door aperture and cave entrance. Lack of scale features (close to the body or larger) may make neurophysiological or cognitive effects of these elements close to daily hand-scale objects (such as using mere handles without a door). Stimuli of the experiments of this thesis were chosen by regarding these aspects. Besides, this thesis also investigates correspondence between contra-lateral architectural interaction (between handle location and used hand for operation) and cross-modal hemispheric interaction (topographic contra-laterality between neurophysiological activities relevant to visual and motor processes). This thesis examines architectural agency in terms of embodied account (especially embodied perception) and in the mode of mental agency (i.e., implicit motor imagery).

In this regard, in addition to original contributions to three mentioned literature within the close horizon of the thesis, the original characteristics of the thesis can be listed in four categories. These are 1) coping with the prioritisation problem without ignoring the ontological stability of participants, 2) dealing with the unique features of human architecture within architecture-specific context, 3) contra-lateral architectural and hemispheric interaction, and 4) cross-modality between embodied and visual processes. These features define the position of this thesis and its value. In addition to these strengths of the thesis, there are also weaknesses arising from either theoretical/conceptual problematics or technical/practical limits relevant to the thesis. In terms of theoretical problematics, heuristic limits of definitions relevant to the architectural agency (or their usage with different contents), perspectivism as a result of diversification of prioritised research aspects relevant to formed assumptions increase difficulties and bring new dimensions. The ontology-epistemology gap problems such as truthmaking aspects of architectural agency also provide inevitable complexity. However, although thesis-specific conceptual problems cannot be remedied easily, they cannot be considered big problems because they emerge as a natural result of human science-making or knowledge-forming processes. The technical and practical limits are mainly related to reducing the complexity of either research domains (i.e., brain or architecture) or research process (e.g., sample size). Improving technical conditions can include more complex dimensions relevant to the architectural agency, such as simulating environments as close as to their realistic correspondents or measuring more neurophysiological aspects with improved or combined technologies. Practical limits relevant to the research process can also be remedied by allocating more time and budget for research with bigger sample sizes

(i.e., participant and stimuli number) with additional dimensions. Technical and practical limits form weaknesses of the thesis.

After examining the strength and weaknesses of the thesis by benefitting from horizons, problematics, distinguished characteristics and limits relevant to the thesis, discussing the findings of the thesis will be helpful. In the first experiment, neurophysiological aspects of the architectural agency were examined via doors with varying handles (i.e., doors with a horizontal bar, doors with a knob, doors with push plate/swinging doors, doors with a lever handle, doors with a vertical bar). In Time-Frequency Analysis for ERD of mu oscillation (associated with implicit motor imagery relevant to embodied perception), neither significant main effect nor interaction was found. It can be associated with a lack of realistic effects due to the size of images close to hand-scale. In Time-Domain/Time Lock Analysis for P100 ERP Waveform Component (associated with visual feature processing), contra-laterality between hemispheric topography and required hand for operation (i.e. handedness) was found significant (in without door category separated analysis). Additionally, changes in the amplitude of P100 ERP Waveform were found in a statistically significant level for two-way interactions between handedness and channels in door category-specific analysis. It is interpreted as it may happen due to size of the handle, visual conspicuousness or familiarity, lack of contradicting cue (i.e., hinges), effect of handedness (i.e., right-handed, self-reported). These results can be associated with motoric influences on early phases of visual feature processing and can be considered as an indicator of cross-modality between embodied/motor and visual processes.

In the second experiment, neurophysiological aspects of architectural agency within the observation of execution of agency context were examined through doors with varying handles (i.e., doors with push plate/swinging doors, doors with a lever handle, doors with a vertical bar). In Time-Frequency Analysis of ERD of central mu and posterior alpha oscillations, statistical difference relevant to relative amplitudes was found across head topography (i.e. channel within hemisphere factor). It can be associated with the features of oscillations of interest (i.e., widespread powerful posterior alpha, localised weaker central mu). Additionally, two-level handle factor (i.e., left, right) and three-level door category factor (i.e., doors with push plate/swinging doors, doors with a lever handle, doors with a vertical bar) was found significant for posterior (i.e., PO7, PO8) and central (C3, C 4) electrodes, respectively. These results can be associated with the influence of visual conspicuousness of handles on ERD of posterior alpha (i.e. visual processing) and influence of features of door categories relevant to motor program on ERD of central mu (i.e. embodied/motor processing), respectively. Changing levels of the relative amplitude of ERD of mu oscillation in line with each door category is associated with familiarity,

visual conspicuousness and the existence of contradicting cues such as hinges or lack of cue relevant to the motor program.

