

Caregiver involvement on developmental changes in visual cognition: insights from behaviour and brain

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Project Statement

The data presented in this thesis was collected as part of Project NeuroSync, a larger research project involving multiple collaborators and students. As a result, certain protocols and datasets were shared among contributors. Although some of the data overlap, the analyses, interpretations, and conclusions presented in this thesis represent independent work. This project received ethics approval from the Research Ethics Committee at the University of Nottingham. This project was funded by an external grant awarded to Dr Sobanawartiny Wijeakumar by the Leverhulme Trust (Grant no. RPG-2019-286).

Abstract

Early in development, infants begin to share attention with mature caregivers, learning about objects and their environments. During this period, there are also considerable increases in visual cognition. Given that this system has far-reaching outcomes impacting the quality of life, it is important to study how this emerges and develops early in the lifespan, as well as what factors might influence its developmental trajectory. This thesis aimed to address these gaps, investigating associations between caregiver and infant visual neurocognition, with insights from dyadic play interactions. To do this, the preferential looking task was used to assess visual cognition at multiple timepoints. Caregiver-infant dyads also completed play interactions with objects. To gain a deeper understanding of the neural mechanisms that underly behaviours during the preferential looking task and dyadic interactions, functional near-infrared spectroscopy (fNIRS) was also used to examine brain function.

Previous research has suggested that infants' ability to sustain attention may be influenced by their caregivers' own attentional behaviours. Chapter 3 therefore examined if this association was measurable when visual cognition is objectively measured in caregivers and infants using comparable experimental paradigms. Importantly, findings in this chapter reported associations between caregivers' and infants' abilities to detect change. Further, infants with caregivers who were better able to detect change showed greater left parietal cortex activation. These findings provide first evidence of a visual neurocognitive association between caregivers and their children in the first year of life. To better understand these associations, Chapter 4 investigated how caregiver and infant behaviours and brain function during dyadic play interactions influence infant visual cognition. This chapter focused on unimodal (look only), bimodal (look and touch) and multimodal (look, touch, and verbalisations/vocalisations) object engagement behaviours. While this chapter reported caregiver-infant brain associations during play, there were no associations with infant visual cognition. To analyse the play interaction data in greater depth, Chapter 5 examined periods in which caregivers were showing multimodal engagement whilst interacting with the same object as their infant (joint attention), and periods in which the infant continued to interact with that same object after caregiver multimodal engagement ended (continued attention). Findings in this chapter reported

that greater joint attention between caregivers and infants was associated with greater continued attention in infants. Importantly, this chapter found that reduced activation in the left temporal cortex in caregivers during joint attention was associated with reduced activation in the left temporal cortex in infants during joint activation, longer duration of joint and continued attention, and better visual cognition in infants. These findings contribute to understanding of cortical mechanisms engaged during attention periods in caregiver-infant interactions and how these mechanisms might be linked to visual cognition in infants. However, further investigation is required to better understand longitudinal effects. Therefore, Chapter 6 investigated the impact of caregiver-infant dyadic behaviours on longitudinal changes in visual neurocognition from infancy to toddlerhood. Findings reported developmental changes in behaviour and brain function from infancy to toddlerhood. Furthermore, findings suggested that infants who experienced a shorter duration of joint attention do not show consistency in left temporal engagement from infancy to toddlerhood. In line with findings in Chapter 5, it was suggested that children who demonstrate inconsistency in temporal cortex activation are less able to suppress this region and efficiently recruit neural resources for visual cognition.

Collectively, this thesis highlights the potential mechanisms by which caregiver-infant joint engagement shapes visual cognition and underlying brain function in early life. Ultimately, by shedding light on the role of caregiver behaviours in shaping infant attention and cognitive development, these novel findings have potential implications for informing caregiving practices, early intervention methods, and future visual cognition research.

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List of Abbreviations

Abbreviation	Meaning
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
CP	Change Preference
DFT	Dynamic Field Theory
EEG	Electroencephalography
EF	Executive Function
ERP	Event-Related Potential
fMRI	Functional Magnetic Resonance Imaging
fNIRS	Functional Near-Infrared Spectroscopy
HbO	Oxyhemoglobin
HbR	Deoxyhemoglobin
HbX	Oxy- and deoxyhemoglobin
MRI	Magnetic Resonance Imaging
ROI	Region of Interest
SD	Standard Deviation
SES	Socioeconomic Status
SR	Switch Rate
T1	Timepoint 1
T2	Timepoint 2
TLD	Total Look Duration
VWM	Visual Working Memory

Abbreviation	Brain Region
AG	Angular Gyrus
DLPFC	Dorsolateral Prefrontal Cortex
FEF	Frontal Eye Field
IFG	Inferior Frontal Gyrus
IPL	Inferior Parietal Lobule
IPS	Intraparietal Sulcus
MFG	Middle Frontal Gyrus
MOG	Middle Occipital Gyrus
MTG	Middle Temporal Gyrus
SFG	Superior Frontal Gyrus
SMG	Supramarginal Gyrus
SPL	Superior Parietal Lobule
STG	Superior Temporal Gyrus
TPJ	Temporo-parietal Junction
VLPFC	Ventrolateral Prefrontal Cortex
VOC	Ventral Occipital Cortex
SOG	Superior Occipital Gyrus

Prefix	Meaning
l	Left
r	Right
s	Superior
p	Posterior
a	Anterior

Thesis overview

The ability to shift and sustain attention emerges in infancy and steadily improves across childhood. This system is collectively referred to as visual cognition, and is predictive of academic achievement, IQ, global fluid intelligence and social abilities. Given the far-reaching outcomes impacting quality of life, it is important to understand how this system emerges and develops early in the lifespan and what factors might impact its developmental trajectory.

Existing research has used brain imaging techniques, such as fNIRS, to examine developmental shifts in visual cognition and associated brain function across childhood. Furthermore, there is evidence that infants' attentional behaviours are associated with their caregivers' attentional behaviours during interactions. However, a gap remains in the literature in our understanding of how caregiver behaviours influence this. Moreover, whilst previous studies have investigated the role of dyadic behaviours during early development, the neural mechanisms underlying these interactions and their impact on infant visual cognition remain unclear. Finally, there is limited research investigating developmental trajectories of visual cognition from infancy to toddlerhood. This thesis therefore aims to address these gaps by investigating neurocognitive associations between caregiver visual cognition and child visual cognition development, with a focus on insights from dyadic interactions.

The first chapter in this thesis reviews literature on visual cognition across development, focusing on visual working memory (VWM) and attention. Further, the second chapter in this thesis reviews literature on dyadic interactions in early life, with an emphasis on caregiver influences on child cognitive development. Together, these introductory chapters aim to provide a foundation for understanding how caregiver behaviours during dyadic interactions might shape the development of visual neurocognition from infancy to toddlerhood. To guide the reader with the relevant content, some of this literature is briefly revisited at the beginning of each experimental chapter.

The third chapter in the thesis explores whether individual differences in caregiver visual cognition are associated with differences in infant visual cognition. Here, caregivers and their infants (aged 6- to 10-months) were presented with

comparable age-specific variants of a preferential looking task. During this task, load demand was manipulated across trials (low, medium, and high load) and a measure of the subject's ability to detect change was extracted (CP score). fNIRS was also used to measure brain activation. In the behavioural results, load-dependent modulation was found in both groups, as well as a positive association between caregiver and infant CP score at the low load. Additionally, there was a neural association between caregivers and infants, with greater activation in the left parietal cortex in infants linked to higher CP scores in caregivers. These findings demonstrate first evidence of a neurocognitive association between caregiver and infant visual cognition during the first year of life, however, it is still unclear how social interactions between caregivers and their infants might influence these associations.

The fourth chapter in the thesis examines differences in infant and caregiver brain function across different types of object engagement during dyadic interactions. This chapter also examines the influence of caregiver-infant object interactions on infant visual cognition. To do this, caregivers and their infants were recorded for 5- to 7-minutes whilst they interacted together with toys. Brain function was recorded from both partners using fNIRS. Video recordings were divided into 5-second epochs, and coded for unimodal (look only), bimodal (look and touch), and multimodal (look, touch, and vocalisation/verbalisation) engagement. Both caregivers and infants predominantly engaged in bimodal interactions. Caregivers showed right parietal engagement across engagement categories. Further, infants showed modality specific right fronto-parietal engagement, as well as a 'source-sink' effect, with greater right frontal activation and a trend towards greater right parietal suppression across all engagement categories. Whilst these findings provide novel contributions to the understanding of cortical mechanisms underlying different types of object engagement, there were no associations between caregiver-infant behaviour or brain function and infant visual cognition.

Subsequently, the fifth chapter in the thesis examines differences in caregiver-infant joint attention and infant continued attention collapsed across modalities. Here, greater joint attention between caregivers and infants was associated with greater continued attention in infants. Further, reduced left temporal activation in caregivers during joint attention was associated with reduced left temporal activation in infants during joint activation, longer duration of joint attention and longer duration of

continued attention. Interestingly, infants whose caregivers showed greater left temporal suppression during joint attention, also performed better on the preferential looking task. These findings contribute to our understanding of how caregiver behaviours during day-to-day interactions with their infants might contribute to cognitive development. They also highlight the importance of studying changes in brain function during caregiver-infant dyadic interactions.

The sixth chapter in the thesis focuses on developmental changes in visual cognition from infancy to toddlerhood. Here, the same children were presented with the same preferential looking task in toddlerhood. Differences in visual cognition and underlying brain function across development were examined. From infancy to toddlerhood, children showed increased visual cognitive abilities. Across both time-points, children's ability to detect change was also modulated by load demand. Infants showed greater activation in frontal regions, whereas toddlers showed greater activation in posterior parietal regions, suggesting the refinement of parietal regions involved in visuospatial attention in early development. Further, infants who experienced greater joint attention during infancy differently recruited the temporal cortex across infancy and toddlerhood. This study provides evidence for the role of cortical regions and importance of early caregiver-infant interactions in the development of early visual cognition.

Finally, the seventh chapter in this thesis discusses the implications of experimental findings. This chapter also addresses overarching strengths and limitations of the thesis and proposes informed future directions. Collectively, this thesis offers insights into the developmental dynamics of visual cognition in infancy and toddlerhood, highlighting the significant role of caregiver-infant interactions. Using fNIRS to study brain activation, this thesis contributes to a growing body of literature which examines the interplay between early caregiving, infant behaviour and infant brain function. These findings demonstrate the importance of studying visual neurocognition during infancy and toddlerhood to better understand how intervention efforts may influence positive developmental outcomes.

Contribution statement

The current thesis utilises data from Project NeuroSync, a larger research project led by Dr Sobanawartiny Wijeakumar and involving multiple collaborators. Dr Wijeakumar was responsible for the overall conceptualisation and design of the broader project, securing funding (Leverhulme Trust Grant no. RPG-2019-286) and obtaining ethics approval. Dr Wijeakumar provided supervision throughout the PhD and feedback on the current thesis. Dr Wijeakumar was also responsible for the methodological design and validation of analyses, and provided review, editing, and feedback on related manuscripts.

Various aspects of data collection and processing were shared among team members. At both timepoints, participant recruitment, scheduling, and data collection were shared equally between Aimee Theyer, Christina Davidson, and Ghada Amaireh.

The preferential looking task used in this thesis was adapted from the work of Ross-Sheehy et al. (2003). Christina Davidson created the version used in PsychoPy at T1. Aimee Theyer modified this version for use at T2. The modality coding scheme was developed by Aimee Theyer and Dr Wijeakumar.

At T1, PLT coding was divided between Aimee Theyer, Christina Davidson, and Ghada Amaireh, with 23% of the data coded by all three to assess reliability. For caregiver data, PLT coding was divided between Aimee Theyer and Christina Davidson, with 23% of the data coded by both researchers to assess reliability. Aimee Theyer completed all modality coding for the dyadic interactions, with 23% of the data also coded by Christina Davidson to assess reliability. At T2, PLT coding was divided between Aimee Theyer and Aria Dabholkar, with 22% of the data coded by both researchers to assess reliability.

All brain analyses were conducted by Aimee Theyer. The analyses, interpretations, and conclusions presented in this thesis also represent independent work.

Chapter 1:

Visual cognition and attention – a review of the literature

1.1 Introduction

The aim of this chapter is to provide a review of the literature on visual cognition across development. Visual cognition is an overarching term, covering multiple cognitive processes involved in perceiving, interpreting, and manipulating visual information. Broadly, visual cognition encompasses various aspects of how people process and respond to visual stimuli, generally allowing them to 'make sense' of their environments. Visual cognition therefore comprises multiple overlapping sub-domains, including perceptual processing, attention, visual short-term/working memory, higher-level visual cognition, decision-making, and learning and memory. These processes are introduced below, with an emphasis on attention and VWM, as they are repeatedly discussed throughout the thesis.

1.1.1 Perceptual processing

Perceptual processing refers to the process by which the brain interprets visual information captured by the eyes. This early process begins with the coding of simple visual features, such as colours, shapes, sizes, and locations (Treisman, 1986). Relatedly, depth and spatial perception is the ability to perceive and combine the depths, sizes and positions of objects in space (Gogel, 1963). Collectively, this allows for the perception of distances and sizes of objects relative to others and space. Finally, motion perception allows individuals to perceive movement within their environments, tracking moving objects or detecting changes in position over time (Albright & Stoner, 1995). However, with a high volume of information entering the visual system from one moment to the next, it is not possible for all information to be processed in detail. The need to prioritise relevant stimuli necessitates visual attention processes, which allow individuals to efficiently interact with their surroundings.

1.1.2 Attention

Attention, in its broadest sense, can be defined as a general state of alertness or ability to engage with or respond to the environment. This fundamental cognitive ability facilitates selective concentration on specific stimuli, whilst suppressing irrelevant or competing information. Attentional abilities support cognitive functioning, playing an integral role in perception, learning, memory, and action, allowing individuals to flexibly navigate the demands of their environment. Saccades, which are small, rapid eye movements occurring several times per second, can reveal

information about where attention is focused. Researchers have therefore frequently employed the tracking of eye movements to analyse patterns of attention. As this is outwardly visible, it is known as overt visual attention (Lindsay, 2021).

Attention has typically been divided into distinct types based upon the context in which it operates. Among these, *selective attention* refers to the ability to focus on a specific stimulus or task for further processing, whilst simultaneously filtering out irrelevant or distracting stimuli. Competing information can occur both externally, as visual or auditory stimulation in the environment, or internally, as distracting thoughts or responses which interrupt the task at hand (Stevens & Bavelier, 2012). *Divided attention* involves the simultaneous allocation of cognitive resources to focus upon multiple tasks or stimuli at the same time (Näätänen, 2018; Talalay, 2024), and *sustained attention* refers to the capacity to maintain focus over prolonged periods. Sustained attention is also sometimes referred to as vigilance, resources for which can decrease over time (Esterman & Rothlein, 2019). Note that in this thesis, the term *continued attention* is also used when referring to Chapter 5 to differentiate periods of sustained attention following joint attention periods.

The ability to filter and prioritise stimuli within a complex environment relies on internal mechanisms that govern how attention is directed. These processes ultimately allow for appropriate responses to environmental stimuli and/or the achievement of behavioural goals. Attention is therefore thought to be driven by either top-down or bottom-up processing (Katsuki & Constantinidis, 2014). Top-down (or endogenous) attention is voluntary and goal-directed, enabling individuals to focus on tasks based on their intentions or objectives (Connor et al., 2004; Corbetta & Shulman, 2002; Katsuki & Constantinidis, 2014). This process is thought to include regions in the intraparietal cortex and superior frontal cortex, which have been associated with anticipatory eye movements driven by task expectations or cues. For instance, the lateral intraparietal area has been associated with preparation of saccadic eye movements, and the frontal eye fields (FEFs) have been associated with controlling eye movements and guiding attentional shifts to relevant locations (Corbetta & Shulman, 2002). In contrast, bottom-up (or exogenous) attention, is driven by external stimuli, in which information is selected due to highly noticeable or salient features, such as oriented edges, spatial frequency, colour contrast, intensity, or motion (Itti & Koch, 2001). This process is thought to include the temporo-parietal and inferior

frontal cortex and be largely lateralised to the right hemisphere. For instance, the right inferior frontal gyrus (rIFG) and the right temporo-parietal junction (rTPJ) have been associated with detecting and re-orienting attention to unexpected stimuli or events. This network is thought to act as a 'circuit-breaker' for the dorsal system, directing attention to salient events or stimuli (Corbetta & Shulman, 2002). Both mechanisms are therefore thought to interact dynamically, ensuring a balance between responses to salient environmental changes and intentional focus (Corbetta & Shulman, 2002; Katsuki & Constantinidis, 2014).

1.1.3 Visual short-term/working memory

Visual short-term memory and VWM are both typically used to describe the brief storage of information from one moment to the next. However, in the wider literature, distinctions between these terms are not always clear (Aben et al., 2012). Short-term memory is generally understood to describe the rapid formation of memory representations, limited to a number of items at a time and requiring active rehearsal to maintain beyond a few seconds (Ross-Sheehy et al., 2003). Similarly, VWM, also describes the temporary storage and recall of visual information, used in comparing and detecting changes from one moment to another (Luck & Vogel, 2013). However, in contrast to short-term memory, VWM also involves the manipulation of visual information, prior to recall (Baddeley, 1992). This system facilitates the completion of complex tasks involved in comprehension, learning, and problem-solving (Baddeley & Hitch, 1974). VWM is considered to be a sub-component of executive function (EF), as it plays an essential role in complex cognition (Baddeley, 2003; Miyake & Friedman, 2012; Miyake & Shah, 1999)

Luck & Vogel (2013) defined VWM as having three key components. Firstly, to qualify as VWM, the information representation must be visual in nature. Therefore, if the information is stored as verbal information or as a conceptual representation, regardless of it being acquired through a visual modality, then it is no longer considered as VWM. Secondly, VWM must be based on active maintenance via an increase in neural demand, rather than by changes in synaptic strength, discriminating VWM from long-term memory, in which information is passively stored over time. Finally, to be classed as VWM, the stored information must be used in the completion of cognitive tasks.

VWM has a limited capacity, meaning that humans can only store and manipulate a certain number of visual items at a time. This capacity can be influenced by individual features, objects, and contexts, but is generally thought to be limited to approximately four chunks of information at a time (Cowan, 2001). These capacity limits are thought to increase across infancy and childhood. Notably, across development, behavioural and neuroimaging data has highlighted a network of brain regions associated with VWM (Cowan, 2001). These are discussed in greater detail in Section 1.4 *Visual cognition across development: neuroimaging insights*.

1.1.4 Higher-level visual cognition

Higher-level visual cognition describes the integration, processing, and interpretation of visual information beyond that of basic perception. These processes might include object recognition, which describes the ability to identify and categorise objects based on their visual features, such as recognising a face or a shape (Schwartz & Yovel, 2016). Higher-level visual cognition processes might also include the integration of visual information such as objects, surfaces, and spatial properties into visual scenes (Oliva & Torralba, 2006; Rensink, 2000; Schyns & Oliva, 1994). Further, these processes may also support the generation of mental images or representations, that are not in the visual field (Boccia et al., 2019). Importantly, the integration of this visual information supports cognitive functions, such decision-making, learning, and memory processes.

1.1.5 Learning and memory

Learning and long-term memory enable people to store visual information over long periods, allowing individuals to recall past experiences, scenes, or environments. Long-term memory formation is a dynamic process that occurs through several phases, including encoding, retrieval, storage, and consolidation (Bisaz et al., 2014). These recollections can be retrieved consciously, known as explicit memory, or unconsciously, known as implicit memory (Camina & Güell, 2017). Importantly, long-term memory is proposed to differ from short-term memory in that it has a much larger capacity, retaining information for extended periods, and is less susceptible to temporal decay and capacity limits (Cowan, 2008).

1.1.6 Decision-making

Finally, visual decision-making thereon describes the cognitive processes that use visual information to make judgements, choices, or actions in the environment (Gold & Stocker, 2017). This process combines visual perception with higher-order cognitive functions like reasoning, memory, and problem-solving. As a result, it enables individuals to make decisions based on visual information, such as analysing visual cues during problem-solving, or determining where to direct attention to next. This process also enables the interpretation of unclear visual information in complex scenes.

1.2 The importance of studying visual cognition in early childhood

The development of visual cognitive systems, such as VWM and attentional control, plays a pivotal role in predicting later cognitive and academic outcomes. For instance, research has associated VWM capacity with both measures of general intelligence (Conway et al., 2003) and fluid intelligence (Fukuda et al., 2010). Further, VWM is linked to reading (Alloway & Alloway, 2010; Gathercole et al., 2004; Leather & Henry, 1994) and mathematics outcomes (Alloway & Alloway, 2010; Bull & Scerif, 2001; Gathercole et al., 2004; Leather & Henry, 1994; Swanson & Beebe-Frankenberger, 2004). Beyond academic outcomes, these systems also influence social functioning, with deficits associated with difficulties in peer relationships and classroom behaviour (de Wilde et al., 2016; McQuade et al., 2013). For instance, poor working memory abilities have been associated with general social difficulties, such as peer rejection and lower social competence, as well as more specific social impairments, such as aggression and problems with conflict resolution (McQuade et al., 2013). Lower working memory scores have also been associated with increased teacher-child conflict, decreased teacher-child warmth, and decreased likeability by peers (de Wilde et al., 2016). Given the significant impact of visual cognition on both academic and social outcomes, it is crucial to study the factors that influence its development.

Deficits in these cognitive systems are also evident in clinical populations, such as children with attention-deficit/hyperactivity disorder (Kofler et al., 2020; Willcutt et al., 2005) and autism (Steele et al., 2007). In attention-deficit/hyperactivity disorder, working memory and attentional control impairments may contribute to

behavioural symptoms associated with self-regulation, task persistence, and academic performance (Kofler et al., 2020). Similarly, children with autism often experience spatial working memory deficits, which might exacerbate challenges in navigating both academic and social environments (Steele et al., 2007). Deficits in working memory tasks have also been seen in children with preceding/predictive traits of schizophrenia (Cullen et al., 2010), developmental coordination disorder (Alloway, 2007), and children born preterm (Vicari et al., 2004). These findings emphasize the importance of early identification and targeted support for children with these deficits.