In the third experiment, differently from previous experiments dealing with the architectural agency, neurophysiological aspects of agency with daily hand-scale objects were examined. One of the daily hand-scale objects in the experiments is cups/mugs with/without handles (i.e., left handle, right handle, no handle). Additionally, chosen cup/mug images were also classified in line with material/semiotic properties (i.e., robust, fragile) and handle typicality (i.e., typical, atypical). According to the position of the handle of cups/mugs (i.e., left handle, right handle), relative amplitude changes on central electrodes relevant to ERD of mu oscillation (associated with motor/embodied processes) was found at a statistically significant level. The weakest relative amplitude of ERD of mu oscillations was found for cups/mugs without handle among other handle categories, which can be associated with lack of cue relevant to motor program/affordance grasping. Facilitating effects in terms of ERD of mu oscillation was found for the fragility in terms of material/semiotic properties of cups/mugs and atypical handles in terms of typicality of handles and left handles for the location of handles. These results can be associated with precision calculations relevant to the motor program (i.e., fragile cups/mugs), novelty or unfamiliarity (atypical handle, left handle).

In the fourth experiment, cognitive aspects of the architectural agency were examined via images of doors with varying handles, which were the same stimuli with the stimuli of Experiment 1. In response time analysis, the significant effect of contra-laterality between response hand and afforded hand operation by presented images of the doors could not be found, which had been predicted before experiment design. The lack of affordance effect can be associated with the size of presented images which can decrease the sense of realisticity. Additionally presenting the architectural elements close to hand-scale may create cognitive effects similar to hand-scale daily objects, where the handle and afforded hand operation is ipsi-lateral in contrast to architectural elements (contra-lateral interaction). Moreover, presenting images without volumetricity as mere visual images may also decrease the affordance effect. Furthermore, the task's difficulty might have increased the participants' fatigue and might have decreased the affordance effect. Thus, adjusting the timing of the trials may increase the affordance effect.

To sum up, these experiments show that during the perception of (architectural) affordance, there are some indicators for cross-modal interactions. Cross-modality was found between visual processes and embodied perception relevant to the motor program (in the mode of implicit motor imager/mental agency) for both neurophysiological activity of interests (i.e., P100 ERP Waveform, ERD of mu oscillation). Additionally changing degree of neurophysiological activity of

interest in line with the category of the doors or cups/mugs was associated with several factors. These are the degree of familiarity (also unfamiliarity and novelty), visual conspicuousness (relevant to the size of handle), the existence of cue or contradicting cue (i.e., hinges) relevant to motor program, action observance relevant to the motor program, handedness of the participants. Furthermore, lack of neurophysiological/cognitive activity of interest in a statistically significant level either for factors or interactions can also be associated with technical/practical limits of experiment conditions. These can be listed as presenting images as mere images (without volumetric structure) and smaller size than their real correspondents (lack of realistic effect) where participants were exposed to images statically due to technical limits (e.g., for avoiding muscle artefacts). These limitations can be handled by improving technical EEG devices, which allow dynamic participation and benefitting from mixed reality technologies that allow the presentation of architectural elements in their real size with a more realistic effect (i.e., volumetricity). Moreover, improving practical conditions such as budget and time could also provide better results. Besides, results of neurophysiological and cognitive investigations within these experiments relevant to the perception of architectural affordance can be addressed close and far conceptual horizon of the thesis. They can be issued within different disciplinary contexts or further inter- or trans-disciplinary contexts with additional dimensions.

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APPENDIX 1:

	Title	Author	Key Terms
Architecture and Empathy (2015)	Empathic and Embodied Imagination: Intuiting Experience and Life in Architecture	Juhani Pallasmaa	• form, experience & poetic aspects of architecture • imagination, (collaborative) creativity, embodied simulation in architectural design process
	Enculturation, Sociality, and the Built Environment	Harry Francis Mallgrave	• relationships between mind, culture and architecture, aesthetical attunement • social brain hypothesis and human enculturation • architecture & human sociality
	Boundaries of Skin: John Dewey, Didier Anzieu and Architectural Possibility	Sarah Robinson	• bodily basis of human cognition • sensation, emotions and ecological dimension of empathy • haptic sense, materiality, thinking through skin and primary role of touch
	Architectural Space from Within: The Body, Space and the Brain	Vittorio Gallese	• metaphors & mirror neurons& embodied simulations • evolutionary aesthetics • nature, anatomy and functions of brain areas • sensorimotor processing in brain

Table a: Structure & Content of Architecture & Empathy published in 2015 (Pallasmaa et al.,2015).

	Title	Author	Key Terms
Mind in Architecture (2015) (ed. by Juhani Pallasmaa & Sarah Robinson)	Survival through Design	Sarah Robinson	• psychology, physiology and survival via arch. settings • shelter aspects of architectural environments
	"Know Thyself": or What Designers can Learn from the Contemporary Biological Sciences	Harry Francis Mallgrave	• ideas of architectural theoreticians about sensation and experience of architecture, historically • Dissaneyake's evolutionary aesthetics • empathy, emotions & mirror neurons
	The Embodied Meaning of Architecture	Mark Johnson	• embodied dimension of architectural meaning • embodied meaning and affordance • qualitative dimensions of meaning and experience • force, motion, verticality and balance in architectural

			meaning
	Body, Mind and Imagination: the Mental Essence of Architecture	Juhani Pallasmaa	• physical & experiential dimension of architecture and their effects on task of architecture • integrative role of architecture linking contradictions • self, identification, empathy and architecture • atmospheric sense, imagination
	Towards a Neuroscience of the Design Process	Michael Arbib	• nature, anatomy and functions of brain • sensorimotor schemas & mirror neurons • hand-brain relationships • neuroscientific dimension of user experience
	Tending to the World	Ian McGilchrist	• neural mechanism beyond attention • functions of frontal cortex • bodily basis of architectural experience
	Architecture and Neuroscience: A Double Helix	John Paul Eberhard	• experiencing architecture and effects on creativity • DNA and brain development • effects of golden ratio on mental activity • light-sensitive proteins in brain and optogenetics • design criteria for neonatal units • potentials of integration of neuroscience to architecture
	Nested Bodies	Sarah Robinson	• body and its role on mental activity • body schema and arch. space (extension of bodies) • nested body in architectural settings • spatial cognition and senses • haptic system and texture of architectural settings
	Embodied Simulation, Aesthetics and Architecture: An Experimental Aesthetic Approach	Vittorio Gallese & Alessandro Gattara	• architecture-body-brain relations in terms of cognitive neuroscience • self-identification and bodily ownership in spatial context • empathy, embodiment and aesthetic appraisal
	From Intuition to Immersion: Architecture and Neuroscience	Melissa Farling	• potentials of ANFA • intuition in architectural experience • applying neuroscience to education of architects • empathy and creativity • designing architectural setting in different scale (ind., public)
	Neuroscience for Architecture	Thomas D. Albright	• role of human biology on architecture • neuroscience & Ancient Indian wisdom on designing built env.

			• visual perception- brain-architectural settings
	Mood and Meaning in Architecture	Alberto Pérez-Gómez	• Cartesian Philosophy & Cognitive Neuroscience • Neurophenomenology & Post-Cognitivism • Architectural experience- (un)consciousness, meaning

Table b: Structure & Content of Mind in Architecture: Neuroscience, Embodiment, and the Future of Design edited by Sarah Robinson & Juhani Pallasmaa in 2015 (Robinson and Pallasmaa, 2015).

Title	**Brain correlates of aesthetic expertise: A parametric fMRI study**				
Experimenter(s)	U. Kirk, M. Skov, M. S. Christensen, Niels Nygaard	**Year**	2008	**Method**	fMRI
Aim	• investigating the relationships between levels of expertise and perceptual processing, memory and reward processing				
Stimuli	• 86 faces of unknown people and 86 building facade images classified as formal stylistic (modernist and non-modernist) and typological (private and public)				
Brain Scanning Session	• Every stimuli was shown for 3000 ms • Between stimuli, fixation cross on a gray background was displayed for 1000 ms				
Additional Experiment (s)	• Participants were requested to press one of five buttons on a response key-pad with their right hand to indicate their aesthetic judgment (1 = least, 5 = most appealing)				
Data Analysis	• 40 axial slices each 3.00 mm thick consisting of a 64 x 64 matrix with an in-plane resolution of 3 x 3mm was obtained from fMRI • Parametric regression analysis for generating statistical parametric maps • Random Effect Analysis used for analysing maps to examine the role of expertise				
Regions of Interest	• subcallosal cingulate gyrus • medial Orbito-Frontal Cortex (reward outcome processing) • ventral striatum (nucleus accumbens-NAcc) (reward prediction processing) • amygdala (reward processing) • ventral tegmental area (reward processing) • hippocampus (memory) • precuneus (memory) • cerebellum (memory)				
Results & Contributions	• classification of stimuli (building facade images) did not show any significant difference between experts and non-experts in terms of brain activation • significant differences in the activity of subcallosal cingulate gyrus and medial Orbito-Frontal Cortex when making aesthetic judgments of buildings between experts and non-experts • the role of expertise not only affects perception and cognition processes but also modulates the response of brain areas associated with the processing of reward • experts use various information related with reward processes such as price, brand category; visual word descriptors influence preference for odours in their aesthetical				

	judgment processes • NAcc activity is very high when the aspects of stimulus referring to reward processes needs to be estimated in aesthetical judgment process • high activity in the areas related with memory among expert participants during categorical judgment processes

Table c: Content of experiment conducted by Ulrich Kirk and his colleagues in 2008 (Kirk et al., 2008).