Importantly, working memory is receptive to intervention efforts during early childhood. Studies have demonstrated that structured interventions, such as online training, physical activity programs, and EF focused curricula, can improve EF abilities. For example, both educational and physical programmes have been shown to promote self-regulation and attentional control, leading to increases in cognitive flexibility and academic readiness (Lakes & Hoyt, 2004; Lillard & Else-Quest, 2006). Further, interventions targeting low-income preschoolers have successfully improved classroom behaviours and pre-academic skills, underpinning the profound impact of addressing EF deficits early in the lifespan (Raver et al., 2008, 2011).

These findings highlight not only the critical role of VWM and attentional systems to broader developmental outcomes but also their malleability during early childhood. By understanding the trajectories of these systems and the factors influencing their growth, interventions can be designed that maximise developmental outcomes, particularly in populations that may face additional challenges in these areas.

1.3 Visual cognition across development: behavioural insights

1.3.1 Visual cognition in infancy

Visual cognition encompasses multiple sub-domains, covering both attentional, perceptual, and VWM processes. These processes overlap and interact, often making it difficult to disentangle or isolate their individual contributions to visual cognition. This overlap is particularly relevant to studies in early development, which typically present infants with passive looking tasks due to their limitations in comprehension. These tasks primarily examine spontaneous looking behaviours associated with novelty detection or changes in the environment. As a result, a

substantial body of research has focused upon VWM in early life. The following sections therefore place emphasis on VWM studies, with occasional references to studies that have focused on attention and related processes. Throughout this thesis, the term VWM is used to reflect the view that visual short-term memory serves as a working memory system, involved in the service of other cognitive processes, such as perception and learning (Buss et al., 2018; Luck, 2008; Oakes et al., 2013).

Infants begin to develop foundational attentional and visual cognitive abilities in the first year of life, which are crucial for their cognitive and perceptual development. Early in infancy, attention emerges as the ability to direct, engage, and re-orient towards stimuli. Initially, infants begin to exhibit exogenously driven alertness, which becomes more sustained and regulated across the first year (Colombo, 2001). Examining eye movements in infancy provides ample insight into how visual cognition emerges and develops, as during this period it is not feasible to administer experimental tasks typically used with children and adults. For example, the direction, latency and form of saccadic eye movements towards peripheral targets have been investigated in very young infants, aged 1 and 2 months old (Aslin & Salapatek, 1975). At both ages, infants consistently made appropriate first saccades in the correct direction towards a peripheral target. This ability was somewhat limited to 30 degrees from the horizontal and diagonal axes from their line of sight, and 10 degrees from the vertical axis from their line of sight. Additionally, the likelihood of accurate target localisation was reduced upon the introduction of a second target into the visual field. They also found that latency to responses was highly variable, although most often less than 500 ms. In comparison to adults, these first saccades often fell short of meeting the targets' exact location and were often followed by a second, corrective saccade, to bring gaze closer to the target. These findings revealed that very early in infancy, young infants demonstrate basic saccadic responses to visual stimuli, which are slow and less precise in comparison to adults. This highlights the immaturity in the infant visual system at this age.

Visual orienting has been comprehensively studied in infants who are 2, 3, and 4 months old (Johnson et al., 1991). Here, the authors focused on infants' abilities to disengage their attention from a central stimulus, make anticipatory eye movements on where a target may appear and use a central cue to predict where a target might appear. They found that older infants were more easily able to disengage from the

central target and orient towards a peripheral target. Older infants also showed more than double the rate of anticipatory looks in comparison younger infants. Only the 4-month-old group showed the ability to shift towards a target's location based on a directional cue. These findings suggest that even at this young age, infants can orient their attention and plan eye movements. At this stage, evidence also suggests that voluntary control over eye movements begins to develop, as infants show enhanced abilities to shift attention and process multiple visual cues (Richards, 2001).

These abilities are crucial for the development of more complex attentional functions. For example, one study examined the early development of attention and distractibility in late infancy and childhood (Ruff & Capozzoli, 2003). Changes in attention were observed across ages, with casual attention, in which the child might be aware of but not fully engaged with the object or task decreasing with age, and focused attention, in which the child is intently engaged with an object or task increasing with age. Infants were also more easily distracted, demonstrating that older children have greater control over their own attention, reflecting the development of executive attention systems and self-regulation during childhood. It is thought that at birth, basic forms of attentional functions are present and that these undergo distinct periods of change over the first few years of life (Colombo, 2001). Generally, attentional control develops from more exogenously stimulus-driven processes in early infancy, to more voluntary, goal-directed processes by the end of the first year.

During the earliest months, infants also begin to exhibit an attentional preference for novelty (Fantz, 1964). In this study, infants were presented with a complex visual pattern across successive 1-minute exposure periods. Infants fixated less towards familiar patterns in comparison to novel patterns, highlighting that infants are more attentive towards novel stimuli. Following this, research has examined novelty preferences in infancy in the presence of a delay period (Fagan, 1970). This allowed the authors to examine memory retention, rather than immediate novelty preferences. Here, they found that infants as young as a few months old possessed the capability to retain information about visual patterns over short periods. Research has also investigated how familiarisation duration impacted this ability (Courage & Howe, 2001). Here, infants who had 30 seconds of familiarisation time, displayed novelty preferences after 1 minute, in contrast to infants who had 20 seconds of familiarisation time, which was insufficient to produce novelty preferences. Therefore, a longer

familiarisation duration improved infants' ability to retain information over time. Additionally, individual differences in attention style, such as the speed and depth of infants' engagement with the stimuli, also impacted retention, highlighting the relevance of the child's attentional patterns alongside exposure to the stimulus.

Afore-mentioned attentional behaviours suggest that infants are capable of visual discrimination and that their visual experience is guided by novelty. These behaviours are thought to reflect the development of infant VWM systems. For instance, Rose et al. (2001) used a novelty preference procedure to study VWM in 5-, 7-, and 12-month-olds. During a familiarisation phase, infants were presented with varying numbers of items. While previous procedures presented items for 30 seconds or longer, in this procedure, items were presented for 3 to 10 seconds prior to testing. This shorter presentation time was designed to focus on the rapid formation of memory representations, and thus, better isolate VWM systems. During the test phase, the familiar objects would then each be paired with a novel object. If infants showed a looking preference towards the novel item, it was assumed that they had consolidated the recognised item from the familiarisation phase, and therefore the number of items shown in the familiarisation phase was within their working memory capacity. To test capacity limits, infants were presented with either one, two, three, or four items. This study found that younger infants had a memory capacity of one or two items, but this began to reach three or four items in older 12-month-old infants. However, two aspects of this study raise uncertainty about whether VWM was successfully isolated. Firstly, although the infants were only briefly familiarised with the stimuli, exposures still lasted between 3 and 10 seconds, which may be sufficient time to allow for long-term memory formation. Secondly, each item was presented one at a time, so as the number of items/load was increased, the delay from the initial exposure to the test period was also increased. Encoding additional items and encountering additional stimuli made performance on the trial more likely to be influenced by competing information disrupting the retention of previously encoded information (referred to as interference) and by memory decay, rather than load capacity alone.

Other experimental tasks have been created to reduce the influence of long-term memory, interference, and decay during visual cognition. For instance, Ross-Sheehy et al. (2003) created a preferential looking task to investigate visual cognition in infancy. During this task, infants were presented with two flashing/blinking displays

of coloured shapes. On one of these displays, the coloured shapes presented were the same between each flash, and on the other display, one shape randomly changed in colour between each flash. Each flash was presented for 500 ms, requiring rapid encoding, with a delay of 250 ms, maximising the requirement to consolidate the display rapidly whilst minimising contributions from iconic memory and long-term memory (Ross-Sheehy et al., 2003). These displays were presented for a total of 20 seconds for each trial, with trials varying in the number of shapes on each display (load). Here, it was hypothesised that if infants could hold representations of the changing item(s) in VWM, they would detect the change and stay fixated on the changing side. This paradigm was used in infants between the ages of 4 and 13 months and revealed age-related differences in infants' ability to detect and show a looking preference towards the changing display. Infants at 6 months of age could only detect changes in displays of one item, but by 10 months of age, they could reliably detect changes in displays of up to four items. The authors also conducted additional experiments to further understand these findings. Critically, they adapted the paradigm to confirm that the decline at higher set sizes was not due to perceptual or attentional constraints. Here, they removed the delay period in the task, thereby eliminating the requirement for VWM storage between successive presentations. Here, infants showed comparable change preference abilities across all set sizes, suggesting that the previously observed decline at higher set sizes in the presence of the delay period was due to infants' inability to store items in VWM.

While novelty preferences observed in the preferential looking task likely reflect VWM processes to store and detect changes between flashes, these preferences may also stem from repeated presentations. Notably, in adult studies, change detection tasks are frequently employed in the study of VWM (e.g., Alvarez & Cavanagh, 2004; Ambrose et al., 2016; Awh et al., 2007; Eng et al., 2005; Fougnie et al., 2010; Luck & Vogel, 1997; Song & Jiang, 2006). During this task, participants are shown a sample array of coloured shapes. Following a short delay, they are presented with a test display, which either matches the sample array (same condition) or has one item which has changed (different condition). Participants must then indicate whether the test display was the same or different. Studies have therefore developed tasks for infancy, that more closely resemble the temporal features of change-detection tasks used in adults. To this end, Oakes et al. (2013) created and presented a one-shot change

detection task to 6- and 8-month-olds. In this task, a sample array of coloured items was presented, followed by a brief delay, and then a test array in which one item had changed in colour. The goal was to determine whether infants could form a mental representation of the initial array and show a preference for the novel stimulus in the test display. Findings revealed developmental differences in VWM capacity. At 8 months, infants reliably detected and demonstrated a preference for the changed item when the sample array contained two differently coloured objects, indicating their ability to encode and store two distinct items. In contrast, 6-month-old infants showed a preference for the changed item only when the sample array consisted of two objects of the same colour, thereby removing the requirement to encode them as separate objects. This finding suggested that between 6 and 8 months, infants undergo significant improvements in their ability to encode and store multiple, distinct items in VWM. Building on this, Oakes et al. (2017) extended the investigation to 8- and 10-month-old infants using a similar task, with results supporting earlier findings. By 8 months, infants consistently demonstrated robust VWM capacity for detecting changes in arrays with multiple distinct objects, and this ability remained stable at 10 months. The study also examined colour-location binding in VWM, further confirming that the ability to store multiple features and their associations becomes reliably established by 8 months of age.

While novelty preference procedures primarily focus on passive responses to changes, other paradigms, such as the delayed match-retrieval paradigm, require participants to actively recall and act upon the stored memory of object locations. This paradigm has therefore also been used to study location binding in infancy, confirming that infants can actively recall items stored in VWM. During this task, three face down virtual cards are presented to the child. Two of these are turned over and presented, then turned to face back down. Following this, a third card, which matches one of the now face-down cards, is then turned over and revealed to the child. If infants show a preference for looking towards the matching face-down card, it is assumed that the location of the matching card was stored within VWM. This task has been used to study VWM location binding in 8- and 10-month-old infants (Kaldy et al., 2016). In the 8-month-olds, performance was at chance levels, however, in the 10-month-olds, performance was significantly greater than chance, indicating that the ability to bind the object location of two items had emerged by this age. These findings further

support the growing body of literature highlighting rapid developmental progression in VWM capacity during infancy, with infants progressively able to process and store increasingly complex visual information. These findings also underscore the robustness of these abilities by the end of the first year.

Research has also investigated whether infants utilise information stored in memory to guide their subsequent search behaviours. This ability was assessed using a simplified cued visual search task, where a single sample stimulus was presented at a central fixation point, followed by a brief delay. A test array was then displayed, containing a stimulus that matched the sample and a novel non-matching stimulus, both in new spatial locations. Mitsven et al. (2018) used this paradigm to test 10-month-old infants, finding that they showed a looking preference towards the novel stimulus in the test array, compared to the familiar one. This behaviour indicated that infants at this age could store a representation of the sample stimulus in VWM and use it to guide their subsequent eye movements during the test phase. Further, these findings also suggested that infants must actively inhibit attention towards the familiar stimulus despite it appearing in a new location, prioritising exploration of the novel stimulus instead. This ability to regulate attention demonstrates increasingly advanced use of VWM across infancy to support goal-directed visual attention. Interestingly, these results were consistent, regardless of whether the authors presented simple shapes or object images, suggesting a robust mechanism by which 10-month-old infants use stored visual information to guide their behaviour. These findings highlight how VWM supports infants' exploratory strategies and selective attention, underpinning its role in cognitive development and learning.

Taken together, an array of experimental studies have highlighted important developmental changes in visual cognition occurring across the first year of life. These studies demonstrate that as VWM capacity increases, there are shifts in infants' allocation of attention and looking behaviours. Building upon foundational abilities observed in infancy, visual cognition thereon continues to progress, with further improvements in performance and capacity, into childhood.

1.3.2 Visual cognition in childhood

Across childhood, there is evidence of further improvements in children's ability to detect changes. Delgado Reyes et al. (2020) administered the preferential

looking task to children aged 4 months, 1 year, and 2 years, varying item loads of one, two, and three for 4-month-olds, and two, four, and six for older children. Their findings revealed age-related changes in change-preference abilities. The authors modelled how change preference developed over the 10-second trial. At 4 months, infants showed a robust change preference at a load of one item only. When presented with two items, this preference emerged by the middle of the trial, and for three items, it appeared by the end of the trial. By 1 year of age, robust change preference abilities were evident at a load of two items within 4 seconds of the trial, with preferences for higher loads emerging by 7 seconds. By 2 years of age, children demonstrated above-chance performance at a load of six items within 2 to 4 seconds of the trial. These results suggest that the latency of robust change preference abilities improves between 1 and 2 years of age. Importantly, these developmental changes reflect an increasing ability to hold and process more complex visual information, with the improvement in performance correlating with growing memory capacity.

Infant paradigms, which are often based upon looking behaviours, are difficult to use later in toddlerhood, as toddlers may lose interest, become distracted or refuse to comply with passive tasks. Further, paradigms employed in childhood studies typically involve explicit goals, which are not feasible for use with toddlers' due to demands on comprehension (Kaldy et al., 2016). Nonetheless, some researchers have sought to adapt some paradigms to investigate changes in visual cognition extending later into the toddlerhood period. For example, one early study used a sorting replication task to study changes in working memory from 12 to 36 months of age (Alp, 1994). In this task, several objects are sorted into two containers. The child is asked to replicate this sorting. Throughout this task, the number of objects is increased, and the largest number that the child can replicate is thought to represent working memory capacity. The authors found that with age, working memory scores increased linearly by about 1 unit every 6 months. Whilst this task allowed the researchers to study increases in capacity, it introduced additional demands beyond those of visual processing, such as the requirement of motor skills to physically move the objects. Since these abilities are still developing in early childhood, they may pose an added challenge, diverting attention away from the primary task.

Adaptations of delayed match-retrieval paradigms have also been used to examine changes in visual cognition in toddlerhood. In contrast to the sorting

replication task, these do not pose additional demands beyond those of visual cognition. For instance, one study examined how attention-based measures, including anticipatory gaze and pupil dilation, impacted 13-month-old children's performance on the task. Here, the authors reported that infants who showed increased focused attention during the presentation of the memory array, also had better performance on the task. Further, correct responses were more frequent in trials in which children showed greater pupil response (Cheng et al., 2019a). This task has also been conducted with 20-month-old and 25-month-old toddlers (Cheng et al., 2019b). Task conditions were varied across three experiments, in which the items were either static, moved in the same direction, or moved in different directions. Whilst both groups could track the items when static, only the 25-month-old group could maintain items within working memory when movement was added. Another study conducted two experiments to investigate how item similarity influenced performance in toddlers aged 30 months old (Cheng et al., 2020). In the first experiment, the objects were unique to one another, and in the second experiment, one of the objects shared features, such as a similar colour or shape. In the first experiment, toddlers succeeded in locating the previously presented card. In comparison, in the second experiment, toddlers only performed marginally better than chance. Here, the authors also found that the toddlers were also not more likely to select the decoy item instead, indicating a complete loss of the items stored in VWM.

Adaptations of change detection tasks in later childhood have shown that capacity continues to increase linearly. Unlike infants and toddlers, older children are able to indicate whether a display is the same or different. For instance, Simmering (2012) used a change detection task to examine visual cognition in children. Here, they wanted to adapt the task for use in younger children in the 3- to 5-year age range and compare this to results in older children in the 5- to 7-year age range. They found that VWM capacity steadily increased with age, from two to three items between the ages of 3 and 5, to approximately four items by the age of 7. Further, they wanted to examine whether higher capacity limits seen in the infant preferential looking task were due to the change-detection task being too difficult for young children and subsequently underestimating capacity. While comparisons revealed that the modified task allowed for higher capacity estimates, these estimates were still broadly consistent with the original task and did not overestimate capacity. Similarly, Buss et al. (2014)

used the same task in children aged 3 and 4 years old. Consistent with findings from Simmering (2012), they found that children's performance declined, as load increased from one to three items. Further, older children had better performance, with significantly higher correct responses. Riggs et al. (2006) also found similar results using the same paradigm in older children aged 5, 7 and 10 years old. Similarly, they found that performance on the task improved significantly, with VWM capacity doubling between 5 and 7 years old, after which it reached adult-like capacity of around three to four items.

Notably, the aforementioned studies report inconsistencies in VWM capacity across infant and childhood measures of visual cognition. Specifically, studies using the preferential looking task in infancy and toddlerhood have reported increases in VWM capacity to approximately four items by the end of the first year (Delgado Reyes et al., 2020; Ross-Sheehy et al., 2003) and six items by the end of the second year (Delgado Reyes et al., 2020). In contrast, studies using the change detection task in childhood have reported increases in VWM capacity from around two to three items between 3 and 5 years (Buss et al., 2014; Simmering, 2012), to around four items by 7 years (Riggs et al., 2006; Simmering, 2012). These inconsistencies are thought to arise as a result of several factors. The first explanation is that looking behaviour during preferential looking tasks involves more passive processes compared to the explicit goal-directed actions required in change-detection tasks (Riggs et al., 2006; Simmering, 2012). Specifically, the preferential looking task relies on infants' novelty preferences, as change preference (CP) scores, a key measure of VWM, are extracted based on the time spent looking at each display. This task therefore has perceptual, attentional and cognitive components, as for infants to detect and develop a preference for change, they need to hold item(s) within VWM, switch between sides, and inhibit distraction towards the changing side. While the task is designed to examine VWM function, a variety of other processes also support task performance (Ross-Sheehy et al., 2003; Simmering, 2016a). Although one-shot change detection tasks have been adapted to more closely resemble temporal features of change-detection tasks, these still involve passive looking behaviours based upon novelty preferences (Oakes et al., 2013, 2017), making findings less dependent on VWM alone. In contrast, change-detection tasks require children to actively compare the two displays and make an explicit decision on whether they are the same or different.

The other explanation for task-based discrepancies suggests that VWM capacity does reach adult-like levels during infancy and that developmental improvements in change detection instead reflect the maturation of other cognitive abilities, such as processing speed and task strategies. This hypothesis suggests that improvements in VWM performance are likely driven by a combination of capacity increases and the refinement of broader cognitive and attentional systems, highlighting the dynamic interplay between VWM and other developing visual processes. Both explanations are consistent with the observed developmental shifts in change-preference abilities found in the preferential looking task across the second year of life (Delgado Reyes et al., 2020).

1.4 Visual cognition across development: neuroimaging insights

1.4.1 Childhood, adolescence, and adulthood visual neurocognition

Whilst research has highlighted significant shifts in visual cognitive abilities across development, there remains a gap in our understanding of the neural mechanisms that underly these changes. Understanding these mechanisms provides a more comprehensive view of the brain's role in visual cognition, enabling researchers to infer the role of specific regions in visual cognitive behaviours and increasing our understanding of how brain maturation supports cognitive development. For instance, across development, neuroimaging data has highlighted a consistent network of brain regions within the frontal, temporal, and parietal cortices, that are associated with VWM function (Cowan, 2001). This consistency indicates that early in development, some core regions are already reaching functional levels observed in the canonical network in adults. It is therefore thought that improvements in VWM across development stem from increasing capacity and more efficient use of attentional and storage mechanisms (Cowan, 2001). This literature is discussed in greater detail below.

Research has consistently shown that a number of frontal and parietal regions play a crucial role in VWM development, with changes in activation patterns observed across childhood and adolescence. Geier et al. (2009) used fMRI to study working memory-related brain activation in children, adolescents, and adults completing a delayed-response task. Here, participants were required to maintain the spatial locations of a target stimulus in memory over a delay period. Findings reported

consistent activation across all age groups in a core network of regions, thought to support basic task performance. These regions included the right FEF and middle occipital gyrus (MOG), which were thought to be involved in response preparation and attention shifts, the left superior parietal lobule (lSPL) and right superior frontal gyrus (rSFG), which were thought to be involved in maintenance and the left lingual gyrus, which was thought to be associated with visual-related response. Importantly, age-related differences were also observed in regions including the SFG, IFG, and middle frontal gyrus (MFG), in which activity increased from childhood. Here, the authors suggested that these regions, which are implicated in higher-order cognitive control, may support the improved VWM performance seen in adults.

Other research has emphasised a shift towards greater specialisation and refinement of the fronto-parietal network in the development of visual cognition. For instance, Scherf et al. (2006) used fMRI to investigate the neural correlates of VWM in children, adolescents, and adults completing a delayed-response task. Here, they found that children showed limited activation in core VWM regions, such as the dorsolateral prefrontal cortex (DLPFC) and the parietal cortex, and relied more heavily on ventromedial regions, such as the caudate nucleus and anterior insula. In adolescence, this network expanded to include areas such as the DLPFC, anterior cingulate cortex, posterior parietal cortex and anterior insula, as well as the integration of regions involved in response preparation. Adults were found to recruit the most specialised network of regions, including the left-lateralized DLPFC, ventrolateral prefrontal cortex (VLPFC), and supramarginal gyrus (SMG). These age-related changes were thought to reflect the refinement of neural networks supporting VWM, which underly improvements in top-down cognitive control and attentional processes, ultimately increasing adult visual cognitive abilities. These findings align with those of Kwon et al. (2002), who also examined age-related differences in visual cognition using fMRI and an N-back task that required the storage and manipulation of spatial information. In this study, they found increases in task performance, including accuracy and response latency, from childhood to adulthood. Alongside this, they also found increases in activity in the bilateral DLPFC, left VLPFC, left premotor cortex, and bilateral posterior parietal cortex, further supporting the importance of the frontal-parietal network for higher-order cognitive control in VWM. Thomas et al. (1999) has also provided evidence for the maturation of the frontal-parietal network. Here,

cortical activity was measured using fMRI in children and adults using a spatial working memory task. The authors reported activation across both age groups in the right SFG, right DLPFC, right superior parietal cortex, and bilateral inferior parietal cortex, further supporting the recruitment of these regions during VWM.

Research has also highlighted the importance of the posterior parietal cortex, particularly the intraparietal sulcus (IPS), in association with VWM capacity (Todd & Marois, 2004, 2005). In these studies, load was manipulated during a delayed recognition task, to study modulation of brain activity associated with VWM capacity demands. Here, the authors presented the participants with increasing load demands, including, one, two, three, four, six, and eight items at a time. They reported increased activity in the IPS as load was increased across one, two, and three items. However, upon reaching four items and above, this activity plateaued (Todd & Marois, 2004). These findings were further extended, showing that individual differences in VWM capacity were strongly predicted by IPS activation. These findings suggest that the IPS plays a central role in encoding and maintaining VWM representations, and its development may contribute to the improvements in VWM capacity observed across childhood and adolescence. These findings are in agreement with Klingberg et al. (2002) who used fMRI to record brain activity from children and adults whilst they recalled the locations of sequentially presented visual stimuli. Here, they also found increased activation in the IPS and DLPFC in adults, which was also correlated with increasing load demands. Here, the authors proposed that performance on VWM tasks not only depends on activation within a specific region, but also communication across a network of regions.

Diffusion tensor imaging has further shed light on the structural integrity in brain regions involved in VWM processing. Nagy et al. (2004) revealed increased white matter integrity in the superior and inferior left temporal lobe – regions associated with working memory abilities. In another study, Olesen et al. (2003) combined diffusion tensor imaging and fMRI to examine how maturation in white and grey matter contributes to the development of VWM in childhood. Similarly, their findings demonstrated that maturation in white matter was correlated with both scores of VWM and activity within the superior frontal sulcus and the intraparietal lobule, supporting the role of these regions in visual cognitive development.

Together, these findings illustrate that the development of the fronto-parietal network is central to the maturation of visual cognition. Functional and structural changes within this network support improvements in VWM capacity and reflect broader developmental processes, including enhanced connectivity, refinement of neural circuits, and the emergence of top-down cognitive control mechanisms.

1.4.2 Early visual neurocognition: cross-sectional evidence

The infancy period provides a unique window into the early emergence of the VWM network, although neuroimaging research early in development are limited in comparison to later childhood, adolescence, and adulthood. Across infancy, both frontal and posterior regions have been implicated in visual cognition (Buss et al., 2014; Delgado Reyes et al., 2020; Ellis et al., 2021; Wijeakumar et al., 2019, 2023). Some research has indicated that the frontal cortex plays a key role in visual cognition in early childhood. For instance, Delgado Reyes et al. (2020) used fNIRS to explore the brain networks underlying VWM. The authors found activation in regions across the fronto-parietal network, including the rDLPFC, lSFG, lTPJ, and left ventral occipital cortex (lVOC), all regions associated with working memory and attention in adults (Boisgueheneuc et al., 2006; Cieslik et al., 2013; Deen et al., 2017; Yarkoni et al., 2011). They also reported age-related changes in frontal cortex activation. Specifically, in the rDLPFC, there was greater activation during the task in infants aged 4 months in comparison to infants aged 1 year. The authors hypothesised that this finding represented the emergence of early looking abilities, such as shifting between displays, controlling consolidation, and releasing from fixation (Perone et al., 2011; Perone & Spencer, 2013). Similarly, performance-related frontal cortex activation has also been observed in cross-cultural samples. In one such study, the preferential looking task was administered in low-resource settings in children aged 4 to 48 months (Wijeakumar et al., 2019). In this study, findings reported increased suppression in the lDLPFC in association with early distractor suppression mechanisms.

Other neuroimaging methods have also reported frontal activity during infancy. For example, Ellis et al. (2021) used fMRI to investigate infant brain activity during an attentional cueing task. In this study, behavioural and fMRI brain data was collected from awake infants aged 3 to 12 months old. Here, the authors found increased attentional engagement when trials were preceded by a valid cue. During infant attention, activation was observed in regions from the cingulo-opercular

network, including the anterior cingulate cortex and basal ganglia. Attention-related activation was also observed in regions from the fronto-parietal network, including the MFG and IFG. Interestingly, during trials preceded by an invalid cue, there was increased engagement in frontal regions, which was thought to be due to attentional reorientation. With age, there was no change in behavioural or brain effects, suggesting that the activation patterns observed develop early in infancy. EEG studies have also implicated the frontal cortex in attention processes during infancy. Perry et al. (2016) examined EEG activity during an attention task in infants aged 10-months. Here, greater EEG power in frontal regions was associated with increased attentional behaviours. Further, increased attention at 10 months of age was associated with lower frustration levels at 3 years, highlighting a link between infant neural activity and greater emotional regulation in childhood. Similarly, Cuevas et al. (2012) also investigated EEG and heart rate activity during working memory and inhibitory control tasks. Here, increased inhibitory control was linked to increased heart rate and greater frontal EEG coherence.

In addition to the frontal cortex, previous research has also highlighted the role of the posterior parietal cortex in visual cognition. For example, Wilcox & Biondi (2016) investigated infants' capacity to represent objects in VWM between the ages of 3 and 13 months. To do this, infants were shown moving objects that became occluded and upon reappearance, either the same object, or an object with distinctly different features emerged. Using fNIRS, they found that younger infants, between 3 and 6 months, showed increased activation in the posterior temporal cortex regardless of object changes. However, older infants, between 10 and 12 months, showed reduced activation in this region regardless of object changes. These results were interpreted as evidence of refinement of object-processing regions during the first year of life, with older infants potentially utilising more specialised networks for VWM.

Studies using the preferential looking task have also reported posterior parietal engagement in early childhood. For instance, Delgado Reyes et al. (2020) reported an increase in activation in the laIPS with age. Interestingly, the authors also observed load-dependent modulation in the laIPS. In this region, there was a pattern of decreased activation upon memory load surpassing capacity, potentially reflecting an inability to consolidate and maintain representations at high load demands in infancy. The same load-related activation patterns have also been observed in the laIPS in

cross-cultural samples (Wijeakumar et al., 2023). These findings partially align with adult studies that find increased activity in the IPS with increased VWM demand, but differ in that activity decreases, instead of plateauing, once VWM capacity is surpassed (Todd & Marois, 2004, 2005). Moreover, Delgado Reyes et al. (2020) also identified regions that were thought to represent distractor suppression in infants, a mechanism proposed to aid their ability to maintain and detect change. Specifically, activation within the left TPJ was associated with CP scores, which represented the child's ability to detect the changing display. Younger infants with higher CP scores showed greater activation in the left TPJ, while older children exhibited greater suppression. These findings suggest that there is refinement of visual cognitive processes anchored in posterior regions in toddlerhood.

Building on these findings, evidence from early childhood also points to continued parietal specialisation alongside the emerging involvement of frontal regions. For example, Buss et al. (2014) used fNIRS to study VWM in children aged 3.5 and 4.5 years old. Here, the authors used an adapted version of the change-detection task (Simmering, 2012). They found activation across both the frontal and parietal cortices. Importantly, they also found increasing activation with increasing VWM load in the aIPS, with activation decreasing after VWM capacity was surpassed. Consistent with Delgado Reyes et al. (2020), these findings only partially aligned with results from adult VWM studies (Todd & Marois, 2004, 2005), highlighting the immaturity of working memory systems in early development and their gradual refinement across time. Immaturity of the frontal cortex, may explain why younger children rely more on posterior parietal regions during VWM tasks. Perlman et al. (2016) examined prefrontal activation during a working memory task in infants aged between 3 and 7 years old. Here, they found developmental increases in activation in the pre-frontal cortex alongside increases in accuracy and response speed. It seems that later in childhood, frontal regions become more specialised, reflecting the gradual maturation of executive processes required for efficient visual cognitive abilities.

These studies highlight the dynamic nature of VWM functional brain networks, showing the gradual specialisation of regions such as the DLPFC, IPS, and l-TPJ. The emergence of these specialised regions, alongside the development of distractor suppression mechanisms, appears to support improvements in VWM precision, capacity, and attention control over development. While the fronto-parietal

network underlying VWM in adulthood is well-documented, its developmental trajectory from infancy through childhood remains a focus of ongoing research, with mixed findings across the frontal and parietal cortices.

1.4.3 Early visual neurocognition: longitudinal evidence

Longitudinal research has also provided further insight into the development of frontal and parietal brain regions that support visual cognition. Following the same cohort over time allows researchers to more directly examine how changes in behaviour and brain function are associated with emerging performance-related behaviours. Ultimately, by tracking how behaviour and brain function evolve, become stable, or undergo significant change, researchers can gain a deeper understanding of the trajectory of brain maturation and its role in visual cognition development. For example, Baird et al. (2002) used fNIRS to study brain activation in infants completing an object permanence task. During this study, the children were followed longitudinally at 4-week intervals, between the ages of 5 and 12 months. In this task, infants were presented with a toy for a brief period, which was then hidden. If the infant searched for the object on each trial, they were considered to have achieved object permanence. Findings reported an increase in frontal lobe activation associated with the emergence of object permanence. This increase was suggested to reflect the functional maturation of frontal regions.

Furthermore, longitudinal studies have also suggested that the frontal cortex contributes towards task performance and cognitive outcomes. For instance, Wolfe & Bell (2007) investigated how cognitive and emotional development were linked during early childhood. Here, children were observed in infancy at 8 months old, then again in childhood, at 4.5 years old. Across the study, EEG recordings were collected during a working memory task. In addition, temperament and language measures were also collected. The authors found that at 8 months, frontal cortex activity and temperament both predicted working memory abilities. Similarly, at 4.5 years, frontal cortex activity, temperament, and language predicted working memory abilities.

Longitudinal research has also examined differences in fronto-parietal activation in older children. For instance, one study examined the impact of exposure to formal schooling on VWM and brain function (Davidson, Shing, et al., 2023). The authors compared performance and brain function during a change-detection task in

children who were enrolled in school earlier and those who deferred school entry by one year. Children who were enrolled in school earlier showed greater activation in the lIPL and lIFG, alongside greater VWM performance. Here, it was thought that children enrolled earlier, may routinely engage left-lateralised fronto-parietal engagement to support increasing executive control demands associated with school. It is clear that regions across frontal and parietal cortices play a key role in visual cognition, however, more research is required to understand how regions within this network contribute to different components of visual cognition, as well as how these regions emerge and develop in early life.

1.5 Developmental frameworks and models of visual cognition

To better understand visual cognition, several theoretical and computational models have been proposed. These perspectives have led to increased hypothesis precision, interpretation of findings, and understanding of underpinning mechanisms. The sections below provide a brief overview of the key models associated with visual cognition.

1.5.1 Baddeley and Hitch's model of working memory

Baddeley & Hitch (1974) first proposed a working memory model, involving the temporary storage and manipulation of information in completion of complex tasks. This was based on the hypothesis that attention and short-term memory function as a unified system, resulting in a model that combines a fixed multi-component structure with flexible, goal-directed control processes (Baddeley et al., 2020). Specifically, Baddeley & Hitch (1974) proposed a working model with three components that were developed from earlier concepts of short-term memory (Atkinson & Shiffrin, 1968; Broadbent, 1958). This model comprises of three capacity-limited systems: the central executive system, phonological loop, and visuo-spatial sketchpad. The central executive system is thought to act as control centre for attention, with two subsidiary systems: the phonological loop and visuo-spatial sketchpad. The phonological loop is thought to process verbal and auditory information, and the visuo-spatial sketchpad is thought to process visual and spatial information. The visuo-spatial sketchpad has been further divided into two subsystems: the visual cache, which stores visual information, and the inner scribe, which processes spatial and movement information (Baddeley & Logie, 1999). This

model was further updated (Baddeley, 2000) to include a fourth component: the episodic buffer, which integrates information from the subsidiary systems, as well as from long-term memory, to form episodic representations.

1.5.2 Posner and Petersen's model of attention

Posner & Petersen (1990) proposed a model that describes attention as being controlled by three distinct but interacting systems in the brain: alerting, orienting, and executive control. The alerting system is responsible for allowing individuals to be optimally vigilant and therefore prepared to respond to stimuli. This system is linked to neurotransmitter release in the locus coeruleus.

The orienting system directs attention to specific stimuli, enabling focus on locations or features. This system is thought to involve two interconnected brain networks: the dorsal fronto-parietal network and the ventral fronto-parietal network, which together facilitate the strategic control and reactive modulation of attention (Corbetta & Shulman, 2002). The dorsal network, which includes the FEFs and regions in the parietal lobe (such as the IPS and SPL), is associated with voluntary or endogenous orienting, enabling the intentional and goal-directed control of attention. In contrast, the ventral network, encompassing the TPJ and the ventral frontal cortex (largely lateralized to the right hemisphere), supports involuntary or exogenous orienting, allowing for reflexive responses to salient sensory events. These two systems work in unison within the orienting network to integrate top-down control with bottom-up responses, ensuring efficient and adaptive attentional shifts.

Finally, the executive attention system involves mechanisms for monitoring and resolving conflicts between thoughts, emotions, and responses, as well as managing attentional resources and suppressing distractions (Talalay, 2024). This system is thought to comprise two distinct but interacting networks: the fronto-parietal network and the cingulo-opercular network. The fronto-parietal network, including regions such as the FEFs and parietal lobe, is thought to be responsible for task initiation, switching and attentional adjustments. The cingulo-opercular network, comprising the anterior cingulate cortex and anterior insula, plays a critical role in maintenance across trials and overall task performance. Although these networks function independently, they frequently interact to coordinate executive control,

highlighting a dynamic and adaptable system rather than a unified model of cognitive control (Petersen & Posner, 2012; Posner & Petersen, 1990).

1.5.3 Cowan's embedded-processes model of working memory

The embedded-processes model of working memory was first introduced by Cowan (1988) and later formally named by Cowan (1999). This model proposes that working memory is a set of embedded-processes both from attention and long-term memory (Cowan et al., 2020). The first component in this model is a brief sensory store, where a stimulus is held for a few hundred milliseconds after stimulus presentation. The sensory store then activates elements of the long-term memory system. Information can be directed to the focus of attention, where at most several meaningful ideas can be kept. Poorly consolidated items can become inactive within seconds, whereas strongly consolidated items can remain active for longer. A neural model of the environment is formed wherein familiar stimuli are stored in activated long-term memory, while detected changes lead to attention, resulting in an orienting response. Central executive processes enable goal-directed attention processes; however, these sometimes compete with uncontrollable orienting responses. In the brain, the frontal lobes are considered to be associated with central executive processes, the parietal lobe with attention focus, and various posterior cortical regions with long term memory representations that can become temporarily active (Cowan et al., 2020).

1.5.4 Contextualising early visual cognition in theoretical working memory models

How do the aforementioned theoretical frameworks contextualise how infants allocate attention, process visual stimuli, and retain items in visual cognition? Ross-Sheehy et al. (2003) proposed that the memory system engaged in infants during the preferential looking task corresponds to the visual cache sub-component of the model developed by Baddeley and colleagues (Baddeley, 2000; Baddeley & Hitch, 1974; Baddeley & Logie, 1999). In the preferential looking task, infants looking preferences reflect their ability to detect novelty. Importantly, across the flashes, the ability to detect changes requires the retention of previously viewed items in memory. For example, infants might be presented with two items in each display. If infants are able to consolidate the two familiar colours within memory, they should be able to detect

if one of these changes between the flashes. Thus, if infants show a looking preference towards the changing side, this indicates successful encoding and retention of the visual information. Further, as the number of items increases, infants' novelty preferences decline, aligning with the limited capacity of the visual cache. Visual cognition elicited by the preferential looking task therefore aligns with the visual cache sub-component of Baddeley and colleagues model. Ross-Sheehy et al. (2003) therefore proposed it was likely that the preferential looking task captures the origins and early development of the adult working memory system.

Visual cognition elicited by the preferential looking task also corresponds in part with other models of attention and memory. For instance, Cowan (1999) conceptualises working memory as a set of embedded processes involving both attention and long-term memory. During the task, infants are presented with flashing displays, corresponding to visual information (e.g. two coloured shapes) entering the brief sensory store. A subset of these items may enter the focus of attention, wherein they can be actively retained across flashes. If a change is detected in the focus of attention, attention shifts towards the novel stimuli. While long term memory may retain familiar items for comparison, this information is not actively processed. As the number of items increases, fewer can be directed to the focus of attention, reducing the likelihood that a change will be detected. While Cowan's model accounts for attention shifts toward novel stimuli, it assumes that the focus of attention can operate through both voluntary (top-down) and involuntary (bottom-up) mechanisms. However, the preferential looking task primarily relies on automatic novelty detection, rather than a deliberate, goal-directed shifts. Similarly, visual cognition elicited in the task only partially aligns with Posner & Petersen's (1990) model of attention. Although the initial display may trigger engagement, in line with the alerting system, the fit with the orienting system is less compelling, as infant attention is largely driven by novelty preferences, rather than an interplay between exogenous and endogenous attentional control. More broadly, findings from the preferential looking task also indicate that capacity limits increase in early development. Critically, the models discussed above do not account for developmental changes and thus do not capture age-related shifts in how infants consolidate and retain information in VWM.

1.5.5 Dynamic field theory of VWM

Whilst aspects of visual cognition in infants can be aligned with components of afore-mentioned verbal theories, there are some shortcomings. In the context of looking behaviours elicited in the preferential looking task, these models do not fully account age-related changes in capacity limits or the automatic nature of novelty detection. On the other hand, neuro-computational models such as those based on dynamic field theory (DFT) can be used to simulate visual cognition processes across trials and over time. DFT comprises of a class of continuous attractor neural network models. These models have previously been used to capture the dynamic interactions driving neural and behavioural processes in perception, cognition, and action (Schoner et al., 2015). Across a series of studies, this framework has been used to explain encoding, consolidation, maintenance, and comparison of items during visual cognition, and also capture age-related changes across development (Wijeakumar & Spencer, 2020).

Applications of DFT in cognition is grounded in work by Thelen and Smith (Thelen & Smith, 1994, 2007). In DFT, behaviour emerges through the interaction of multiple processes. Neural populations in dynamic systems move in and out of attractor states. These neural systems can exist in at least three attractor states: a 'resting' state, where the system is inactive but can be activated following input, a 'stabilised' state, where the system is anchored to external input, and a 'self-sustaining' state, where internal interactions and interactions with other systems can sustain activation even after the input stops (Wijeakumar & Spencer, 2020). DFT was first used in the study of motor planning and reaching in early life (Smith et al., 1999; Thelen et al., 2001). Thelen et al. (2001) used a DFT model to explain performance on the A-not-B task in 7- to 12-month-old infants. Traditionally, infants repeatedly demonstrate an error in which they persistently reach for a toy in location "A", despite seeing it moved to location "B". Here, the authors propose that this error arises from the dynamic interactions between ordinary goal-directed processes, such as looking, planning, reaching, and remembering. They presented a DFT model, that integrated mental process like perception, planning, and memory in terms of continuous dynamics, integrating them with bodily movement, to demonstrate how stronger neural connections improve the maintenance of memory representations and suppress competing responses.

DFT models had been used to capture and predict behaviours and brain function in change-detection and preferential looking paradigms (Costello & Buss, 2018; Johnson, Spencer, Luck, et al., 2009; Johnson, Spencer, & Schöner, 2009; Johnson et al., 2014; Simmering, 2016a). In these models, VWM representations are supported by excitatory and inhibitory neural interactions, with neural units tuned to perceptual features like colour. Simmering (2016) used a DFT model to capture developmental changes in children engaging with the change-detection task. This model was able to simulate performance on change-detection tasks, matching the accuracy observed in experimental studies. As neural interactions strengthen with development, the model's performance aligns with developmental improvements in VWM accuracy, demonstrating how changes in neural connectivity contribute to enhanced memory capacity and resolution.

The DFT model used to capture change detection performance was adapted to capture infant looking behaviours in the preferential looking task (Perone et al., 2011). Here, the authors used simulations of a DFT model to explore how looking behaviours related to memory capacity, what infants are comparing across flashes, and what mechanism drives developmental improvements in performance. In this model, when a novel item is presented, fixation leads to excitation in a perceptual field, responsible for encoding items, thereby reinforcing fixation. However, when repeated items are shown, strong peaks form in a working memory field, responsible for forming self-sustaining peaks representing items. These peaks inhibit the relevant positions in the perceptual field. Regarding developmental differences, the model suggests that older infants, with stronger neural interactions, exhibit more stable memory representations. For example, when older infants encounter repeated items on the non-changing display, they are more likely to shift their attention toward the changing display, encode the novel item, and maintain fixation on it. This ability to sustain working memory representations and effectively compare them with novel stimuli leads to a preference for change. In contrast, younger infants, with weaker neural interactions, may experience less stable memory representations, resulting in spontaneous destabilisation and a weaker preference for change.

Much work remains to be done to use these models to capture individual differences in behaviours, and perhaps brain function, alongside behaviour. For instance, one study demonstrated that a DFT model could simulate both behavioural

performance and brain activation during an inhibitory control task (Wijeakumar, Ambrose, et al., 2017). Nonetheless, existing work is important as no verbal theory or modelling framework has attempted to provide a mechanistic understanding of visual cognition in infants – a 'black box', that can only otherwise be explained through interpretations from childhood and adulthood studies.

1.6 Summary and research gaps

Visual cognition encompasses a range of cognitive processes enabling individuals to perceive, interpret, and respond to visual stimuli. These processes include perceptual processing, attention, VWM, higher-level visual cognition, decision-making, and learning and memory. Together, these systems allow individuals to process and respond to visual stimuli, enabling completion of complex tasks in learning, problem-solving, and social interactions. This system is predictive of academic achievement, IQ, global fluid intelligence, and social abilities. Given the far-reaching outcomes impacting quality of life, it is important to understand how this system emerges and develops early in the lifespan and what factors might impact its developmental trajectory.