Title	**Exploring the neurological basis of design cognition using brain imaging: some preliminary results**				
Experimenter(s)	K. Alexiou, T. Zamenopoulos, J. H. Johnson, S. J. Gilbert	**Year**	2009	**Method**	fMRI
Aim	• investigating the relationships between neural mechanisms beyond architectural design process as ill-defined problem solving activity and well-defined problem solving activity as control condition • comparing brain activation while design thinking and performing • comparing brain activation while thinking and performing problem-solving activity				
Stimuli & Task	• eight bedroom plans and furniture of bedroom as sofa, desk, bed, wardrobe, bookcase, television, table and chair for both problem-solving and designing tasks • In problem solving task- participants were requested to locate; o The bed is in the corner of the room with the head on the west o The wardrobe is next to the door and next to the bed o The desk is under the window • In designing task-participants were requested to arrange the furniture so that o The room is functional o The room is comfortable o It has at least a bed, a wardrobe and a desk				
Brain Scanning Session	• 30 s for thinking for designing & problem solving • 15 s for resting between thinking and performing • 50 s performing via using the trackball mouse				
Regions of Interest	• pre-motor cortex (planning of movement) • primary somatosensory cortex (touch) • cerebellum (integration of sensory perception, coordination and control of movement) • anterior, medial & dorsal prefrontal cortex (high level cognitive processes, planning) • secondary visual cortex • cingulate cortex • anterior insula • Broadmann Area 8				
Results (Activated Brain Areas)	Design Thinking	dorsal prefrontal cortex, frontal eye fields, anterior prefrontal cortex, anterior cingulated cortex, pars			

		orbitalis, secondary visual cortex, middle temporal gyrus
	Design Performing	pre-motor cortex, primary somatosensory cortex, cerebellum, secondary visual cortex, middle temporal gyrus, arcuate fasciculus
	Thinking for Problem-Solving	anterior & dorsal prefrontal cortex, secondary visual cortex
	Performing for Problem-Solving	pre-motor cortex, primary somatosensory cortex, cerebellum

Table d: Content of experiment conducted by Katerina Alexiou and her colleagues in 2009 (Alexiou et al., 2009).

Title	**Weak Architecture: How to Enhance Neural Efficiency Using Public Space**				
Experimenter(s)	Diogo Teixeira and his colleagues	**Year**	2012	**Method**	loco-behavioural observations & semi-structured interviews
Aim (s)	• investigating how weak design strategies (i.e., based on experiential events) in the public space can affect human behaviour regarding memory, consciousness, and emotions • evaluating whether these effects can be determined at the neuro-physiological level • investigating the process associated with perception and encoding of architectural cues that induce emotional attachment and enhanced use of public place				
Stimuli (Case Study)	• a public space in Hong Kong • 3D Virtual Environment				
Issues of Interest	• evaluating movement patterns, physical use and social interactions related with the objects via loco-behavioural observations • assessing attention, emotions and short-term and/or long-term memories associated with the case areas through semi-structured interviews • measuring event-related brain activity, heart rate, skin conductance and eye movement simultaneously via 3D virtual environment under laboratory controlled conditions				

Table e: Content of experimental study conducted by Diogo Teixeira and her colleagues (Teixeira et al., 2012)

Title	**fMRI Study of Architecturally-Induced Contemplative States**				
Experimenter(s)	Professor Julio Bermudez and his team	**Year**	2014	**Method**	fMRI
Aim	• to test whether the perception of environments designed for contemplation elicit brain activations similar to those found under contemplative states				
Stimuli	• images of ordinary buildings and contemplation-inducing constructions				
Brain Scanning Session	• a Baseline period in which a gray colour plate was presented for 60 sec • four images were shown for 20 seconds • between image sets given 40 sec for recovery period (gray plate)				
Additional Experiment(s)	• a short questionnaire • 20 minute exit interview				

Results & Contributions	• brain regions activated in subjects with architecture expertise when viewing contemplative buildings overlap with brain regions activated in adept meditators during meditation (with some differences) • distinct neural activations occur when subjects experienced ordinary vs. contemplation-inducing buildings • correlations between subject-reported anxiety, depth of experience and brain physiology attributable to the induced contemplation

Table f: Content of experimental study conducted by Professor Julio Bermudez and his colleagues (Bermudez et al., 2014).

Title	**Exploration of Neural Correlates of Restorative Environment Exposure through Functional Magnetic Resonance Imagining**				
Experimenter(s)	Joel Martínez-Soto and his team	**Year**	2012 (?)	**Method**	fMRI
Aim	• exploring the neural correlates of restorative environment exposure				
Stimuli	• photographs of environments with low or high restorative potential				
Results (Activated Brain Areas)	Environments with high restorative potentials	• dominant activation in middle frontal gyrus, middle and inferior temporal gyrus, insula, inferior parietal lobe, and cuneus • activation in brain areas associated with involuntary attention			
	Environments with high restorative potentials	• dominant activation in superior frontal gyrus, precuneus, parahippocampal gyrus, and posterior cingulated • activation in brain areas associated with directed attention			
Future Directions	• perception of restorative qualities and a building-integrated vegetation could be considered for architects in order to provide cognitive resources necessary for adequate human functioning				

Table g: Content of experimental study conducted by Joel Martínez-Soto and his team (Martínez-Soto et al., 2012).