Visual cognition begins to emerge in infancy and undergoes significant changes throughout childhood and adolescence. Early in infancy, foundational attentional mechanisms, such as saccadic eye movements and exogenously driven alertness, enable infants to engage with their environment. Novelty preferences for visual patterns also emerge early in infancy, reflecting foundational VWM processes. By the end of the first year, infants demonstrate significant improvements in attentional regulation, goal-directed behaviour, and memory precision, supported by a gradual shift from stimulus-driven to goal-directed attentional control. Into childhood, VWM abilities increase steadily, alongside improvements in selective attention, task flexibility, and processing speed. Studies have shown that between the ages of 3 and 7, children's memory capacity nearly doubles, reaching adult-like levels of three to four items. The increasing complexity of visual cognition during this period is closely tied to brain maturation, particularly in the frontal and parietal cortices. By adolescence and adulthood, the visual cognition system becomes highly specialized, allowing for efficient integration of visual features, object recognition, and adaptive decision-making.

Advances in neuroimaging have allowed the study of the structural and functional underpinnings of visual cognition. fNIRS is a valuable neuroimaging tool in early visual cognition, as it is quiet, non-invasive, and tolerant to movement. This has provided insight into early visual cognitive development, revealing key networks across frontal, temporal, and parietal regions. Research has implicated both the frontal and parietal cortices early in life. Differences across childhood are thought to be due to the immaturity of the frontal cortex, leading to greater reliance on posterior parietal areas. Over time, increased activity in frontal-parietal regions, including the DLPFC and IPS, are thought to support improvements in cognitive functions, such as attentional regulation and VWM consolidation. Age-related activation changes in frontal-parietal regions align with growing VWM abilities and capacity, underpinning the refinement of these neural systems.

Despite progress in early visual cognition research, critical gaps remain, particularly regarding the early influences on its development. Firstly, whilst there is a wealth of evidence studying visual neurocognition in childhood, adolescence, and adulthood, less is known about the neural mechanisms underlying early visual cognition. Further, there is limited research investigating developmental trajectories of visual cognition from infancy to toddlerhood. The literature reviewed in this chapter highlights the complexity of visual cognition development, highlighting the association between brain development, behavioural abilities, and developmental outcomes. However, there remains a gap in our understanding of how other factors, such as caregiver behaviours might influence this. Thus far, studies have investigated the role of dyadic behaviours during early development, but the neural mechanisms underlying these interactions and their impact on visual cognition remain unclear. The next introductory chapter will therefore discuss current findings from dyadic interactions, and the influence of caregiver input on child visual cognition.

Chapter 2:

Dyadic interactions – a review of the literature

2.1 Introduction

Whilst there is evidence for the rapid progression of visual cognition throughout early childhood, critical gaps in the research remain. Specifically, it is unclear how other factors, such as caregiver attention, influence this development. It is therefore important to examine caregiver influences during play interactions, to provide deeper insight into how they support and scaffold infants' attention and learning in everyday life. The aim of this chapter is to provide a review of the existing literature examining behavioural and neural correlates of dyadic interactions.

2.2 Foundations of caregiver-infant interactions

During the first year of life, four key attentional functions are believed to emerge: alertness, spatial orienting, attention to object features, and endogenous attention (Colombo, 2001). In the early months, infants demonstrate exogenously driven alertness, which becomes more sustained and better regulated by 2 to 3 months of age. Subsequently, between 2 and 6 months, they rapidly develop the ability to engage, disengage, and shift attention across spatial locations. The growing ability to shift and sustain attention also supports infants' exploration of their environment. Early in life, infants make brief, frequent, and varied object play bouts. For example, Herzberg et al. (2022) studied frame-by-frame videos obtained during home visits with children aged 13 months, 18 months, and 23 months. Across all object interactions, children frequently switched between toys and non-toys. Play durations with objects lasted a median duration of 9.8 seconds and play bouts ranged from 41 to 99 bouts per hour for each child. Notably, 80% of the infants spent more time interacting with the objects in comparison to not, indicating that object interactions take up a significant proportion of infants' time.

As infants increasingly interact with and explore their environments they create many opportunities to gain information about objects properties and function. Needham (2000) studied how infants develop the ability to use object features to identify boundaries between two adjacent objects. They found that 3.5-month-old infants can use object features to perceive distinct objects, and that infants who showed more active object exploration were better at making these distinctions. It was proposed that these active exploration skills enabled infants to learn about object features (such as edges, shapes and textures) and also, how these features relate to

spatial boundaries. Research has also shown that infants vary exploratory actions based upon differences in weight, sound, texture, and other properties of objects, and that objects with multiple functional properties lead to a wide range of actions during object exploration (Palmer, 1989). Notably, manual exploration at 9 months has been linked to later cognitive functioning (Ruff et al., 1984). The way in which infants interact with objects also changes with age. For example, research investigating how children aged 11 to 37 months learn to interact with everyday objects, showed that they move from more basic exploration, or actions unrelated to the objects design, to object specific actions, such as twisting or pulling on lids (Rachwani et al., 2020). These findings further support how children learn to interact with everyday objects.

With infants' growing engagement and exploration, they create multiple opportunities for shared experiences with social partners, who may be able to provide knowledgeable context and information (Bruner, 1975; Vygotsky, 1997). Tamis-LeMonda & Bornstein (1991) investigated differences in symbolic play and non-symbolic play between mothers and their children aged 13 and 20 months of age. Here, symbolic play describes imaginative play, using objects to represent or symbolise other objects or ideas. In contrast, non-symbolic play refers to functional play, interacting with objects in ways that focus on their functional or physical properties. From 13 to 20 months, both the caregiver and toddler progressed towards more sophisticated play types, often with changes in one partner's play associated with changes in the others. After accounting for partner influences, the authors found that developmental changes in play remained for both partners, suggesting that the developmental changes and individual differences in dyadic play across development are partly influenced by independent processes as well their interactions with each other. Interactions between infants and objects with influence from knowledgeable social partners, is therefore thought to contribute to learning about object properties, motor skill development and increases in cognitive, social and language abilities.

2.3 The role of caregivers in early cognitive development

2.3.1 Early gaze following, joint and sustained attention

During early life, infants are sensitive to the gaze of a social partner; infants as young as 3 months shift their attention based upon the gaze direction of an adult (D'Entremont, 2000; Hood et al., 1998). These abilities are influenced both by

environmental factors, such as motion and saliency, and infants own abilities to engage and initiate eye movements (D'Entremont, 2000). For instance, infants' abilities to follow gaze have been shown to improve as targets are positioned closer to the infant's midline (D'Entremont, 2000). Additionally, research shows that infants are more likely to follow a social partner's gaze when the partner's face moves toward the peripheral target, regardless of eye movement, emphasizing the role of motion in directing infant attention (Farroni et al., 2000). By 6 months of age, infants are actively capable of following a social partner's gaze (Lansink et al., 2000; Scaife & Bruner, 1975).

Research has demonstrated that caregivers play a unique role in shaping infant gaze following behaviours. For instance, research by Hoehl et al. (2012) has highlighted the importance of caregivers' gaze over that of a stranger's gaze. In this study, 4-month-old infants were shown objects whilst either their caregiver or a stranger directed their gaze towards an object. The authors used electroencephalography (EEG) to measure neural activity and found that objects viewed alongside caregivers' joint gaze elicited stronger neural markers of stimulus processing. This finding highlights the importance of caregivers' gaze as a social cue, as it is associated with increased infant attention and information processing. Further, this study emphasises the importance of familiar social partners, possibly because their cues are easier for infants to process in comparison to cues from unfamiliar individuals.

Thus far, afore-mentioned research has demonstrated that infant attention is sensitive to the gaze of their caregivers. However, it is important to consider how variations in caregiver behaviours, such as the temporal dynamics of gaze shifts, might contribute to individual differences in infant attention. To investigate this, Yu & Smith (2016) examined caregiver and infant attention to objects during play whilst eye-trackers were used to capture moment-by-moment gaze data. The researchers found that caregivers exhibited rapid gaze shifts between their infant's face and the objects in play, reflecting caregivers' goals of monitoring the objects involved in play and their infant's face and attention. Infants, on the other hand, shifted their gaze more slowly and spent more time attending to objects, aligning with their primary focus of exploring toys. Importantly, to investigate how variations in caregiver engagement durations might influence the attention durations of their infants, the authors then

examined associations between two key caregiver and infant behaviours. Specifically, they focussed on caregiver-infant joint attention (defined here as simultaneous fixation on the same object for at least 500 ms) and infant sustained attention (fixations lasting more than 3 seconds). They found that on average, caregivers and infants jointly attended to the same object for more than a third of the total play time and almost two thirds of sustained attention instances occurred alongside joint attention. Importantly, sustained attention durations were longer when occurring alongside joint attention compared to without, indicating that the presence of joint attention was crucial for sustained attention durations. The authors therefore wanted to examine the process by which caregiver joint attention influenced infant sustained attention. Further analyses revealed several key findings. Firstly, the time at which caregivers joined their infants was not a determining factor in the duration of infant sustained attention. Secondly, sustained attention durations with longer joint attention were longer than those with shorter joint attention periods. Finally, the duration of joint attention significantly predicted how long infants subsequently sustained attention to the same object. Critically, these results highlight the role of caregiver attention in temporally extending their infant's own attention, even *beyond* the shared attention period. These findings illustrate how caregivers' attentional scaffolding supports the development of sustained attention in infants, providing critical foundations for learning and exploration.

To better understand the mechanisms by which caregiver-infant interactions shape learning, it is critical to understand the directionality of these interactions. In infancy, it is thought that joint attention-behaviours can be typically divided into two categories: responding to joint attention bids from others, and self-initiated joint attention. Responding to joint attention typically involves following another person's gaze or gestures to achieve a shared attentional state. In infancy, this may involve infants following their caregiver's gaze, leading to an increased likelihood of joint engagement on the same object. This has been implicated in word-learning opportunities (Baldwin et al., 1995; Mundy & Newell, 2007) and language development, enabling infants to associate objects with socially meaningful contexts (Baldwin et al., 1995). This ability is also thought to emerge early in infancy, reflecting the infant's ability to align their attention with a social partner (Mundy et al., 2007). In contrast, initiating joint attention requires infants to use gestures or eye movements

to direct a social partner's attention toward an object or event. This self-initiated behaviour supports the sharing of interests and experiences between two social partners (Mundy et al., 2007). Unlike responding to joint attention, which emphasises following and learning from others, initiating joint attention allows infants to share their own interests to explore and learn about their environments.

Building on these afore-mentioned distinctions, studies have examined the reciprocity of behaviours during dyadic interactions, more specifically, whether it is caregiver behaviour that predicts infant responses, or if infant behaviour predicts caregiver actions. Wass et al. (2018) examined infant attention during joint and solo play, tracking the gaze of both the infants and caregivers during the interaction. Here, infants showed longer look durations as well as fewer and shorter periods of inattentiveness, during joint play in comparison to solo play. They also found that caregivers' attention forward predicted their infants' attention, suggesting that it was the caregivers' behaviour that motivated infant behaviours.

Finally, research has also highlighted the importance of additional caregiver behaviours alongside gaze, in influencing infant engagement. For instance, Striano & Stahl (2005) focused on infant and adult behaviours within joint attention. Here, 3-, 6- and 9-month-old infants participated in experimental interactions with an adult. During a joint attention condition, the adult alternated gaze between the infant and an object, and during a look away condition they looked only at the object. During the joint attention condition, infants gazed towards the object and smiled more in comparison to the look away condition. In a second study, the infants were exposed to four interaction conditions: coordinated affect and attention, affect only, attention only or being ignored. During the coordinated affect and attention condition, the adult alternated gaze between the object and infant while smiling and talking. In the attention only condition, the adult alternated gaze between the object and infant without smiling or talking. In the affect only condition, the adult smiled and talked, but broke eye contact with the infant for 1 second and before looking at the object. Finally, in the ignore condition, the adult simply looked at the object for 30 seconds. Here, infants gazed most at the adult in the coordinated condition, and showed greater smiling in the affect-only condition, revealing infants' sensitivity to affect and attention during dyadic interactions from as young as 3 months. Michel et al. (2024) also investigated how ostensive signals from caregivers, such as direct gaze and infant-

directed speech, impacted infant attention and learning. Here, they found increased theta power, a neural marker linked to memory and learning, in the presence of caregiver ostensive signals. Collectively, these studies highlight the importance of additional caregiver behaviours in maintaining infant attention during caregiver-infant play.

2.3.2 Caregiver handling and speech during object interactions

Additional caregivers' social cues have also been identified as an important factor guiding infant attention. In particular, verbal and gestural cues have been frequently highlighted across a range of studies. For instance, research has shown that infants are more likely to follow adult's gaze when this is combined with these other cues. For example, Deák et al. (2008) investigated how caregivers' verbal and gestural cues influence infants' attention sharing in environments with multiple competing objects. Here, 15- and 21-month-old infants played with objects while their caregiver shifted their attention to another distant object either with gaze only or in combination with gestures or verbalisations. Here, infants followed gaze alone much less in comparison to gaze combined with pointing or verbalisations. Further, verbalisations also increased infants' focus on the caregiver, and this effect was particularly prominent in older infants. When the authors occluded the caregiver's gaze, infants' responsiveness was reduced. Yu & Smith (2013) similarly examined the role of physical object manipulation in joint attention. Using eye-tracking, they analysed interactions between caregivers and their 1-year-old infants. Here, they found infants were more likely to attend to objects being manually handled, as opposed to static objects or their caregivers' faces. Additionally, caregivers' hand-eye coordination was predictive of the duration of joint attention episodes, suggesting that manual object interactions are key for guiding infant attention. The authors suggested that early attention sharing might begin with gaze following, but that in more complex social situations, infants may also rely on hand-following to coordinate visual attention with social partners. Collectively, these findings highlight the role of manual actions and social cues in infants' attention to objects, but do not necessarily examine the processes through which these behaviours emerge and are reinforced.

Building on these gaps, Deák et al. (2014) proposed two pathways through which hand-following can lead to joint attention between infants and their caregivers. The infant may first handle the object and the caregiver's gaze follows, or the caregiver

may first handle the object, and the infant's gaze follows. They also suggested that gaze-following and hand-following represent distinct pathways to joint attention as they require different behaviours: gaze-following requires looking towards the partner's face and then shifting attention to the location of their gaze, whereas hand-following involves directly looking towards the object being touched. Since hands and objects are spatially close to each other, hands provide a more salient and reliable cue for infants to direct their attention. To investigate hand and gaze dynamics during play, 9- and 12-month-old infants were therefore observed during interactions with their caregivers and objects. Here, infants preferred to attend towards objects being handled by their caregivers, as opposed to static objects or other visual stimuli, such as their caregiver's body. Interestingly, when infants looked at their caregivers while their caregivers were looking towards their own hands, the infants often directed their next eye movement towards the object the caregiver was handling. The authors suggest that the association between caregiver's gaze direction and interesting sights, such as the toys, may reinforce the learning of gaze-following behaviours.

To explore how infants learn to track both hand and gaze movements in the context of attention-sharing, Monroy et al. (2021) further investigated attention-sharing behaviours between caregivers and their 9-month-old infants. They tracked infants' anticipatory gaze shifts and found that infants begin to predict caregivers' actions, such as reaching for or manipulating objects. This anticipatory behaviour was also associated with increased infant-led joint attention episodes, where infants initiated the interactions by directing their caregiver's attention to the object. Collectively, these findings further highlight infants' growing abilities to anticipate and initiate attention-sharing moments during interactions. These findings also align with the proposition by Deák & Triesch (2006), that infants may develop gaze-following behaviours by learning that adults often direct their gaze towards an object of interest. This suggests that adults typically focus on things that captivate infants and that infants learn this through observation. Together, these findings emphasise the importance of caregiver hand-eye coordination, on infants' abilities to learn to follow visual and manual cues.

In addition to the physical manipulation of objects, verbal cues have also been identified as a key factor in guiding and shaping infant attention. For instance, Schroer & Yu (2022) used eye-tracking to examine the relationship between caregiver speech

and infant attention in 12- to 24-month-olds. They found that infant visual attention, joint attention, and sustained attention bouts were all significantly longer when caregiver speech accompanied the attention period. These findings suggest that caregiver speech coordinates and increases infants' abilities to engage with objects and maintain focus for extended periods. Furthermore, the combination of gaze, object handling, and object-related verbalisations has been demonstrated to be particularly effective in engaging and sustaining infant attention. For instance, Schatz et al. (2022) investigated the effects of different types of caregiver engagement on dyadic object interactions with children aged 13, 18, and 23 months during everyday activities in the home. Here, they categorised infant play into simple play, in which the infant held or explored objects, and functional or symbolic play, in which they played with the object based either upon its purpose or to represent another object. They also classified the input by the caregiver as manual (involving touching or gesturing towards the object), verbal (object-related or unrelated speech) or multimodal (combining both manual and verbal input) engagement. Here, they found that infants engaged in complex play more frequently and for longer durations when the caregivers used multimodal engagement, with play bouts lasting 7.5 times longer. This study also found that the contents of the caregiver's speech also played a significant role. Object-related verbalisations, for example, action-orienting phrases, such as "twist it" or "feed dolly", were associated with longer and more complex play bouts. These findings demonstrate the importance of caregiver multimodal input and further suggest that object-specific or directive language has the most effective influence on infant engagement durations.

2.3.3 Caregiver behaviours during dyadic interactions

Assessing the quality of caregiver-child interactions involves evaluating how caregivers comfort, guide and respond to their child, as well as how attuned they are to their child's cues (Bozicevic et al., 2024). Notably, caregiver behaviours, such as intrusiveness, responsiveness, and scaffolding have all been shown to influence child outcomes. Intrusiveness refers to the disruption of a child's activities either by imposing excessive control over their actions or ideas or by overwhelming the child with stimulation. This behaviour limits the child's opportunities to independently learn and master developmental skills (Ispa et al., 2004). In contrast, caregiver responsiveness refers to instances when caregivers respond appropriately and promptly to infants' needs. Responsiveness can include behaviours that positively

encourage focus on the task at hand, positive affect and positive verbal statements (Scherer et al., 2019). Finally, scaffolding refers to offering suggestions, giving feedback, or positively altering a child's environment to facilitate learning opportunities (Williams et al., 2010). Scaffolding requires caregivers to allow their children to demonstrate independence and step in when they are struggling or need help to focus (Mortensen & Barnett, 2019). Collectively these behaviours play interrelated roles and can be observed during dyadic interactions, in which caregivers respond to their child's behaviours through visual attention, manual actions or speech (Schatz et al., 2022). These behaviours are therefore important to consider in the context of joint and sustained attention, as they have the potential to influence the likelihood of shared attention as well as the quality of the interaction itself.

In the context of joint and sustained attention, intrusive caregiving behaviours may disrupt the balance between caregivers and infants during interactions. Notably, maternal intrusiveness has been linked to negative outcomes, such as children's tendency to look away from the caregiver (Malatesta et al., 1989) and avoidant attachment (Carlson & Harwood, 2003; Isabella & Belsky, 1991). It is thought that three factors contribute to these negative outcomes in children (Ispa et al., 2004). First it is thought that intrusive parenting may overwhelm children with excessive stimulation, leading the child to shut down, or become avoidant to protect themselves from overarousal (Ainsworth et al., 2015; Belsky et al., 1984). Second, intrusiveness may be stressful for children because it undermines their ability to exercise control over their own interactions and establish mutual reciprocity and regulation (Malatesta et al., 1989; Tronick, 1989). Finally, intrusive parenting often involves disregarding children's interests and taking control of tasks or play, which can foster negative feelings of incompetence, and in turn lead to disengagement or other negative behaviours (Kahen et al., 1994; Pettit et al., 1991; Tronick, 1989). During caregiver-infant interactions, intrusive caregiving behaviours may manifest as interruptions or excessive control, which may disrupt infant's focus, and hinder joint attention and subsequent sustained attention.

Responsive and scaffolding caregiving behaviours encourage caregiver-child shared attention and consequent positive outcomes in infants. For instance, responsive caregiving behaviours have been examined across early infancy (6, 12, and 24 months) and later childhood (3 and 4 years) (Landry et al., 2001). Here, the authors categorised

the children into groups based upon whether responsive behaviours were low or high across each timepoint and found that consistent 'high' responsiveness was most beneficial towards cognitive development. More recently, Schroer & Yu (2022) discussed the relationship between caregiver responsiveness and infant engagement. They proposed that responsive behaviours must have two characteristics: temporal contingency, wherein caregivers promptly respond to infant's cues, and semantic relevancy, wherein responses are appropriate and relevant to the infants focus. Importantly, responsive caregiving behaviours are interrelated with and set the foundations for effective caregiver scaffolding.

Critically, it is thought that both increased opportunities for scaffolding as well as more effective scaffolding, may contribute to high-quality infant attention (Schroer & Yu, 2022). This view aligns with findings that report positive outcomes stemming from more effective scaffolding behaviours in toddlerhood. For example, using diverse and sophisticated vocabulary during toddlerhood has been shown to predict later vocabulary abilities, highlighting the importance of both the quality and quantity of input in vocabulary development (Rowe, 2012). Additionally, quality indicators, including symbolic joint engagement, routines, and fluent communication, have been shown to more strongly predict later language ability, in comparison to the quantity of words spoken or sensitive parenting (Hirsh-Pasek et al., 2015). Further, Schatz et al. (2022) also reported that the contents of caregiver speech played a significant role in infant sustained attention. Notably, object-related verbalisations, such as action-orienting phrases, were associated with longer and more complex play bouts, suggesting that object-specific/directive language also increases infants' engagement. Collectively, these findings provide support for both increases in, as well as the relevance of caregiver scaffolding in promoting infant joint and sustained attention.

2.3.4 Caregiver attention and EF in dyadic contexts

Caregivers play a key role in shaping their child's cognitive development. Importantly, caregivers' own cognitive abilities, are particularly relevant during interactions, as they influence how caregivers allocate attention, inhibit distractions, and adapt their behaviour to dynamic social environments, thus influencing how they might engage with their child and environment (Barrett & Fleming, 2011; Calkins, 2011). It is therefore important to consider the underlying mechanisms and factors that shape adult cognition.

Caregiver visual attention is a central component of joint attention during dyadic interactions. Attentional allocation determines whether caregivers notice and respond to infant cues, objects and contextual changes. Studies of adult visual attention have shown that salient features, such as oriented edges, spatial frequency, colour contrast, intensity, or motion, can influence how adults allocate attention (Howard & Holcombe, 2010; Itti & Koch, 2001; Nothdurft, 2006). Further, distracting stimuli have also been shown to increase saccade rates and impair task performance (Annerer-Walcher et al., 2020). Generally, these findings suggest that the presence and features of external stimuli can impact adults' ability to sustain attention. While these findings originate from experimental tasks, they have implications for interaction contexts, wherein competing stimuli might draw caregivers' attention away from their infant, thereby disrupting shared focus.

Further, broader EF skills, such as inhibition, working memory, and cognitive flexibility might also contribute to how adults manage attention in everyday contexts. For instance, inhibitory control allows individuals to regulate attention, behaviour, thoughts, or emotions to override strong internal impulses or external distractions and instead act in a more appropriate or goal-oriented manner. This may allow individuals to filter out noise, suppressing attention to salient stimuli and focussing on others based upon goals (Aron, 2007; Diamond, 2013). For example, inhibition has been shown to support suppression of dominant responses when task goals shift or unexpected events occur (Miyake et al., 2000). Further cognitive flexibility involves the ability to adapt behaviour in response changing goals, perspectives, or environmental demands (Diamond, 2013). In the context of caregiver-infant interactions, this may allow caregivers to shift their responses as new situations arise with different demands (Barrett & Fleming, 2011). Finally, working memory may allow caregivers to track their infants' behaviours, anticipate needs, and adapt to changes. Collectively, these cognitive abilities allow caregivers to create a responsive and engaging environment that promotes learning and attention (Barrett & Fleming, 2011; Calkins, 2011; Cuevas, Deater-Deckard, Kim-Spoon, Watson, et al., 2014).

While broader EF abilities support flexible and goal-directed behaviour, specific limitations in VWM may further constrain how caregivers manage multiple elements during interactions. Research suggests that adults can typically retain around four chunks in VWM under carefully controlled conditions (Cowan, 2001; Luck &

Vogel, 1997). Further, this capacity is also influenced by both complexity and similarity of items. For example, Awh et al. (2007) investigated the influence of object complexity on change detection accuracy. Findings reported that capacity limit estimates decreased as object complexity increased, but that this reduction was also correlated with increased similarity between sample and test displays. When this similarity was reduced, capacity estimates for complex and simple objects were equivalent indicating that VWM maintains a fixed number of items regardless of complexity. Other research has also argued that items maintained within VWM are influenced by other items also retained in memory. This phenomenon is known as an item-resolution trade off, wherein the precision of stored items decreases as the number of items increases. For instance, Wilken & Ma (2004) examined how accurately participants detected changes in visual features. They reported that as load demand increased, the resolution of stored representations declined. Similarly, Zhang & Luck (2008) used a short-term recall paradigm, that required subjects to recall item features with increasing load. Here, when load capacity was surpassed, high-resolution representations were retained for approximately three items, while others were discarded. Fougnie et al. (2010) reported similar findings with the same paradigm, showing that the precision of stored representations significantly declined with increasing VWM load. Critically, when cognitive load is increased, caregivers may struggle to sustain accurate representations of relevant objects or actions. These constraints may in turn affect how promptly and accurately caregivers respond to child cues and support learning during dyadic interactions.

Finally, caregivers' own novelty preferences may also influence their preferences and engagement during interactions. While infants show general preferences for novelty, adult responses to novelty vary across different contexts. For instance, studies indicate that adults show a familiarity preference when viewing faces, whereas they exhibit novelty preferences when viewing natural scenes (Park et al., 2010). Task engagement, exposure duration, and viewing context also influence novelty preferences in adults. Research has shown that adults exhibit a stronger preference for novelty during active task engagement compared to passive viewing (Liao et al., 2011). In another study, adults showed a preference for familiar items when asked to choose those they liked, whereas in a learning context, they showed a preference for novel items. Collectively, these findings indicate that adult novelty

preferences are influenced by individual goals, exposure and learning contexts, all of which may shape their behaviours during interactions.

In summary, adult cognition is influenced by multiple factors that shape how individuals attend to, interpret, and respond to their environment. Cognitive abilities, such as attention, inhibition, working memory, and cognitive flexibility may allow caregivers to manage distractions, adapt to changing demands, and process information effectively. Further, VWM capacity limits also govern how much information caregivers can manage from moment to moment. Additionally, preferences for novelty and familiarity have been shown to be shaped by context and goals. Importantly, these factors may contribute to how caregivers engage with their child, objects and environment during everyday interactions.

2.3.5 The self-regulatory framework

How might caregivers' own cognitive abilities influence their infants in early development? The self-regulatory framework emphasises how caregiver behaviours influence infants' cognitive development across multiple biological and behavioural levels (Calkins, 2011). Within this framework, effective caregiving not only requires the ability of the caregiver to regulate their own thoughts and behaviours, but also to co-regulate with their child, responding to their needs in a flexible and timely manner. To do this, caregivers must therefore rely on neurocognitive processes, such as attentional control, working memory and cognitive flexibility. These processes enable caregivers to interpret their infant's cues, even within distracting or dynamic environments. For instance, attentional control might support caregivers in selectively tuning into subtle behavioural cues, such as infants' facial expressions, gestures, or vocalisations, while ignoring irrelevant background stimuli. Working memory may help caregivers to monitor ongoing patterns in behaviour, anticipate likely needs, and respond accordingly. Similarly, cognitive flexibility supports adjustments in caregiving strategies as new challenges or demands emerge (Barrett & Fleming, 2011). Collectively, these cognitive abilities allow caregivers to create a responsive and engaging environment that promotes learning and attention (Barrett & Fleming, 2011; Calkins, 2011; Cuevas, Deater-Deckard, Kim-Spoon, Watson, et al., 2014).

Importantly, how caregivers respond to their infants' cues can also be influenced by a number of factors. For instance, Barrett & Fleming (2011) highlighted

that whilst a caregiver may show enhanced sensitivity to their infants' cues, they must also be able to effectively integrate these signals. These cues must be rewarding to the caregiver to promote emotional and social engagement. Major life experiences such as postpartum depression and early experience in childhood can influence these processes. Consequently, this can affect caregivers' abilities to respond to their children's cues, bond with the child and engage in consistent sensitive caregiving. Further, the brain networks that underlie these systems often overlap, with disruptions in one often influencing the other, ultimately leading to challenges in caregiver motivation and caregiving behaviours. Studying these systems may help us understand the brain mechanisms involved in caregiving. Barrett & Fleming (2011) also emphasise that differences in caregivers are not always fully explained by past and current experiences/circumstances, and that genetics can also contribute to individual differences in caregiving abilities (Bakermans-Kranenburg & Ijzendoorn, 2008).

2.4 Neural mechanisms during dyadic interactions

While there is a wealth of research exploring caregiver-infant engagement during social interactions, fewer studies have examined the neural mechanisms of attention processes in infants and caregivers. Importantly, studying brain activity during dyadic interactions might offer unique mechanistic insight into the attentional pathways in both partners. In the following sections, current evidence for neural mechanisms underlying, joint, sustained, and multimodal attention are therefore discussed. It is important to note that research that extracts measures of inter-brain synchrony (Leong et al., 2017; Marriott Haresign et al., 2023; Nguyen et al., 2020, 2021; Papoutselou et al., 2024; Piazza et al., 2020), is not covered in the coming sections, as it examines a different construct.

2.4.1 Neural correlates of joint attention

The social-cognitive model of joint attention suggests that in infancy, children develop the ability to monitor both their own goal-directed activity as well as the goal-directed activity of others (Tomasello et al., 2005). Building upon work from Posner & Petersen (1990), Mundy et al. (2000) suggested that joint attention arises from the interaction between two attentional systems: the posterior attention system, associated with the ability to respond to joint attention, and the anterior attention system, associated with the initiation of joint attention. The posterior attention system is

thought to develop early in infancy, be largely involuntary, and prioritise attention towards biologically relevant stimuli, such as a social partner's face, gaze, or gestures. Neuroimaging studies have implicated regions including the parietal cortex, superior temporal gyrus (STG), and angular gyrus (AG) in this system, regions thought to play key roles in representing, imitating, and interpreting social cues, such as eye and head movements, and spatial relationships between oneself, others, and the environment (Mundy & Newell, 2007). In contrast, the anterior attention system is thought to develop later and is associated with goal-directed attentional allocation. This system involves brain regions such as the FEFs, DLPFC, orbitofrontal cortex, pars orbitalis, and anterior cingulate cortex (Morales et al., 2000; Posner & Rothbart, 2007). It is thought that these areas work in association with the intentional initiation of joint attention, as infants direct their social partner's focus to specific objects or events. These systems are proposed underpin distinct yet interrelated roles in the coordination of joint attention.

In adults, a number of MRI studies have provided support for the anterior-posterior model of joint attention. For instance, Materna et al. (2008) examined brain regions involved in observing gaze shifts. In this study, participants followed either gaze cues or symbolic cues to redirect their attention towards an object. The pSTS and cuneus were activated during gaze-based joint attention whilst the IPS mediated spatial shifts of attention regardless of the cue type. In contrast, Williams et al. (2005), examined brain regions involved in initiation of gaze shifts. Here, subjects were shown video clips of a moving dot, which they were told to follow on the screen. Above this, a video clip of a person, who either also followed the dot, creating a joint attention condition, or diverted their gaze elsewhere, simulating a non-joint attention condition, was shown. To simulate the experience of initiating joint attention, the video clip of the person was slightly delayed, so that the gaze was no longer a cue for predicting the movement of the spot. The authors found activation in the lSFG, ventromedial frontal cortex, cingulate cortex, and caudate nuclei. While these studies were designed to emulate initiating and responding to joint attention, it is important to acknowledge that these paradigms were based on a pre-determined conditions. Importantly, it has been argued that joint attention requires a dynamic, interactive exchange between two people, rather than a pre-programmed reaction (Redcay et al., 2012). Therefore, this dynamic exchange requires the responder to appropriately react to the initiator's bids,

and the initiator to perceive that their bids for joint attention receives an appropriate and related response.

As such, research investigating the neural mechanisms of joint attention in adults has since aimed to better capture the dynamic nature of social interactions. For example, Redcay et al. (2012) also examined brain regions involved in responding to joint attention. Here, participants either followed an experimenter's gaze, directed the experimenter's gaze or shifted gaze to a target alone. In line with the anterior-posterior model of attention, they found that the pSTS and inferior parietal lobule (IPL) showed greater activation in responding to joint attention. These regions are thought to be associated with interpreting social signals and consequent shifts of attention, critical for two social partners to engage in joint attention. Similarly, Schilbach et al. (2010) employed an interactive paradigm. In this study, the authors used participants' gaze behaviour, measured using eye-tracking, to control the gaze of a computerised character. In this study, the subject was informed that the character on the screen was controlled by a real person outside of the scanner. However, findings from this study did not align with the anterior-posterior model of joint attention. Notably, the authors found that gaze following activated the anterior medial frontal cortex (mPFC), whilst directing someone else's gaze activated the ventral striatum, a region associated with reward processing and motivation. Relatedly, other research has associated the mPFC with processing socially relevant gaze cues (Bristow et al., 2007) and direct eye contact (Schilbach et al., 2006) during social interactions. Findings from more naturalistic interaction studies in adults therefore suggest that the neural mechanisms underlying socially meaningful joint attention may be more complex than the anterior-posterior model alone accounts for.

Research in infants has further provided support for the anterior-posterior model of joint attention. For example, Grossmann et al. (2013) used fNIRS to investigate 5-month-old infants brain responses when a social partner followed their gaze towards an object. Here, infants interacted with a virtual partner presented on a screen. This virtual partner either followed the infant's gaze to an object or looked towards an object they had not previously attended to. They found left prefrontal activation associated with detecting when a social partner followed their gaze. Similarly, Naoi et al. (2022) investigated brain responses and functional connectivity in 7- to 12-month-old infants in initiating and responding to joint attention bids. In this

study, fNIRS was used to measure brain activation, whilst a live experimenter played the role of the social partner with the infant. The experimenter either followed the infant's gaze (infant initiating joint attention) or guided the infant's attention by gazing at objects (infant responding to joint attention). Specifically in response to initiating joint attention bids, they found activation across the bilateral dorsal prefrontal cortex. They also found right lateralised prefrontal activation during both initiation of and response to joint attention, with greater functional connectivity here during the response condition. This finding is consistent with research in adults that suggests that co-ordination of joint attention may be more complex than the anterior-posterior model alone accounts for (Bristow et al., 2007; Schilbach et al., 2006, 2010).

Finally, research has explored how brain function related to joint attention develops across early childhood. For example, Mundy et al. (2000) examined neural correlates of initiating and responding to joint attention bids at 14, 16, and 18 months of age. This objective was addressed by using a series of joint and turn-taking activities alongside a social communication questionnaire. The authors found that initiation of joint attention was linked to anterior activity, and responding to joint attention was linked to posterior parietal activity. Additionally, the authors also found a shift in activation patterns involved in initiating and responding to joint attention from 14 months to 18 months of age. At 14 months, joint attention was associated with fronto-parietal activation, but at 18 months, this shifted to occipital activation patterns. This aligns with research that suggests more anterior brain regions guide early development, whilst posterior brain regions contribute to later consolidation skills (Fischer & Rose, 1994).

2.4.2 Neural correlates of sustained attention

Thus far, behavioural research has highlighted the important role of caregiver-infant joint attention on subsequent infant sustained attention (Deák et al., 2014; Schatz et al., 2022; Schroer & Yu, 2022; Yu & Smith, 2013, 2016). Despite these findings, there is limited research examining changes in brain function underlying subsequent sustained attention during interactions. Exploring how social interactions influence attention and learning in the brain is particularly important during the early stages of development, as these lay the foundation for cognitive and social abilities later in life.

In line with this, findings from dyadic interaction studies have revealed the influence of caregiver input on neural markers of subsequent sustained attention processes. These findings underscore the critical role caregivers play in shaping and supporting their infants' attention and learning processes. For instance, Striano et al. (2006) studied neural mechanisms of joint and sustained attention in 9-month-old infants. Here, EEG was used to study brain activity in two conditions. In the joint attention condition, an adult alternated gaze between the infant and an object and in the non-joint attention condition, the adult looked solely towards the object. Here, the negative component of the infant event-related potential (ERP) was enhanced in amplitude during joint attention interactions. This neural marker has previously been implicated in the development of memory processes over the first year of life (Webb et al., 2005). It has also been associated with attentional orienting to salient stimuli (Courchesne et al., 1981; Nelson et al., 1994) and arousal states (Richards, 2003). These results suggest that joint attention during interactions supports infants in directing their limited attentional resources towards objects in their environment, as reflected in the enhanced marker of attentional orienting. This finding underscores the contribution of joint attention to the development of attentional processes.

Expanding on this research, studies have investigated sustained attention processes by examining the neural dynamics between caregivers and infants. Focusing on the caregiver is crucial, as it better captures how caregivers might shape infant attention and cognitive development during day-to-day life. For instance, Wass, Noreika, et al. (2018) used EEG to investigate neural dynamics between caregivers and their infants during joint and solo play. They found that infant theta power more strongly predicted visual attention in solo play. Theta power has previously been associated with object exploration (Begus et al., 2015) and periods of anticipatory (Orekhova et al., 2006) and sustained attention (Orekhova et al., 2006; Xie et al., 2018) in infants. Further, theta power has also been implicated in social, naturalistic settings (Jones et al., 2015). These findings suggest that during solo play, infants showed more reliance on endogenous attention mechanisms, reflecting greater self-driven control. During joint play, infants were generally more attentive, and caregiver theta power closely tracked changes in infant attention. Greater neural responsivity in caregivers was also associated with greater infant sustained attention periods. Overall, these findings suggest that caregivers exhibit neural responsivity to infant behaviours, with

greater caregiver neural responsivity associated with increased infant attentiveness during play. These findings emphasize the role of caregivers in modulating infant attention processes during early play interactions, highlighting their contribution to the development of attentional control and learning.

Collectively, these studies demonstrate that investigating brain function during dyadic interactions provides unique insights into the attentional pathways of both caregivers and infants. Importantly, both caregiver behavioural and neural activity play a role in shaping and supporting infant attention during shared interactions. These findings also highlight the bidirectional nature of joint attention, wherein both partners co-ordinate behaviour and brain activity during interactions, to increase attention and learning. This growing body of evidence points to the critical role of caregiver input in both providing social cues and scaffolding infants attentional development. Despite growing evidence, it remains unclear how this neural activity is shaped by different engagement modalities during shared attention.

2.4.3 Neural correlates of modality differences

There is limited work examining how differences in caregiver input might influence infant neural activity during dyadic interactions. Despite recent research highlighting that multimodal engagement scaffolds infant play durations and complexity (Schatz et al., 2022; Schroer & Yu, 2022; Suarez-Rivera et al., 2019), to date, no study has directly compared brain function during unimodal (look only), bimodal (look and touch), and multimodal (look, touch and verbalisations/vocalisations) engagement in caregiver-infant interactions.

Although there is limited research comparing different modalities, studies have examined neural activity during manual actions, which form the basis of bimodal interactions. For instance, research has examined how neural activity varies between the observation and completion of manual actions. A key framework guiding this research is based upon the mirror neuron system, a network of brain regions across the frontal, temporal, and parietal cortices, that are active both when individuals perform and observe actions (Morales et al., 2019). For example, one fMRI study compared brain activation during observation and execution of actions in adults and children (Morales et al., 2019). Here, adults demonstrated greater activity in the right parietal cortex during action execution and greater activity in the occipital cortex during action

observation. Additionally, greater overlaps between action observation activation and execution activation were observed in adults. Interestingly, the extent of overlap in children was associated with increased motor skills and action representation. Further, in infants, action execution has been demonstrated to be restricted to central electrode sites, whereas observation is associated with frontal, central and parietal activity (Marshall et al., 2011). Here, infant brain responses to execution and observation overlapped but were weaker relative to the responses seen in older children and adults, indicating continued development of these systems throughout early childhood. More generally, these findings highlight the development of brain regions that may be critical for infants to co-ordinate their own actions with those of a social partner, critical for social interactions.

Building upon this, research has also examined how infants might track manual actions during social interactions. For instance, one study examined how observation of neural activity influences neural responses in 18-month-olds (Monroy et al., 2019). This study was informed by motor theories of action observation, which suggest that individuals predict the actions of others through their own motor systems (Flanagan & Johansson, 2003; Kilner, 2011; Rizzolatti & Craighero, 2004). Findings reported increased Mu rhythm suppression, an indicator of anticipatory activation of observed action (Marshall & Meltzoff, 2011; Southgate et al., 2009), during anticipation of statistically likely actions. This finding suggests that infants make motor-based predictions based upon learnt actions. Similarly, findings have reported that 9-month-old infants exhibit motor activation when observed actions allow them to infer a likely goal (Southgate et al., 2010). It is possible that these studies indicate a neural mechanism through which infants learn to anticipate, predict, and follow caregiver's actions, such as reaching for and manipulating objects during dyadic interactions (Deák et al., 2014; Deák & Triesch, 2006; Monroy et al., 2021).

While studies have not directly examined brain function underlying multimodal engagement, research has highlighted that increased caregiver input influences infant neural activity during caregiver-infant interactions. For instance, one study has examined how ostensive signals influence infant neural activity during interactions. Michel et al. (2024) investigated the impact of caregiver ostensive signals, including direct gaze and infant-directed speech, on neural activity and object encoding in 9- to 10-month-old infants. Here, the use of ostensive signals increased

infants' attention to both the caregiver and the object. Ostensive signals were also associated with increased theta synchronization. Notably, greater theta activity during these interactions also predicted better object encoding, suggesting that social engagement with caregivers enhances infants' ability to process and learn about objects. In another study, Bánki et al. (2024) investigated how communicative signals, such as eye contact, pointing, and infant-directed speech influence infants' attention when infants and caregivers were jointly presented with images of objects. Here, the authors examined steady-state visual evoked potentials, previously associated with enhanced attention in adults (Gulbinaite et al., 2019; Morgan et al., 1996; Müller et al., 1998) and infants (Robertson et al., 2012). Communicative signals increased steady-state visual evoked potentials at central-occipital-parietal and central electrode sites in both caregivers and infants. Further, communicative signals also increased gaze behaviour in infants. Whilst these studies do not directly compare modality differences, they highlight that increases in caregiver cues play an important role in shaping the neural processes underlying infant attention and learning. Further modality-based research is required to better examine these mechanisms.

2.5 Implications of examining dyadic interactions in early development

Understanding the link between caregiver and child cognition raises important questions regarding the influence of genetics, caregiver behaviours, and the home environment on visual cognition development. Studying caregiver and infant behaviours during dyadic interactions allows for greater understanding of influences on infant cognitive development, and in turn, identify appropriate intervention techniques that promote positive outcomes for both caregivers and their children.

Several studies have linked caregiver behaviours during dyadic interactions to long-term outcomes in children. Notably, there is a wealth of research that has linked caregiver behaviours to child EF development. In one study, caregivers and their infants completed age-appropriate interactions at 10, 24, and 36 months, as well as a battery of EF tasks at 24, 36, and 48 months. Here, caregiver EF abilities as well as negative caregiving behaviours during interactions both accounted for unique variance in child EF at 36 months (Cuevas, Deater-Deckard, Kim-Spoon, Watson, et al., 2014). In another study, caregivers and their infants completed a series of EF tasks at 14 months (Ribner et al., 2022). Following this, at 24 months, caregivers and their infants completed a series of further EF tasks alongside both a structured and unstructured

play interaction. Here, caregiver EF abilities predicted working memory and shifting from 14 to 24 months of age. Further, caregiver sensitivity and autonomy supportive practices during interactions mediated the link between caregivers' and children's EF. In another study, caregiver behaviours during interactions at 15 months, joint attention during a picture book task at 24 months, and child EF at 48 months were examined (Brandes-Aitken et al., 2020). Attuned caregiving behaviours during the interaction positively predicted joint attention measures at 24 months. Further, joint attention also partially mediated the relationship between attuned caregiving at 15 months and child EF abilities at 48 months. Additionally, measures of caregiving quality, based on observations of dyadic interactions and family resources, have been linked to child cognitive abilities at 14, 24, and 36 months (Lugo-Gil & Tamis-LeMonda, 2008). Finally, the association between caregiving behaviours, such as maternal sensitivity, mind-mindedness, and autonomy support during interactions at 12 and 15 months of age, have been shown to predict child EF at 18 and 24 months of age, with autonomy support the strongest predicter regardless of maternal education/cognitive ability (Bernier et al., 2010). Broadly, these findings highlight that behaviours during early dyadic interactions are linked to child EF development.