Title	**Towards User Personalized Environments: An Artistic Exploration Using an EEG-Based Brain-Computer Interface**				
Experimenter(s)	Mirjana Prpa and her colleagues	**Year**	2014 (?)	**Method**	EEG
Aim	• exploring the ways of designing 3D computer-simulated VR environment that directly responds to users' current cognitive states • testing what degree users are aware of their influence on the system				
Stimuli & Task	• virtual-reality-based artistic installation in Unity3D (virtual environment)				
Brain Scanning	• participants were asked to explore the system during scanning session				

Session	• participants were requested to fill in the affect grid prior to and after the session	
Additional Experiment (s)	• an audio-recorded interview • a questionnaire	investigating degree of immersion, system responsiveness, degree of users' influence on the system
Results	• participants could perceive differences in virtual environment model adapting the changes in their inner states • participants could understand the links between changes in their emotions and adaptive changes in their model	

Table h: Content of experimental study conducted by Mirjana Prpa and her colleagues (Prpa et al., 2014)

Title	**Electroencephalographic Signatures of Interior Design Appreciation in a CAVE System: A Pilot Study**				
Experimenter(s)	Dr. Giovanni Vecchiato and his colleagues	**Year**	2014 (?)	**Method**	EEG
Aim	• examining the possible ways of correlating neuro-physiological parameters with the appreciation of interior designs • to examine how the motivational factors, as indexed by EEG asymmetrical activation of left and right hemispheres over the prefrontal cortex, can be related with the experience of familiar and novel environments				
Stimuli & Task	• three kinds of interior designs o empty o common furniture o cutting edge furniture				
Brain Scanning Session	• an immersive virtual reality CAVE system projected in different three rooms designed in real size while EEG scanning				
Results	• they found correlations between EEG alpha rhythms and the judgments of participants about familiarity and novelty • they found asymmetrical activations of the prefrontal cerebral areas as signs of motivational factors				
Future Expectations	• these findings may allow developing quantifiable neural markers for testing how the design process of architectonical environments matches the changing needs of man				

Table i: Content of experimental study conducted by Dr. Giovanni Vecchiato and his colleagues (Vecchiato et al., 2014)

Title	**An fMRI-Based Exploration of Neural Correlates of the 'Formal' Environmental Attributes of Healthcare Settings**				
Experimenter(s)	Dr. Debajyoti Pati and his colleagues	**Year**	2014 (?)	**Method**	fMRI
Aim	• testing the findings of previous studies examining the relationships between sharpness and curvilinearity contours of objects and activity of amygdala responsible for emotions especially fear leading and influences of contours on shaping the emotional affordance of an				

	environment
Stimuli	• four classes of images (exteriors, interiors, objects, and landscapes), in three contour types (sharp, curved, and balanced)
Brain Scanning Session	• during scanning session, participants were exposed to stimuli
Region of Interest	• amygdala and limbic system
Results & Contributions	• They found amygdala was significantly more active for sharp objects compared with their curved contour counterparts by adding healthcare dimension

Table j: Content of experimental study conducted by Dr. Debajyoti Pati and his colleagues (Pati et al., 2014).

Title	**Electroencephalographic Correlates of Sensorimotor Integration and Embodiment during the Appreciation of Virtual Architectural Environments**				
Experimenter(s)	Giovanni Vecchiato, Gaetano Tieri, Andrea Jelić, Federico De Matteis, Anton G. Maglione Fabio Babiloni	**Year**	2015 (?)	**Method**	EEG
Aim	• understanding of neuro-physiological correlates of architectural perception such as correlations between involvement of sensorimotor integration and sense of presence of participants, or correlations between comfort and familiarity				
Stimuli	• three immersive virtual architectural environments as; o empty room o room with modern furniture o room with cutting-edge furniture designed via 3D Max Software (implemented in XVR for generating immersive VR medium)				
Brain Scanning Session	• 20 participants were asked to explore and judge surrounding virtual real environment during scanning				
Additional Experiment (s)	• Participants were asked to describe their experience through such categories as; Familiarity, Novelty, Comfort, Pleasantness, Arousal and Presence-assessing the realism of the virtual stimulation- by rating from 1 to 9 degrees (Behavioural Experiment)				
Data Analysis	• Behavioural Experiment data were transformed to z-scores and then used to perform Pearson's correlation • Output data were analyzed Power Spectral Density (PSD) in terms of frequency of brainwaves as theta, delta, mu and alpha waves • Time-frequency analysis and topographic statistical maps were generated				
Findings	• They found frontal-midline theta activity pointing out the involvement of sensorimotor integration when participants feel more presence, comfort and familiarity in immersive virtual realities • In the feeling of pleasant, theta power increase across visuo-motor circuits and alpha band activity in areas related with visuo-spatial exploration and categorical spatial relation processing				

	• In the perception of pleasantness and comfort they also found de-synchronization of the mu rhythm indicating left motor area activity and embodied mechanisms of environment appreciation
Result	• They claimed perception of architectural settings include sensorimotor integration, spatial navigation and embodiment

Table k: Content of experiment conducted by Giovanni Vecchiato and his colleagues (Vecchiato et al., 2015).