In addition to child EF development, caregiving behaviours have also been linked to the development of social cognition in children. For example, Carpenter et al. (1998) investigated joint attentional engagement, gaze and gesture following in infants between 9 and 15 months of age. The authors found that the duration spent in joint attention, as well as the use of language to follow or direct focus, significantly predicted infants' early gestural and linguistic skills. Furthermore, joint attention during interactions has been associated with theory of mind, which describes the ability to understand others' thoughts, intentions, and perspectives. Brooks & Meltzoff (2015) investigated infant gaze following at 10.5 months and theory of mind abilities later at 2.5 years and 4.5 years. Infants with higher gaze-following scores used more mental state terms at 2.5 years and were more successful on a theory of mind test at 4.5 years. This finding is further supported by work by Charman et al. (2000), who tested the relationship between joint attention, play, and imitation at 20 months, and theory of mind tasks at 44 months. Here, imitation abilities at 20 months were associated with expressive language ability at 44 months. Additionally, joint attention

behaviours, such as gaze-switching between an adult and a toy, were linked to later theory of mind abilities.

Observation of dyadic interactions in populations with a higher likelihood of atypical development has also enabled researchers to gain a better understanding of developmental variation. For example, Ruff et al. (1990), studied early attention in full and preterm children during free play and structured activities. In full-term children quantitative measures of inattention at 2 years predicted comparable measures of inattention at 3.5 years. However, in pre-term children these predictive associations emerged earlier, at 1 year. Lawson & Ruff (2004) also investigated attention in children born preterm at 7 months, 2 years, 3 years, and 4/5 years. Here, focused attention during object play predicted later hyperactivity/impulsivity and cognitive abilities. However, casual attention did not show the same relationships. Collectively these findings indicate that early, focused attention is linked to the development of attentional skills and cognitive abilities in infants born pre-term.

Research has also examined early joint attention processes in autistic children during social interactions. For instance, autistic children have been shown to be less responsive to adult joint attention bids, compared to children with developmental delay (Leekam & Ramsden, 2006). In another study, autistic children were found to achieve high rates of joint attention during caregiver-infant interactions, despite reduced face-looking, suggesting that autistic children rely on alternative pathways, such as hand-following or manual engagement (Yurkovic-Harding et al., 2022). Further, at 12 months, autistic children have been shown to exhibit fewer joint attention and requesting behaviours, in comparison to controls. Interestingly, no group differences were observed at 6 months in social gaze, affect, vocalisations or responsiveness to caregiver disengagement, suggesting that joint attention deficits emerge during the second half of the first year (Rozga et al., 2011). Along a similar line, children with higher likelihood of autism have been shown to respond to more complex joint attention cues later than those with a lower likelihood (Stallworthy et al., 2022). Together, these findings highlight that the developmental timing and pathways to joint attention may vary in autistic children, with implications for understanding the mechanisms underlying atypical trajectories.

Furthermore, research with autistic children has investigated the potential of caregiver-led interventions to improve social and cognitive outcomes. For instance, research has examined how coaching of caregiver-child play routines, with a focus on responsive interaction techniques, can influence joint attention skills in autistic toddlers (Kasari et al., 2010). In this study, principles of the intervention approach involved strategies such as following the child's lead and interests, imitating their actions, commenting on their activities, repeating and expanding on the child's speech, providing corrective feedback, maintaining physical proximity and eye-contact, and modifying the environment to promote engagement. Here, toddlers in the intervention group showed greater responsiveness to joint attention and greater diversity in functional play, with these effects maintained one year after the intervention. Similar coaching of play routines between caregivers and autistic toddlers have also showed significant improvements in social interaction and communication skills (Perera et al., 2016), play diversity (Kasari et al., 2015), and language development (Drew et al., 2002; Ingersoll & Wainer, 2013). These findings emphasise the value of studying early interactions to identify potential intervention strategies, particularly in populations that may face additional challenges.

Collectively, these findings highlight the connection between early social interactions between infants and their caregivers and cognitive development, such as EF, social cognition and language acquisition. Findings suggest that caregivers with better EF abilities may be more equipped to help their infant stay focused on tasks or redirect their attention when needed. Over time, as these regulated interactions are repeated and reinforced, infants' abilities to regulate attention are in turn also supported. Importantly, evidence from populations with atypical developmental pathways further underscores this connection, demonstrating that caregiver-led interventions may support improvements in both social and cognitive domains.

2.6 Summary and research gaps

Infants are natural explorers, constantly seeking new objects and environments to explore. These interactions are brief but frequent, evolving from simple manipulations to more sophisticated and complex object-specific actions across development. This exploration forms the foundation for motor skills, problem-solving, and cognitive development. Caregiver involvement plays a critical role in shaping these early experiences, providing guidance and context, ultimately enhancing early

experiences. Interactions between infants and their caregivers are dynamic and bidirectional, with each partner's behaviour influencing the other's. For example, caregivers' cognitive abilities such as attentional control, VWM and cognitive flexibility might allow them to successfully interpret infant cues, adapt to changing demands and ultimately create responsive and engaging environments. This ultimately allows caregivers to scaffold their infant's attention and learning.

In early development, joint attention, in which infants and caregivers focus on the same object or activity, has been shown to facilitate learning by aligning objects with meaningful contexts or labels. In turn, joint attention has been shown to support infant sustained attention, the ability to extend attention durations for longer periods of time. This is thought to support deeper engagement and learning. Caregivers therefore play an active role in supporting infant attention through gaze, the use of gestures, and verbal cues. For example, joint attention increases infants' focus and creates increased language learning opportunities. Caregiver manual actions and verbalisations, particularly those specific to objects in play, further increase engagement and promote longer engagement durations, ultimately creating rich learning opportunities. While research has highlighted that multimodal engagement is beneficial to extending and supporting infant attention, gaps in the research exist in our understanding of neural mechanisms underlying joint and sustained attention, as well as long-term cognitive outcomes.

In development, it is thought that the posterior attention system emerges early in infancy and is responsible for responding to social cues. In contrast, the later-developing anterior attention system is thought to support goal-directed behaviours. Integration of these systems are thought to work in tandem to support initiation and response to attention bids in complex social interactions. Thus far, a number of infant studies have provided support for this model. Building on this, studies that have focused on neural activity in both caregivers and infants have also revealed that caregiver attention further shapes this neural activity. For instance, joint attention periods have been associated with changes in brain activity, such as increases in theta power, which has been linked to attention and learning. Caregiver behaviours, such as gaze and speech, have also been shown to enhance this neural activity, suggesting that social interactions might support the development of attention-related brain networks.

While some progress has been made into understanding these mechanisms, several key gaps remain. Firstly, despite neuroimaging studies increasing our understanding of neural mechanisms, the majority of these studies either use structured tasks and/or pair the infant with a virtual partner/experimenter instead of their caregiver. These are therefore less likely to represent the true nature of familiar caregiver-infant interactions during day-to-day life. There is also a limited number of studies examining brain function in *both* caregivers and their infants during dyadic interactions. Secondly, while research has examined the longitudinal impact of caregiver behaviour on infant outcomes, the neural mechanisms by which these processes occur remain unclear. Importantly, examining these neural mechanisms allows for a deeper understanding of the relationship between visual and social cognition in caregivers and their infants throughout development. The current thesis aims to address these gaps, combining behavioural and brain data from experimental and dyadic interaction paradigms, to explore the relationship between caregiver and infant visual neurocognition across the first few years of life.

Chapter 3:

The association between caregiver and infant visual neurocognition

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3.1 Introduction

3.1.1 Infant looking behaviours involved in visual cognition

Infants learn to direct, engage, and re-orient attention towards objects as early as the first few months of life. Infants around 1- and 2-months of age are able to reliably execute saccades towards peripheral targets (Aslin & Salapatek, 1975) and infants between 2 and 4 months of age show increasing anticipatory looks (Johnson et al., 1991). Moreover, from around 3 to 6 months of age, infants show increased voluntary control of their eye movements. For instance, infants at 4 months of age demonstrate the ability to disengage from a central stimulus, and re-engage with a simultaneously presented target, as well as the ability to follow a directional central cue (Johnson et al., 1991). Additionally, there is evidence from ERP studies, that saccade planning occurs in infants at 5 months of age (Richards, 2001). Further, there is a wealth of research demonstrating infants' preference for detecting novelty (Fantz, 1964; Rose et al., 2001). Collectively, the integration of these abilities is referred to as visual cognition.

Visual cognition continues to develop following the infancy period and has broad implications across the lifespan. For instance, studies have shown that visual cognition is predictive of academic achievement (Conway et al., 2003; Rose et al., 2012), IQ (Cohen & Sandberg, 1980), global fluid intelligence (Cochrane et al., 2019; Jaeggi et al., 2008; Zhao et al., 2011), and social abilities (de Wilde et al., 2016; McQuade et al., 2013). Further, visual cognition has been linked to academic abilities such as reading (Leather & Henry, 1994) and mathematics (Gathercole et al., 2004). Deficits in visual cognition, such as increases in errors made during tasks, have also been observed in clinical populations including attention-deficit/hyperactivity disorder (Kofler et al., 2020) and autism (Steele et al., 2007). Given the far-reaching outcomes impacting quality of life, it is important to understand how this system emerges and develops early in the lifespan and what factors might impact its developmental trajectory.

Ross-Sheehy et al. (2003) used a preferential looking task to study visual cognition in infants. In this task, infants eye movements were coded as they were presented with two flashing/blinking displays of coloured squares, where on one side, the colours remain unchanged and on the other side, one square consistently changes

colour. The flashes/blinks represent a delay period during which item representations are held in VWM. In this study, memory load was varied between one and six items, depending on age. The authors found that infants at 4 to 6.5 months of age were able to maintain one item in memory. By 10 months of age, their capacity increased to four items, highlighting the dynamic changes in visual cognition across the first year of life. This study also further demonstrated that this ability was not due to limitations in perceptual or attentional abilities, as when infants were presented with a version of the same task with the delay removed, they exhibited a change preference at all loads. Research has since shown that infants are able to process increasing complexity in stimuli, such as the colour and location information of items (Oakes et al., 2013, 2017) and complex images (Mitsven et al., 2018). Further, the use of tasks which more closely resemble temporal features of change-detection tasks used in adults also demonstrate that novelty preferences seen in preferential looking tasks do not reflect gradual habituation to the non-changing array (Mitsven et al., 2018; Oakes et al., 2013, 2017).

3.1.2 Infant brain function involved in visual cognition

As infants' visual cognitive abilities develop, it is likely that brain regions supporting visual cognition begin to overlap structurally and functionally with those identified in childhood and adulthood studies (Cowan, 2001). In adult studies, a common network of brain regions are thought to contribute to different components of visual cognition (Geier et al., 2009; Kawasaki et al., 2014; Nagy et al., 2004; Sauseng et al., 2005; Scherf et al., 2006). The right FEF and MOG have been associated with response preparation and shifting of attention, the lSPL and rSFG with working memory maintenance, and the left lingual gyrus with processing of visual information (Geier et al., 2009). Further, across the lifespan, age-related differences have also been observed, suggesting that developmental changes are still taking place across childhood (Geier et al., 2009). For example, regions including the SFG, IFG, middle temporal gyrus (MTG), insula, and caudate, showed increases in activity from childhood to adulthood. Notably, adult studies have also found increases in parietal brain activity in association with load demand (Todd & Marois, 2004, 2005). In childhood, the aIPS has also shown to be similarly modulated by load (Buss et al., 2014). While these studies highlight brain regions expected to develop across

childhood and adulthood, less is known about brain regions underlying visual cognition in early life.

More recently, neuroimaging techniques have been used in infancy to investigate which brain networks are engaged and how much they are engaged during specific looking behaviours, to collectively inform mechanism(s) underlying visual cognition. Delgado Reyes et al. (2020) used a modified version of the preferential looking task to examine what cortical regions were engaged during visual cognition, and how cortical engagement varied across the first two years of life. They found robust neural activation near the rDLPFC, lSFG, lTPJ, and lVOC, regions that have been associated with adult working memory and attention (Boisgueheneuc et al., 2006; Cieslik et al., 2013; Deen et al., 2017; Yarkoni et al., 2011). Consistent with findings in childhood (Buss et al., 2014), they also reported load-dependent modulation in the lIPS, proposed to reflect an inability to consolidate and maintain representations at high load demands. Further, age-related effects were also found in the left ventral occipital gyrus (lVOC), rDLPFC, and laIPS. Activation in the laIPS increased across the second year, suggesting that there was refinement of visual cognitive abilities anchored within this region in toddlerhood. Older infants also showed increased activity in the rDLPFC, which was linked to the emergence of early looking abilities, such as shifting between displays, controlling consolidation, and releasing from fixation (Perone et al., 2011; Perone & Spencer, 2013). Interestingly, activation in the lTPJ was associated with CP scores, a VWM measure indicating the child's preference towards the changing display. In children with higher CP scores, younger infants showed greater activation within this region, but older infants showed greater suppression. This pattern of activation was thought to be linked to the emergence of distractor suppression, as infants who were better able to suppress looking towards the distracting non-changing side, were thereon greater able to sustain attention towards the changing display.

3.1.3 Caregiver influences on infant visual cognition

How might caregivers' own cognitive functions shape infant visual cognition during early development? There is already some evidence for these associations in early childhood. For instance, research by Cuevas and colleagues has examined the contributions of maternal EF and caregiving to child EF. By 24 months of age, mother and child EF was moderately correlated, and by 36 months of age, mother and child

EF were more robustly correlated (Cuevas, Deater-Deckard, Kim-Spoon, Watson, et al., 2014). Further, both mother EF and negative caregiving behaviours accounted for unique variance in child EF (Cuevas, Deater-Deckard, Kim-Spoon, Wang, et al., 2014). These findings provide support the self-regulatory framework (Calkins, 2011), suggesting that mother EF is critical in the regulation of caregiving behaviours. Ribner et al. (2022) has also examined differences in parental EF and parenting behaviours on children's EF development from 14 months. Here, the authors found that both parents contributed to child EF, and that parents who provided more autonomy supportive and sensitive caregiving environments, had children with better EF. Associations have similarly been seen between parent EF and child EF in older children, with mediating effects from autonomy supportive parenting (Distefano et al., 2018) and EF activities (Korucu et al., 2020). While this research highlights that caregiver behaviours and EF impact child cognitive development, more research is required in this direction to probe other neurocognitive links between caregivers and children, as early as during the infancy period.

3.2 Research Objectives

Whilst visual neurocognition has been studied in childhood, adolescence, and adulthood (Geier et al., 2009; Scherf et al., 2006), less is known in the infancy period. Further, there is a gap in the literature on the influences of caregiver cognitive function on infant visual cognition development. Examining these associations might allow researchers to better understand the contributions of caregivers own visual cognitive abilities on infant visual cognition and establish the extent to which visual cognition is heritable.

This chapter aims to bridge these gaps, by inquiring whether caregiver looking behaviours are associated with infant looking behaviours. To achieve this, caregivers and their 6- to 10-month-old infants were presented with age-appropriate variants of the same preferential looking task (Ross-Sheehy et al., 2003) with a load manipulation (one, two, and three items for infants and four, six, and eight items for caregivers). It is important to note that in line with more recent work (Delgado Reyes et al., 2020; Perone et al., 2011; Wijeakumar et al., 2019, 2023), the display period was reduced from 20 seconds to 10 seconds, to reduce contributions from long-term memory processes. To examine behavioural associations, looking behaviours were extracted from video recordings, and to examine brain associations, brain function was recorded

using fNIRS, from both infants and caregivers as they independently engaged with variants of the task.

This chapter had three key research objectives. The first research objective was to investigate whether caregiver looking behaviours were associated with infant looking behaviours. Using the same task, Ross-Sheehy et al. (2003) and Delgado Reyes et al. (2020) both found increases in VWM capacity, from around one item in younger infants, up to four items in later infancy and toddlerhood. Aligned with previous findings, it was therefore expected that infants would show decreasing CP scores with increasing load. Research has also argued that adult VWM is limited to approximately four chunks (Cowan, 2001; Luck & Vogel, 1997). Caregivers were therefore also expected to show load-dependent changes in CP scores. Consistent with typical adult VWM tasks (Ambrose et al., 2016; Wijeakumar, Magnotta, et al., 2017), caregivers were predicted to show the highest CP scores at the low load of four items. Further, based on previous associations found between caregiver and child EF (Cuevas, Deater-Deckard, Kim-Spoon, Wang, et al., 2014; Cuevas, Deater-Deckard, Kim-Spoon, Watson, et al., 2014), it was predicted that better CP scores in caregivers would be associated with better CP scores in infants. Previous work has also examined other behavioural measures, such as total time spent looking at the displays and switching between displays. However, these measures do not show consistent effects of load in previous literature (Delgado Reyes et al., 2020; Wijeakumar et al., 2019). For example, Delgado Reyes et al. (2020) reported that the rate of switching decreased with increasing load, while total looking durations remained unaffected by load. In contrast, Wijeakumar et al. (2019) observed no effect of load on switching, but reported a main effect of load on total looking durations in a sample of infants in rural India. Consequently, in this chapter, these measures were extracted and examined for an effect of load, but an exploratory analyses approach was followed, as there were no a priori hypotheses.

The second research objective was to examine whether caregiver behaviours were linked to infant brain function. Aligned with the behavioural predictions for the first research objective, it was predicted that better caregiver CP scores would be associated with greater fronto-parietal activation in infants.

The final research objective was to investigate whether there was any spatial and functional overlap in brain areas associated with looking behaviours in caregivers and infants. Based on previous findings, it was expected that caregivers and infants would show load- and performance-dependent modulation of the parietal cortex (Ambrose et al., 2016; Buss et al., 2014; Delgado Reyes et al., 2020; Todd & Marois, 2004, 2005; Wijeakumar et al., 2019, 2023). Further, in line with behavioural predictions for the first research objective, it was speculated that performance-dependent fronto-parietal activation in caregivers would be associated with performance-dependent fronto-parietal activation in infants.

3.3 Materials and Methods

3.3.1 Participants

This chapter is part of a larger longitudinal project. Based on power calculations, a sample size of 85 infants was required to detect an effect of load on behavioural performance (one-factor ANOVA with load on looking measures from Delgado Reyes et al., 2020; effect size = 0.15, alpha = 0.05 and power = 0.80). Participants were recruited via advertisement on social media platforms and by distributing study information to schools, nurseries, shops, and baby and toddler groups – see Appendix A: Recruitment Documents. 111 families expressed interest and were contacted via telephone to provide a detailed explanation of the study. Families were excluded if 1) they did not have normal or corrected-to-normal vision, 2) they had any neurological conditions or had experienced major head trauma, 3) English was not the primary language spoken at home, 4) the caregiver had illicit drug or alcohol usage during the pregnancy, 5) the pregnancy term was not between 37 and 42 weeks, or 6) there were complications in the birth. 17 families dropped out of the study before their first visit and 4 families were not included as the infant was not in the correct age range, resulting in 90 families who visited the lab (including one pair of twins).

In this chapter, data from three families were excluded from analyses due to a familial history of colour blindness. Further, two infants were excluded due to fussiness. As the sample included one pair of twins, data from this caregiver was duplicated. Finally, data from 10 caregivers were excluded from analyses as incorrect task parameters were used. The final sample therefore consisted of a total of 86 infants

(44 female, mean age: 8.24 ± 1.18 months, age range: 6.08 – 10.45 months, including one pair of twins) and 78 caregivers (77 female and 1 non-binary, mean age: 33.31 ± 4.40 years, age range: 22 – 46 years) who contributed to data. Further demographic and socioeconomic status (SES) information is provided in *Table 3.1*. Caregivers provided written informed consent prior to participation in the study and received £10 following each visit. Data collection was carried out at the University of Nottingham. Ethics approval was provided by the Research Ethics Committee at the University of Nottingham (Ethics Approval Number: F1338).

Table 3.1 Socioeconomic and demographic information collected via questionnaire after the family visited the research facility.

Family Member	Measure	N	Mean	± SD
Infant	**Age (months)**	86	8.24	1.18
Primary Caregiver	**Age (years)**	78	33.31	4.40
	Education (years)	67	16.48	2.16
	Income	60	27,949	13,785
Secondary Caregiver	**Education (years)**	66	14.16	4.30
	Income	40	31,717	12,493
Primary Caregiver	**Ethnicity**	**N**	**%**	
	Arab	1	1%	
	Asian	4	5%	
	Mixed	2	3%	
	White British	59	76%	
	Other White	1	1%	
	Did not answer	11	14%	

3.3.2 Infant and caregiver preferential looking tasks

To examine looking behaviours in infants, an adapted version of the preferential looking task was used (Ross-Sheehy et al., 2003) – see *Figure 3.1* (a). The task was run on a laptop using PsychoPy software (v2021.2.3). This laptop was connected to a 121 cm x 68 cm TV screen. Infants were seated in a high-chair or on their caregiver's lap, approximately 120 cm in front of the screen, in a dimly lit room. In the task, prior to each trial, an attentional cue with an audible tone was presented at the centre of the screen to engage the infant. When the infant looked at the cue, the experimenter commenced the trial. In each trial, the infant was presented with two side-by-side flashing displays of coloured shapes (Drucker & Aguirre, 2009; Wijeakumar, Magnotta, et al., 2015). Each stimulus display area was 34 cm x 34 cm and 20 cm away from each other. The displays had a solid grey background. The coloured shapes that were presented on each display were approximately 7 cm x 9 cm each. The colours were selected from a set of 16 colours (RGB values: 0 0 0; 255 255 255; 255 0 0; 0 255 0; 0 0 255; 255 255 0; 0 255 255; 255 0 255; 128 0 0; 128 128 0; 0 128 0; 128 0 128; 0 128 128; 0 0 128; 255 165 0; 222 184 135). On each display, the colours of the shapes differed from each other, but the same colour could appear in both displays across flashes within the same trial. The displays appeared on the screen for 500 ms, and disappeared for 250 ms and so on and so forth for a total of 10.25 s. During each trial, the coloured shapes remained constant on one of the displays (no

change side), and on the other display, one shape randomly changed in colour during each flash (change side). There was an inter-trial interval of 5 s between each trial. Infants were presented with either one (low load), two (medium load), or three (high load) shapes on each side. Each run consisted of 18 trials (6 trials at each load). Infants completed between one and six runs of the task depending on infants' engagement (mean: 3.17 ± 1.29).