Title	**Facades of building significantly modulate EEG signals of brain cortical lobes**				
Experimenter(s)	Parastou Naghibi Rad and her colleagues	**Year**	2016 (?)	**Method**	EEG
Aim	• effects of architectural elements in 3 categories: geometries, materials and proportions of building facades on emotional behaviour and brain activity				
Stimuli	• images of three categories of building facades modelled via 3D Max Software (categories as; geometries and proportions of windows and materials used in the facades)				
Brain Scanning Session	• Images of building facades were displayed to participants during scanning session				
Data Analysis	• EEG signals were low pass filtered with a fourth-order Butterworth filter • Output data were converted to different frequency bands as delta (0.5-3 Hz), theta (3-7.5 Hz), alpha (7.5-13 Hz), beta (13-31 Hz), and gamma (31-100 Hz) frequencies via a fast Fourier transform in MATLAB • They studied the mean power at different frequency bands of EEG signals in different lobes of the brain to investigate the modulation of brain activity of participants				
Findings	• They found increased beta frequency oscillations in occipital and parietal lobes when participants were shown pleasant facades of the geometry of windows and materials • They found decreased beta frequency oscillations in occipital and parietal lobes when participants were shown unpleasant facades of the geometry of windows and materials • They found inversely relation in theta frequency oscillation between small and large proportions of shapes of the windows on facades shown to participants generating horizontal stretch				

Table l: Content of experiment conducted by Parastou Naghibi Rad and her colleagues (Rad et al., 2016).

Title	**Emotional Design in Architecture**				
Experimenter(s)	Richard Georges Aoun	**Year**	2016 (?)	**Method**	EEG
Aim	• measuring influences of architectural environments on our emotions in the case of city of Barcelona				
Stimuli	• specific architectural elements in Barcelona				
Brain Scanning Session	• brain activity of two participants were measured through portable EEG neuro-headset connected to its software on the laptop to connected to its software on the laptop				
Findings	• They found various architectural elements such as water, ceiling height, natural light, colours				

	and styles trigger certain emotions such as engagement, excitement, interest, relaxation and stress
Future Expectation	• Seeking the ways of designing our emotions via designing architectural settings

Table m: Content of experiment conducted by Richard Georges Aoun (Aoun, 2016).

Title	**EEG Pattern Recognition and Classification for Thermal Comfort**				
Experimenter(s)	Xin Shan and his colleague	**Year**	2016 (?)	**Method**	EEG
Aim	• investigating relationships between condition of mind with satisfaction with thermal environment based on the idea that thermal comfort is closely related to emotions				
Stimuli	• different thermal conditions in built environment				
Brain Scanning Session	• They used a 14-channel EEG headset to analyze electrical activity in the brain and to collect power density in different EEG frequency bands while participants were exposed to different thermal conditions in built environment				
Data Analysis	• Output data were used to build LDA/SVM algorithm classifiers to be able to classify mental states of human subjects under different thermal conditions in built environment in 90% preciseness				
Finding (s)	• They found close links between different thermal conditions and emotional conditions of occupants of buildings				
Future Expectation (s)	• This study have potentials to figure out the impact of architectural spaces on building occupants deeply to improve the human-building interaction facilitating the development of future intelligent buildings where occupants are able to control the indoor environment through this human-building interaction process				

Table n: Content of experiment conducted by Xin Shan and his colleague (Shan and Yang, 2016).

Title	**The impact of positional configuration of a desk in a room on attention and creativity measured by behavioural and neuro-physiological recordings**				
Experimenter(s)	Young-Ah Rho and her colleagues	**Year**	2016 (?)	**Method**	EEG
Aim	• investigating with influential effects of architectural features such as window, ceiling, floor, or wall on behaviour and neuro-physiological states of individuals				
Stimuli	• a task demanding creativity and attention (surrounding layout was designed so as to provide reasonable saliency to the priming of concepts such as freedom versus confinement without any additional installations during task)				
Brain Scanning Session	• They measured brainwaves through portable EEG device during task performance to detect how openness versus closeness of space influences behavioural and neuro-physiological states				
Data Analysis	• They examined the levels of attention and creativity of 40 participants in various desk positions sitting toward versus against a wall in the room via psychometric tests				
Finding (s)	• They found there are some influences of desk positions in a room on attention and creativity				

	and on some brain activities.
Future Expectation (s)	• They proposed their findings can provide a guideline to configure workplace, conference room, private room and classroom to improve the efficiency of usage of these spaces

Table o: Content of experiment conducted by Young-Ah Rho and her colleagues (Rho et al., 2016).