The infant preferential looking task was modified to create the caregiver version of the task – see *Figure 3.1* (b). In the caregiver preferential looking task, each trial started with a fixation cross presented at the centre of the screen instead of the attentional cue. After confirming the caregiver was looking towards the fixation cross, the experimenter commenced the trial. To manipulate load, caregivers were presented with either four (low load), six (medium load), or eight (high load) shapes on each side. Caregivers were not provided with any explicit instructions and were simply asked to explore the display. Caregivers were presented with a practice trial prior to completing the task. Caregivers then completed one run of the task which consisted of 18 trials (6 trials at each load).

For both tasks, one video camera recorded the TV display, and another video camera recorded the infant/caregiver's face. These video recordings were used to code looking behaviours. Real-time recordings were presented to the experimenter using Bandicam (https://www.bandicam.com/) and Movavi programs (https://www.movavi.com/mac/).

3.3.3 fNIRS data collection

fNIRS data was collected using the NIRScout System (wavelengths 760 nm and 850 nm). For infants, the probe geometry consisted of 16 sources and 8 detectors creating 20 channels – see *Figure 3.1* (c). For caregivers, the probe geometry consisted of 16 sources and 16 detectors, creating 36 channels –see *Figure 3.1* (d). The infant geometry had a reduced number of detectors to ensure that infants' heads could be comfortably supported during the task. In both groups, the probe geometry covered frontal, temporal, and parietal regions. Multiple cap sizes were used to accommodate for the varying head sizes (caregivers: 54 cm, 56 cm, and 58 cm, and infants: 42 cm, 44 cm, 46 cm, 48 cm, 50 cm, and 52 cm). Source-detector separation was scaled

according to cap size (e.g., 48 cm: 2.4 cm, 50 cm: 2.5 cm, 52 cm: 2.6 cm, 54 cm: 2.7 cm, 56 cm: 2.8 cm, 58 cm: 2.9 cm).

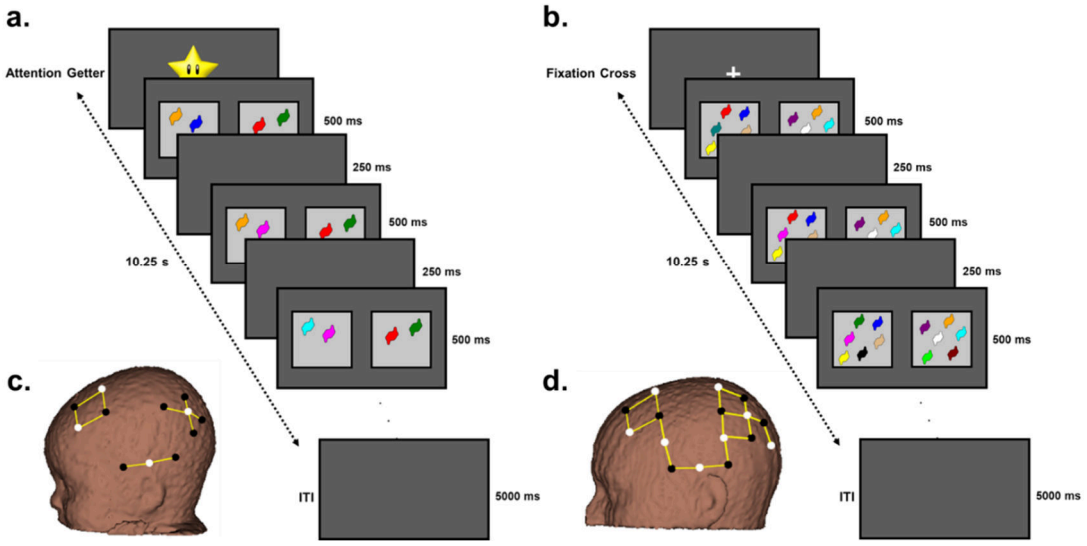


Figure 3.1 (a) Infant preferential looking task and (b) caregiver preferential looking task. During the task, two arrays of coloured shapes are presented side by side. The arrays flashed on the screen for 500 ms, and disappeared for a delay of 250 ms repeatedly, for a total of 10.25 s. On the unchanging side, after every flash, colours stay the same and on the changing side, one shape changes colour. In both panels, the medium load is displayed with the changing side on the left. fNIRS probe geometry with channels covering frontal, temporal, and parietal regions for (c) infants and (d) caregivers. White dots indicate sources, black dots indicate detectors, and yellow connections indicate channels.

3.3.4 Procedure

Upon arrival to the Infant and Toddler Lab at the University of Nottingham, the study procedures were explained to the caregiver. Informed consent was obtained from the caregivers and assent from the infants who participated in the study. Head circumference measurements were taken from the caregiver and infant to find appropriate fNIRS caps. During each visit, one experimenter was responsible for presenting the experimental task and the other experimenter was responsible for monitoring fNIRS signals. During the infants' session, they were either seated in a highchair or on the caregiver's lap, around 100 cm in front of a TV screen. The infant was kept engaged with a cartoon, while two experimenters placed the fNIRS cap onto the infant. When the infant looked ready and engaged, the experimental task ensued. The caregiver was instructed not to interact with the infant during the trials. If the infant did not engage with the display, cartoons were played during the attentional cue

to regain the infant's attention or breaks were taken. In addition, if the infants became fussy, or tired, or caregivers wanted to try another day, this data was collected at another closely spaced visit as per the family's convenience (mean number of visits: 2.73 ± 0.70). Note that infant age was tracked at each visit and an average was calculated across visits. These visits (and this study) were part of a larger project with multiple assessments.

During the caregivers' session, only they were seated in the testing area. When they were ready, the experimenters placed the fNIRS cap onto the caregivers' head. The caregiver was shown one trial of the task as preparation for the experimental run. They were not given any specific instructions but were simply asked to explore the displays. They were asked not to interact with the experimenters during the experimental run. Families were compensated for their time.

3.3.5 Behavioural analyses

DataVyu software (https://datavyu.org/) was used to code video recordings from both infants and caregivers. First, each trial was coded for load and side of change. Next, infant/caregiver looks were coded as either 'left' or 'right' depending on whether they looked to the left or right display. For the infant data, three coders were rigorously trained on how to accurately code trials and looks. Two of these coders were also trained on how to accurately code trials and looks for the caregiver data. 23% of infants and caregivers were coded for checking reliability. Reliability was computed using Cohen's Kappa, a statistic that looks at percent agreement across categories normed by the base rate of each category. This calculation is performed according to *Formula 3.1*.

$$\textit{Formula 3.1:}\quad \kappa = \frac{Po - Pe}{1 - Pe} = 1 - \frac{1 - Pe}{1 - Pe}$$

Where:

P_o = the relative observed agreement among raters.

P_e = the hypothetical probability of chance agreement.

The Kappa statistic varies from 0 to 1 – see *Table 3.2*. For infant data, the mean Kappa value was 0.94 and for caregiver data, the mean Kappa value was 0.98. The Kappa value for both caregiver and infant data therefore indicated near perfect agreement (0.81 to 0.99).

Table 3.2 Cohen's Kappa statistics and corresponding agreement levels used to measure interrater reliability.

Value of Kappa	**Level of agreement**
0	Agreement equivalent to chance
0.1 - 0.20	Slight agreement
0.21 - 0.40	Fair agreement
0.41 - 0.60	Moderate agreement
0.61 - 0.80	Substantial agreement
0.81 - 0.99	Near perfect agreement
1	Perfect agreement

From these coded looks, four looking measures were estimated for the infant and the caregiver. Total look duration (TLD) for each trial was calculated as the total amount of time spent looking at the left and right displays. A greater TLD score represented longer time spent exploring the displays. Switch rate (SR) for each trial was calculated as the number of switches from one display to the other display, divided by TLD and multiplied by 1000. A greater SR score represented more frequent switching between displays. CP for each trial was calculated as the looking time towards the changing display divided by TLD score. A greater CP score represented better ability to detect and stay fixated on the changing display. These scores were weighted ($\bar{x}$) to consider varying number of trials per load per infant. All formulas used are outlined below.

Formula 3.2: $$\text{TLD score} = \text{Total time looking at left display (ms)} + \text{Total looking time at right display (ms)}$$

Formula 3.3: $$\text{SR score} = \frac{\text{Number of switches between displays}}{\text{TLD score (ms)}} \text{ x } 1000$$

Formula 3.4: $$\text{CP score} = \frac{\text{Looking duration towards changing display (ms)}}{\text{TLD score (ms)}}$$

Formula 3.5: $$\bar{x} = \frac{(\text{Average score Run 1 x No.trials Run 1}) + (\text{Average score Run 2 x No.trials Run 2}) \ldots}{\text{Total no.trials}}$$

Outliers were identified and removed for each measure separately if values were outside of ± 3 SDs from the mean. For caregiver looking measures 6 data points were identified as outliers and removed from the dataset (low load – TLD: 2; medium load – TLD: 2; high load – TLD: 2). For infant looking measures 4 data points were identified as outliers and removed from the dataset (medium load – CP: 3; high load – SR: 1).

3.3.6 fNIRS data analyses

3.3.6.1 Pre-processing

To remove noise, artefacts, and other confounding signals, all fNIRS data was pre-processed in *EasyNIRS* using Homer2. Raw data was pruned to remove noisy channels (dRange = 0.03–2.0; SNRthresh = 2; caregiver SDrange = 2.5–4.5 and infant SDrange = 2-3). 3.15 % of the infants' and 0.04 % of the caregivers' channels were pruned. Raw intensity values were converted to optical density units. Targeted principal component analyses were used to detect and remove motion artifacts (tMotion = 1, tMask = 1, STDEVthresh = 50, AMPthresh = 0.5, nSV = 0.97, maxIter = 5). The data were then scanned again for remaining motion artifacts (tMotion = 1, tMask = 1, STDEVthresh = 50, AMPthresh = 0.5). The StimRejection function was used to reject uncorrected motion artifacts (tRange = -1–18). The data were then band pass filtered (hpf = 0.016, lpf = 0.5). Following pre-processing, the percentage of trials lost in the infant dataset was 7.55% for low load, 7.83% for medium load, and 6.96% for high load. No trials were lost from the caregiver dataset. Pre-processed optical density time-series data were then used for image reconstruction described below. *Figure 3.2* presents example channel-level hemodynamic response functions (HRFs) from right parietal channels in infants.

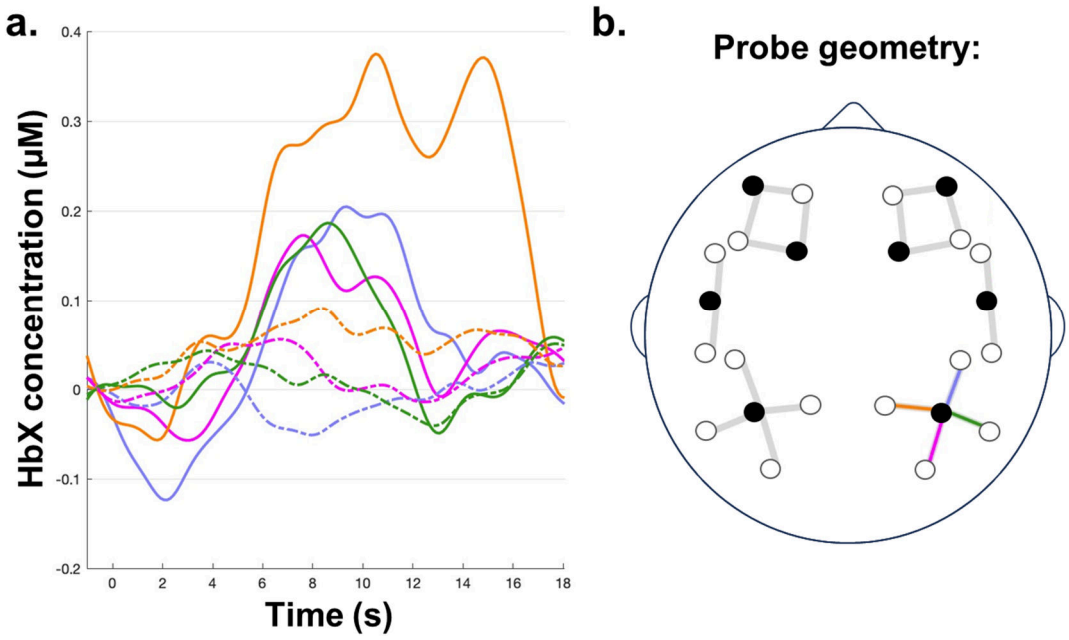


Figure 3.2 (a) Example hemodynamic response functions (HRFs) from selected right parietal channels in the infant dataset. HbO concentration is shown with solid lines, and HbR concentration is shown with dashed lines. (b) Probe geometry with white dots indicating sources, black dots indicating detectors, grey lines indicating channels, and coloured lines indicating the corresponding channels plotted in (a).

3.3.6.2 fNIRS image reconstruction

Details of the methodological pipeline followed for image reconstruction are described elsewhere (Forbes et al., 2021) and have been published previously (Amaireh et al., 2024; Davidson, Caes, et al., 2023; Davidson et al., 2024; Davidson, Shing, et al., 2023; Defenderfer et al., 2021; Fu & Richards, 2021, 2022; Segel et al., 2024; Speh et al., 2023; Theyer et al., 2024; Wijeakumar et al., 2023). To account for age-specific differences in head size and head shape, age-specific atlases (infants: at 6 months, 7.5 months, and 9 months; caregivers: at 20-24 years, 25-29 years, 30-34 years, 35-39 years, 40-44 years, and 45-49 years) were obtained from the Neurodevelopmental MRI database (Richards et al., 2016). To create the tissue model needed for photon migration simulations, each atlas was segmented into four tissue types (scalp, cerebrospinal fluid, grey matter, and white matter). Scalp landmarks and probe geometry were digitized on a single adult wearing a 58 cm cap and a single child wearing a 48 cm cap using a Polhemus Patriot Digitizer. The digitised scalp landmarks and probe geometry were projected onto each age-specific atlas using *AtlasViewerGUI* in Homer2. Monte Carlo simulations with 1 million photons were run to create sensitivity profiles for each channel and for each infant/caregiver. The sensitivity

profiles were converted to NIFTI format. To move from the channel space on the surface of the head into voxel space within brain volume, image reconstruction techniques were used to integrate pre-processed optical density time-series data with the sensitivity profiles. This generates voxel-wise time-series data for each chromophore (HbO and HbR), and infant/caregiver (Forbes et al., 2021).

A general linear model with three regressors (low, medium, and high loads) was separately run for each chromophore and each infant/caregiver. Each trial was modelled with a 10 s boxcar using a hemodynamic response function derived from diffuse optical imaging (Eggebrecht et al., 2014). These analyses generated beta coefficient images for each load, chromophore, and infant/caregiver. Additionally, to control for the variability in the number of trials per load across infants, weighted averages were computed for each load, chromophore, and infant (see Section 3.3.5 *Behavioural analyses – Formula 3.5*). This step was not necessary for caregiver data as only one run was completed. Resulting beta coefficient maps were registered to the MNI space and used in the whole brain analyses described below.

3.3.6.3 Whole brain analyses

To standardise across multiple participants, a group mask was calculated separately for caregivers and infants by masking and summing beta maps representative of each age-specific atlas and extracting voxels that contained data from 65% of the data. Only data from these voxels were used for linear mixed effects modelling.

Separate linear mixed effects models were run for the caregiver brain data and infant brain data (in AFNI using *3dLME)*. For caregivers, the model contained load (low, medium, and high), and chromophore (HbO and HbR) as multi-level factors and caregiver CP score as a quantitative variable. Only effects that included chromophore and caregiver CP score were examined. For infants, the model consisted of load (low, medium, and high) and chromophore (HbO and HbR) as multi-level factors, and infant CP score, infant SR score, and caregiver CP score as quantitative variables. Infant SR score was included in the brain model because it showed an effect of load (discussed in results) and to examine whether it interacted with infant CP score in specific brain regions. Note that for both models, chromophore was included as a variable because increased HbO concentration and decreased HbR concentration is considered to

represent ‘activation’, and decreased HbO concentration and increased HbR concentration is considered to represent ‘suppression’. Throughout the thesis, these chromophore patterns are therefore interpreted as activation and suppression effects, and only interactions involving chromophore and any looking behaviours in the infant and/or caregiver were examined. Resultant F-statistic interaction images were thresholded at an appropriate cluster-wise threshold (237 voxels for infants and 135 voxels for caregivers) and a voxel-wise p-value of <.01 (using *3dClustSim* and *3dClusterize*). Average HbO and HbR concentration was extracted from significant clusters using *3dROIstats* for display and further analyses.

3.3.6.4 ROI analyses

In addition to the whole-brain approach, which considers activity across all channels, it was also necessary to understand whether specific ROIs related to visual cognition, or more specifically VWM, would show these effects. The rationale for these analyses is based on the possibility that whole-brain analyses might suppress weak, but meaningful effects, that do not survive threshold corrections. Therefore, a secondary ROI-based approach was also conducted, focusing on regions of interest from adult VWM literature (Edin et al., 2009; Harrison et al., 2010; Pessoa et al., 2002; Pessoa & Ungerleider, 2004; Shafritz et al., 2002; Todd et al., 2005; Todd & Marois, 2004; Xu & Chun, 2006). These ROIs are outlined in *Table 3.3* and were obtained from a meta-analysis (Wijeakumar, Spencer, et al., 2015). To ensure that ROI analyses were restricted to the standardised group space (see 3.3.6.3 Whole brain analyses), these ROIs were overlayed with both the infant and caregiver group-masks. This ensured that only voxels that contained data from 65% of the data were used in the ROI approach. Therefore, only ROIs that overlapped with the group masks were followed up for each subject (infant voxel overlap – rTPJ: 199, rsIPS: 305, rMFG: 24, rIPS: 92, rDLPFC: 43, lIPS: 148, lDLPFC: 274, laIPS: 20; caregiver voxel overlap – rTPJ: 485, rMFG: 536, rDLPFC: 536, lTPJ: 498, lDLPFC: 498). From each of the overlapping regions, average HbO and HbR concentration for each load was extracted using 3dROIstats for display and further analyses.

Table 3.3 List of regions used in ROI-based analyses. These regions and co-ordinates are taken from a meta-analysis of VWM literature (Wijeakumar, Spencer, et al., 2015). * Indicates ROIs that overlapped with the infant mask and † indicates ROIs that overlapped with the caregiver mask.

ROI	Hemisphere	MNI coordinates		
		x	y	z
Superior intraparietal sulcus (sIPS) *	Right	25	-61	51
Intraparietal sulcus (IPS) *	Right	30	-73	38
Intraparietal sulcus (IPS) *	Left	-21	-65	46
Anterior intraparietal sulcus (aIPS)	Right	40	-36	38
Anterior intraparietal sulcus (aIPS) *	Left	-40	-44	42
Ventral occipital cortex (VOC)	Right	42	-75	-3
Ventral occipital cortex (VOC)	Left	-42	-71	6
Dorsolateral prefrontal cortex (DLPFC) *†	Right	45	42	21
Dorsolateral prefrontal cortex (DLPFC) *†	Left	-42	41	20
Superior frontal gyrus (SFG)	Left	-1	18	51
Inferior frontal gyrus (IFG)	Right	35	22	4
Inferior frontal gyrus (IFG)	Left	-31	23	-1
Frontal eye fields (FEF)	Right	29	-2	52
Frontal eye fields (FEF)	Left	-25	-3	54
Middle frontal gyrus (MFG) *†	Right	49	6	31
Middle frontal gyrus (MFG)	Left	-43	3	29
Anterior cingulate cortex (ACC)	Left	-5	30	27
Occipital (OCC)	Right	34	-87	13
Occipital (OCC)	Left	-34	-85	14
Anterior cingulate cortex (ACC)	Left	-5	30	27
Temporo-parietal junction (TPJ) *†	Right	62	-46	26
Temporo-parietal junction (TPJ) †	Left	-58	-49	28

3.3.7 Statistical analyses

Statistical analyses were run using RStudio (v2023.03.0).

To examine the impact of load on caregiver and infant looking measures, separate analyses were conducted. For caregivers, one-factor ANOVAs with load as a within-subjects factor, were run on TLD, SR, and CP scores. For infants, one-factor ANCOVAs with load as a within-subjects factor and infant age as a covariate, were run on infant TLD, SR, and CP scores. To investigate associations between infant and caregiver looking behaviours, a regression model was run with infant CP score as outcome, and load, infant SR score, and caregiver CP score as predictors. Load was included in the model to examine whether caregiver-infant associations were present at specific loads. Notably, infant SR score showed both load and age-related effects across infancy. Infant SR score was therefore also included in the model to examine whether there was an interaction between infant SR score and caregiver CP score predicting infant CP score. For example, it is possible that higher infant CP scores would be observed in infants who both had caregivers with higher CP scores *and* who also had lower SR scores themselves (indicating that they switched less between the sides).

Following this, brain-behaviour associations were examined. First, to examine key brain regions engaged during the task, separate linear mixed effects models were run for caregivers and infants in AFNI. These models are run at the voxel level in AFNI, meaning that models are conducted independently on each voxel, and significant clusters of effects are then identified. Average HbO and HbR concentration was then extracted from voxels in significant clusters (see Section 3.3.6.3 *Whole brain analyses*). To confirm that the effects observed at the voxel-level were still evident at the cluster-level, the average activation across each cluster was re-examined in RStudio. Additionally, clusters with multiple interactions were further examined for interpretation of results. Clusters showing a chromophore main effect were followed up with pairwise comparisons to confirm significant differences in average HbO/HbR concentrations. Clusters showing an interaction effect were followed up using regression models to examine the nature of the interaction and identify relationships between behaviour, brain function and load. For infants, follow-up tests also examined any effect of infant age. To examine spatial overlap between fronto-parietal regions in caregivers and infants, caregiver and infant load- and performance-dependent clusters

were overlayed using the *3dcalc* function in AFNI. This enabled only voxels that contained data from both clusters to be extracted. The *3dBrickStat* function in AFNI was then used to calculate the spatial overlap between the clusters. Further, the Euclidian distance was calculated between the centre of mass of each cluster.