Title	**Neuroscience Informing Design: Impact of Fluorescent CCT on Neurodiverse Populations**				
Experimenter(s)	Cherif Amor and his colleagues	**Year**	2016 (?)	**Method**	fMRI
Aim	• investigating the relationships between colour warmness and emotions				
Stimuli	• three types of images of illustrations in terms of colour warmness				
Brain Scanning Session	• three types of illustrations via projection and a computer controlled visual presentation system were shown to 20 participants chosen by taking into account gender, age, ethnicity, brain lateralization and colour blindness				
Additional Experiment (s)	• Psychometric test (Likert-Scale test including satisfaction degrees as 1=least satisfied and 7=very satisfied)				
Region(s) of Interest	• occipital cortex, Superior Temporal Gyrus, Angular Gyrus, Middle Frontal Gyrus				
Data Analysis	• Behavioural Data was examined by using t-test factor analysis and one-way analysis of variance • Neural data maps were analyzed through using FSL Neuroimaging Software				
Finding (s)	• warm white colour temperature did not activate occipital cortex as an indicator of disinterest or dissatisfaction with the warm spectrum • cool white spectrum activated Superior Temporal Gyrus implicated in critical structure of social interaction; the Middle Frontal Gyrus implicated in semantic and analytical task and the Angular Gyrus implicated in memory retrieval. • the daylight colour spectrum activated cerebellum involved in cognitive brain processes				
Conclusion	• These findings indicated that satisfaction level is increasing with cool white and daylight full spectrum when compared with the warm spectrum				

Table p: Content of experiment conducted by Cherif Amor and his colleagues (Amor et al., 2016).

Title	**The perception of symmetry in architecture: an eye movement study**				
Experimenter(s)	Shareh Ghanbari Azarneir and his colleagues	**Year**	2016 (?)	**Method**	Eye-tracking
Aim	• examining the effects of symmetry in ancient houses of Iran on human visual system				
Motivation	• They benefitted from previous studies based on the finding about "Eye fixations are usually concentrated along the axis of symmetry or the symmetrical centre of the patterns". • They explained symmetry and repetition were among the earliest properties of an art which gives them high value • They claimed the reasons beyond these influences in two ways as; the existence and repetition of symmetry in nature around us and circular symmetric structure of human visual				

	system appealing to symmetry through emerging resonance between eye and pattern.	
Stimuli	• images of five symmetric of Kashan City in Iran and their distorted versions as control stimuli	
Eye Tracking Session	• every stimuli was shown for 10 seconds on video projector to ten participants- university students, 5 left-handed and 5 right-handed	
Finding (s)	while symmetrical images were shown	• right-handed participants focussed on the left half of the photos with one or three fixation points on the axis of the symmetry • left-handed participants concentrated on the middle of the image around the main axis of the symmetry
	while asymmetrical images were shown	• fixations and the length of saccades were slightly higher than symmetrical photos

Table r: Content of experiment conducted by Shareh Ghanbari Azarneir and his colleagues (Azarneir et al., 2016).

Title	**Transparency as an environmental factor that influences cognitive visuo-locomotive experience in large-scale buildings**				
Experimenter(s)	Vasiliki Kondyli and Mehul Bhatt	Year	2016 (?)	Method (s)	Eye-tracking + Egocentric gaze analysis + external camera based visual analysis + sketch maps + questionnaires determining spatial ability
Aim	• exploring the visuo-locomotive behaviour of users in unfamiliar large-scale built-up spaces and identifying aspects of environment related with visual perception due to its significant role on spatial knowledge acquisition in this context				
Motivation	• They started from formulation as Space = Time (+memory) x Movement which means that an observer in motion perceives changes successively and adjusts his knowledge related with spatial memory directly and depended on spatial aspects as spatial perception, spatio-visual attractiveness, arousal and orientation				
Stimuli & Task	• navigation task (involving way-finding towards a destination) • exploration task (without any specific defined goal)				in New Parkland Hospital (NPH) in Dallas
Experiment Session	• Experimenters gave two different tasks as (navigation & exploration) to participants				
Data Analysis	• They tried; o to measure the embodied visuo-locomotive experience of users o to interpret fine-grained behaviour such as patterns of gaze and route preferences o to construct correlations between these data and outcomes pertaining to spatial knowledge tasks such as pointing and perspective-taking o to create a new framework for visuo-locomotive behaviour analysis targeting Evidence Based Design via various methods				

Finding (s)	• They found extended fixation periods at the visual patterns in a wider surface towards the transparent element during the exploration in comparison to the exploration one and correlations between spatial memory and transparency of physical space

Table s: Content of experiment conducted by Vasiliki Kondyli and Mehul Bhatt (Kondyli and Bhatt, 2016).

Title	**The Impact of Biomorphic Design on the Memorability of Interior Environments- A Preliminary Study**				
Experimenter(s)	Hasti Mirkia and her colleagues	**Year**	2016 (?)	**Method**	Eye-tracking
Aim	• to test three hypotheses addressing the relationships between spaces and memory, emotions, empathy and neuroaesthetics in the built environment as; o images of architectural settings including biomorphic elements more intrinsically memorable when compared with rectilinear minimal architectural settings o intrinsic memorability can be related with feeling of pleasantness caused through architectural settings o intrinsic memorability can be related with visual attention to architectural settings				
Stimuli	• images of architectural settings designed in biomorphic approaches inspired from organic shapes and forms • images of architectural settings designed in minimalist approaches through using boxes and rejecting ornament and decoration				
Experiment Session	• Experimenters gave to participants a cognitive memory task to see which types of design images are more memorable				
Additional Experiment (s)	• They conducted a behavioural experiment using a Likert Scale questionnaire to test points of view of participants and to assess emotional responses • They measured visual attentions of participants through eye tracking technology to identify specific design elements related with memorability				
Finding (s)	• They found some differences between biomorphic and minimalist architectural elements in terms of memorability				

Table t: Content of experiment conducted by Hasti Mirkia and her colleagues (Mirkia et al., 2016).

Title	**Eye Tracking Architecture: A Pilot Study of Buildings in Boston**				
Experimenter(s)	K. Rhett Nichols and her colleagues	**Year**	2016 (?)	**Method**	Eye-tracking
Aim	• to better understand how people see their world especially for using these findings as architect's toolkit				
Stimuli	• 60 images –half of them were photos or renderings of Boston buildings, interiors and exteriors and other half of them were including faces and landscapes				
Eye-Tracking Session	• Every stimuli was shown for 15 seconds on a computer screen				
Data Analysis	• Output data was analyzed through iMotions analysis software to examine;				

	○ common looking patterns ○ videos of individual gaze paths ○ time to first focus on an element ○ revisits as the number of times volunteers looked at the same area • output data was represented through graphic representations as heat maps and spotlight images
Finding (s)	• They found that our perception is very much human-centric

Table u: Content of experiment conducted by K. Rhett Nichols and her colleagues (Nichols et al., 2016).

Title	**Neural Codes of Seeing Architectural Styles**				
Experimenter(s)	Heeyoung Choo and her colleagues	**Year**	2017	**Method**	fMRI
Aim	• to examine differences of entry-level scene categories, architectural styles, buildings of famous architects, faces of infamous males in terms of visual perception				
Stimuli	• images of entry-level scene categories as mountain, pasture, highway and playground • images of buildings belong to different architectural styles as byzantine, renaissance, modern and Deconstructivism • images of buildings built by famous architects such as Le Corbusier, Antony Gaudi, Frank Gehry, Frank Lloyd Wright • images of faces of four infamous males				
Brain Scanning Session	• 22 final year students were selected as participants for the experiment -11 architecture students and 11 psychology and neuroscience students from The Ohio State University- and neural mechanisms beyond their visual perception were scanned through fMRI and recorded in 35 coronal slices covering approximately the posterior 70% of the brain.				
Additional Experiment (s)	• post-scan behavioural experiment through Vanderbilt Expertise Test measuring visual domain knowledge				
Region (s) of Interest	• Parahippocampal place area (PPA)	(understanding spatial structure, texture and material properties and semantic categories which are very important for understanding architectural styles and buildings designed by famous architects based on linking various perceptual instantiations of the same building)			
	• Occipital Place Area (OPA)	(processing primitive scene representations by encoding mid-level visual properties and cross-decoding between interior & exterior views of landmark buildings)			
	• Retrosplenial Cortex (RSC)	(processing mnemonic and contextual aspects of real world scene rather than perceptual aspects)			

	• Lateral Occipital Complex (LOC)	(processing category-specific object statistics and local elements such as motifs and embellishments)
	• Fusiform Face Area (FFA)	(processing of faces as well as visual expertise and configural characteristics of buildings)
	• Primary Visual Cortex (V1)	(conscious processing of visual stimuli)
Data Analysis	• Accuracy rates and response times of Vanderbilt test were calculated via ANOVA	
Finding (s)	entry-level scenes category	activation in all regions of interest areas
	architectural styles category	activation in all regions of interest areas except primary visual cortex (V1)
	buildings of famous architects category	activation in parahippocampal place area and the occipital place area except primary visual cortex area, retrosplenial cortex, lateral occipital complex areas
	faces of infamous male category	activation in only primary visual cortex

Table v: Content of experiment conducted by Heeyoung Choo and her colleagues (Choo et al., 2017).