To analyse ROI brain data, average HbO and HbR concentration for each load was extracted from each ROI (see Section 3.3.6.4 *ROI analyses*). These ROIs were followed up in RStudio for further analyses. In caregivers, a regression model with chromophore, load, and caregiver CP as predictors was run for each ROI. In infants, a regression model with chromophore, infant CP score, caregiver CP score, infant SR score, and load as predictors, and infant age as a covariate, was run, for each ROI. The number of caregivers and infants included in each analysis are presented in *Table 3.4*.

Table 3.4 Number of caregivers and infants included in each analysis. Note that for the infant brain model, the numbers are based on common data across infants and caregivers and loads as the AFNI function 3dLME used for running the linear mixed effects model does not accept missing rows of data.

Analyses	**Variables determining number**	**Low**	**Medium**	**High**
Caregiver TLD ANOVA	Caregiver TLD	76	76	76
Caregiver SR ANOVA	Caregiver SR	78	78	78
Caregiver CP ANOVA	Caregiver CP	78	78	78
Infant TLD ANCOVA	Infant TLD	86	86	86
Infant SR ANCOVA	Infant SR	86	86	85
Infant CP ANCOVA	Infant CP	86	83	86
Caregiver-infant behavioural model	Infant SR	76	74	75
	Caregiver CP	76	74	75
	Infant CP	76	74	75
Caregiver brain model	Caregiver CP	78	78	78
Infant brain model (including caregiver data)	Caregiver CP, Infant CP, Infant SR	76	74	75
Caregiver ROI analysis	Caregiver CP	78	78	78
Infant ROI analysis	Caregiver CP, Infant CP, Infant SR	76	74	75

3.4 Results

3.4.1 Looking behaviours in caregivers and infants

3.4.1.1 Impact of load on caregiver looking behaviours

To examine the impact of load on caregiver looking behaviours, separate one-way repeated measures ANOVAs with load as a within-subjects factor were run on TLD, SR, and CP scores.

The main effect of load was not significant for TLD (low: 9083 ± 337, medium: 9132 ± 246, high: 9126 ± 318) or SR (low: 0.73 ± 0.35, medium: 0.72 ± 0.31, high: 0.69 ± 0.35) scores – see *Figure 3.3* (a-b).

For CP score, there was a significant main effect of load ($F_{(1.63,125.25)} = 25.14$, $p < .001$; low: 0.61 ± 0.11, medium: 0.56 ± 0.09, high: 0.55 ± 0.08). Pairwise comparisons revealed that CP scores at the low load were significantly greater than CP scores at the medium ($p < .001$) and high ($p < .001$) loads – see *Figure 3.3* (c). In addition, to assess whether CP scores were significantly greater than chance (0.5), one-sample t-tests were also run at each load. These revealed that CP scores were significantly greater than chance at the low ($t(77) = 8.94$, $p < .001$), medium ($t(77) = 5.94$, $p < .001$), and high ($t(77) = 5.20$, $p < .001$) loads.

These findings indicate that the total time that caregivers spent exploring the displays, and the rate at which they switched between the displays, did not change with load. However, caregivers were greater able to detect the change at the low load, in comparison to the medium and high load. These findings are presented in *Table 3.5*.

3.4.1.2 Impact of load on infant looking behaviours

To examine the impact of load on infant looking behaviours, separate one-way repeated measures ANCOVAs with load as a within-subjects factor and infant age as a covariate, were run on TLD, SR, and CP scores. Here, infant age was used as a controlling variable, to account for age-related variation in looking behaviours.

The main effect of load was not significant for TLD score (low: 6070 ± 1163, medium: 6098 ± 1152, high: 6186 ± 1329) – see *Figure 3.3* (d). However, there was a significant effect of infant age on TLD score ($F_{(1,254)} = 3.91$, $p = .049$). Here, TLD scores increased with infant age.

The main effect of load was not significant for SR score (low: 0.50 ± 0.19, medium: 0.46 ± 0.17, high: 0.45 ± 0.18) – see *Figure 3.3* (e). However, there was also a significant effect of infant age on SR score ($F_{(1,253)} = 11.97$, $p < .001$). Here, SR scores decreased with infant age.

For CP score, there was a significant main effect of load ($F_{(2,251)} = 13.68$, $p < .001$; low: 0.59 ± 0.08, medium: 0.55 ± 0.07, high: 0.54 ± 0.07). Pairwise comparisons revealed that CP scores at the low load were significantly greater than CP scores at the medium ($p < .001$) and high ($p < .001$) loads – see *Figure 3.3* (f). Similarly, to assess whether CP scores were significantly greater than chance, one-sample t-tests were also run at each load. These revealed that CP scores were significantly greater than chance at the low ($t(85) = 11.01$, $p < .001$), medium ($t(82) = 6.35$, $p < .001$), and high ($t(85) = 4.92$, $p < .001$) loads.

These findings indicate that the total time that infants spent exploring the displays, and the rate at which they switched between the displays, did not change with load. However, these both changed with age across the group, with total looking time increasing with age, and the rate of switching decreasing with age. Age-related findings are presented in Appendix B: Figures *Appendix Figure B.1*. Additionally, infants were greater able to detect the change at the low load, in comparison to the medium and high load. These findings are presented in *Table 3.6*.

3.4.1.3 Association between caregiver and infant looking behaviours

To investigate associations between infant and caregiver looking behaviours, a regression model was run with infant CP score as the outcome, and load, caregiver CP score, and infant SR score as the predictors. Here, infant SR score was included in the model for multiple reasons. Firstly, SR score significantly decreased with infant age and therefore may capture developmental changes relevant to infants' ability to detect change. Further, SR score was more sensitive to age effects than TLD score in infants. Secondly, prior to the addition of infant age into the model, trends were found with infant SR score and load. These findings are reported in Appendix C: Data Tables *Appendix Table C.1*.

The regression model revealed a significant main effect of caregiver CP score ($F_{(1,217)} = 6.14$, $p = .014$, $\eta p^2 = .03$) and load ($F_{(1,217)} = 4.72$, $p = .031$, $\eta p^2 = .02$). Further, there was a significant two-way interaction between load and caregiver CP

score ($F_{(1,223)}$ = 5.98, p = .015, ηp^2 = .03), and a significant three-way interaction between load, caregiver CP score and infant SR score ($F_{(1,223)}$ = 4.40, p = .037, ηp^2 = .02). For each of the interactions with load, follow-up tests were run for each load separately. Follow-up tests for the interaction between load, caregiver CP score and infant SR score, revealed no significant effects at the low, medium or high load. Follow-up tests for the interaction between load and caregiver CP score, revealed that greater caregiver CP scores were associated with greater infant CP scores at the low load (p = .044, ηp^2 = .05), but not at the medium or high loads – see *Figure 3.3* (g). Further, when infant age was included as a factor in this model, this effect remained unchanged. This finding indicated that caregivers who were greater able to detect the change at the low load, also had infants who were greater able to detect the change at the low load.

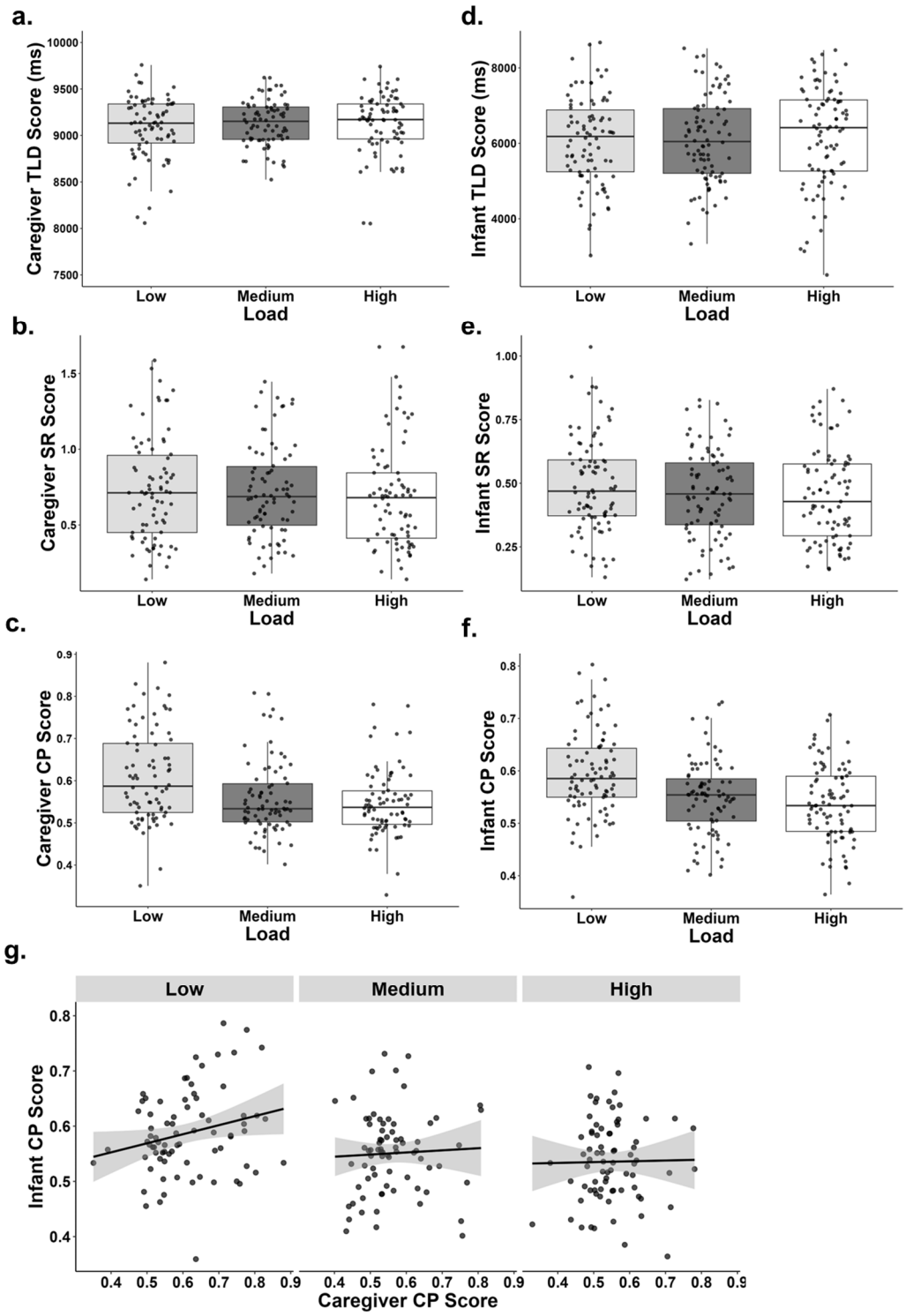


Figure 3.3 Main effect of load on (a) TLD scores, (b) SR scores, and (c) CP scores for caregivers and (d) TLD scores, (e) SR scores, and (f) CP scores for infants. (g) Greater caregiver CP scores were associated with greater infant CP scores at the low load

Table 3.5 Summary of statistics and ANOVA results for caregiver looking measures across load. *** p < .001

Measure	F Statistic	p Value	Sig.	Load	Mean	± SD	Summary of results
TLD	1.41	0.246	ns	Low Medium High	9083.30 9132.25 9126.07	336.89 245.89 318.13	-
SR	2.16	0.119	ns	Low Medium High	0.73 0.72 0.69	0.35 0.31 0.35	-
CP	25.14	< .001	***	Low Medium High	0.61 0.56 0.55	0.11 0.09 0.08	Low > High ***, Low > Medium ***

Table 3.6 Summary of statistics and ANCOVA results for infant looking measures across load, whilst controlling for infant age. * p < .05, ** p < .01, and *** p < .001

Measure	Effect	F Statistic	p Value	Sig.	Load	Mean	± SD	Summary of results
TLD	Load	0.21	0.808	ns	Low	6069.95	1163.35	-
					Medium	6097.72	1152.35	
					High	6185.52	1329.05	
	Age (T1)	3.91	0.049	*	-	-	-	↑ TLD
SR	Load	1.49	0.228	ns	Low	0.50	0.19	-
					Medium	0.46	0.17	
					High	0.45	0.18	
	Age (T1)	11.97	< .001	***	-	-	-	↓ SR
CP	Load	13.68	< .001	***	Low	0.59	0.08	Low > High ***, Low > Medium ***
					Medium	0.55	0.07	
					High	0.54	0.07	
	Age (T1)	3.18	0.076	ns	-	-	-	-

3.4.2 Brain function in caregivers and infants

3.4.2.1 Brain function in caregivers

To examine brain regions associated with caregiver looking behaviours, a linear mixed effects model with chromophore and caregiver CP score was run. Results are summarized in *Table 3.7* and described in detail below.

There was a main effect of chromophore in nine regions i.e. lSFG (x = +24.2, y = -40.2, z = +42.7), rIFG (x = -51.1, y = -18.4, z = +38.3), rIPL (x = -56.4, y = +56.6, z = +37.7), lIPL (x = +59.3, y = +49.1, z = +36.4), lMOG (x = +25.8, y = +86.5, z = +35.3), rIPL (x = -55.0, y = +41.1, z = +53.7), rSOG (x = -24.8, y = +86.3, z = +37.9), lSTG (x = +65.0, y = +25.2, z = +5.5), and rMFG (x = +34.1, y = -45.6, z = +35.5) – see *Figure 3.4*. Follow-up tests were run for each cluster. These tests revealed that HbO concentration was significantly greater than HbR concentration in the rIFG (t(154) = 3.86, p < .001), lMOG (t(154) = 6.35, p < .001), rIPL2 (t(154) = 3.91, p < .001), and rSOG (t(154) = 7.43, p < .001). Further HbR concentration was significantly greater than HbO concentration for lSFG (t(154) = -2.87, p = .005), rIPL1 (t(154) = -4.22, p < .001), lIPL (t(154) = -4.02, p < .001), lSTG (t(154) = -2.02, p = .045), and rMFG (t(154) = -5.85, p < .001). These results indicate that caregivers activated the rIFG, lMOG, rIPL, and rSOG , and suppressed the lSFG, rIPL, lIPL, lSTG, and rMFG during the task.

There was also a significant interaction between chromophore and caregiver CP score in three regions i.e. rSMG (x = -59.5, y = +40.9, z = +42.8), rIFG (x = -53.2, y = -16.0, z = +35.1), and lMFG (x = +28.2, y = -36.3, z = +43.1) – see *Figure 3.5* (a). Follow-up tests were run for each chromophore separately for each of the three regions. These tests revealed that higher CP scores were associated with decreasing HbO concentration in lMFG (p = .015, ηp^2 = .07), and increasing HbO concentration (p = .014, ηp^2 = .08) and decreasing HbR concentration in rSMG (p = .016, ηp^2 = .07) – see *Figure 3.5* (b-c). Follow-up tests were not significant for rIFG. These findings indicate that caregivers with better CP scores, had greater suppression in the lMFG and greater activation in the rSMG during the preferential looking task.

Table 3.7 Significant clusters showing chromophore main effect and interaction between chromophore and caregiver CP score in caregiver brain data. Numbers indicate cluster number where multiple clusters were found within the same region and * indicates significant results after follow-up tests.

Effect	Cluster	Size (mm^3)	MNI coordinates		
			Centre of Mass		
			x	y	z
Chromophore	Left superior frontal gyrus (lSFG)*	639	24.2	-40.2	42.7
	Right inferior frontal gyrus (rIFG)*	380	-51.1	-18.4	38.3
	Right inferior parietal lobule (rIPL)1*	296	-56.4	56.6	37.7
	Left inferior parietal lobule (lIPL)*	262	59.3	49.1	36.4
	Left middle occipital gyrus (lMOG)*	255	25.8	86.5	35.3
	Right inferior parietal lobule (rIPL)2*	211	-55.0	41.1	53.7
	Right superior occipital gyrus (rSOG)*	163	-24.8	86.3	37.9
	Left superior temporal gyrus (lSTG)*	155	65.0	25.2	5.5
	Right middle frontal gyrus (rMFG)*	141	-34.1	-45.6	35.5
Interaction between chromophore and caregiver CP score	Left middle frontal gyrus (lMFG)*	648	28.2	-36.3	43.1
	Right supramarginal gyrus (rSMG)*	358	-59.5	40.9	42.8
	Right inferior frontal gyrus (rIFG)	261	-53.2	-16.0	35.1

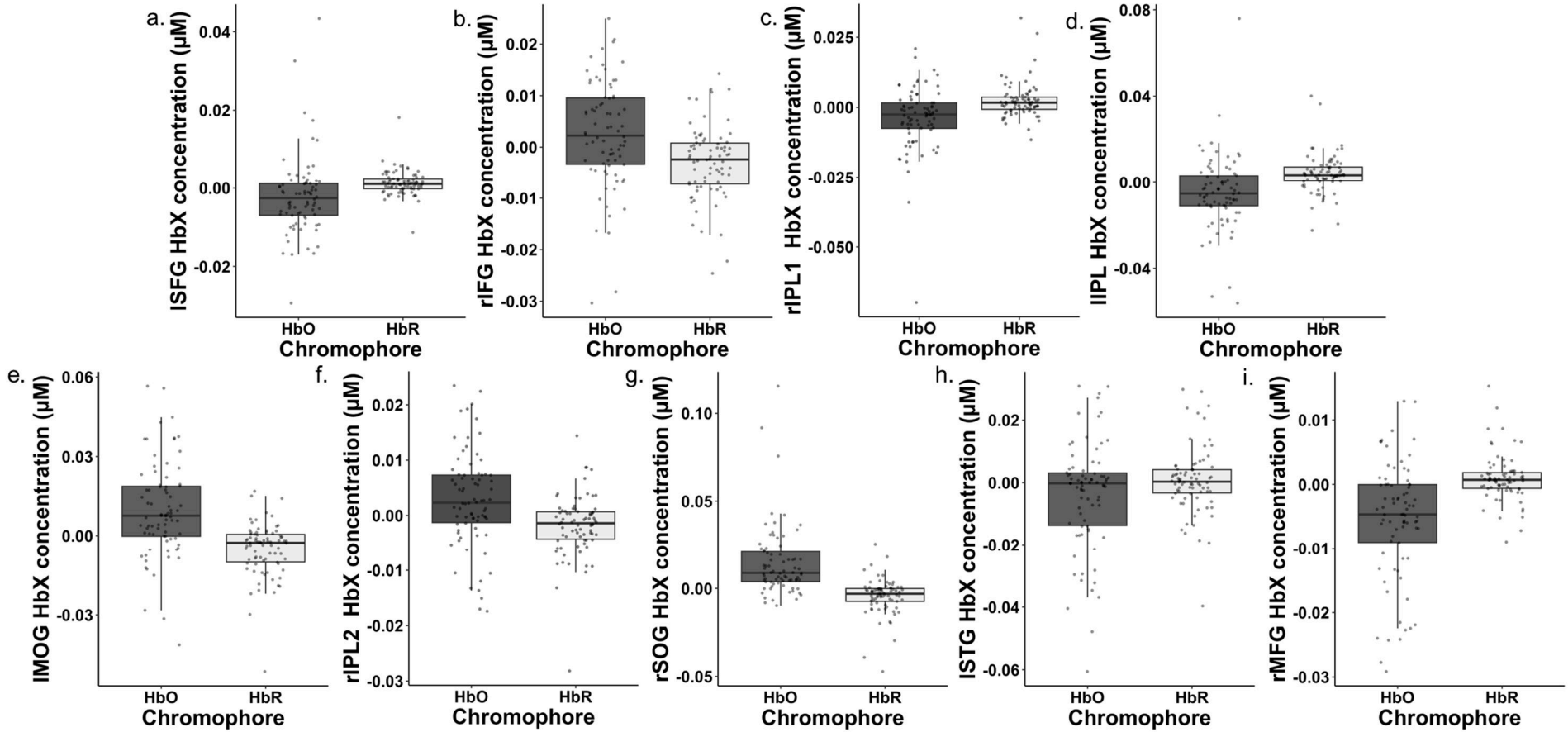


Figure 3.4 Main effect of chromophore from caregiver brain analyses in (a) lSFG, (b) rIFG, (c) rIPL1, (d) lIPL, (e) lMOG, (f) rIPL2, (g) rSOG, (h) lSTG, and (i) rMFG. HbO concentration is shown in black and HbR concentration is shown in grey.

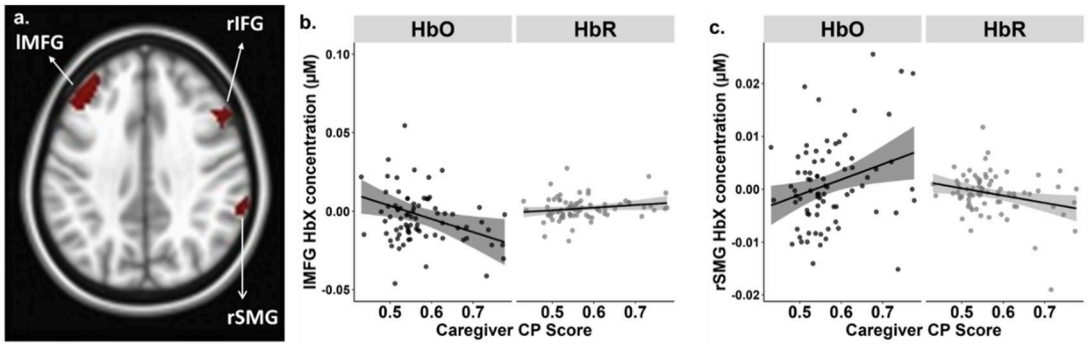


Figure 3.5 (a) Clusters showing interaction between chromophore and caregiver CP score. Follow-up tests revealed (b) decreasing lMFG HbO concentration with increasing caregiver CP scores and (c) increasing rSMG HbO concentration and decreasing rSMG HbR concentration with increasing caregiver CP scores. HbO concentration is shown in black dots and HbR concentration is shown in grey dots.

3.4.2.2 Brain function in infants

To examine infant brain regions associated with both infant and caregiver looking behaviours, a linear mixed effects model with chromophore, load, infant CP score, caregiver CP score, and infant SR score was run. Caregiver CP score and infant SR score were included in the infant brain model for the same rationale as for their inclusion in the infant behavioural model in Section 3.4.1.3. Results are summarised in *Table 3.8* and described in detail below.

There was a main effect of chromophore in three regions i.e. lMFG (x = +40.4, y = -37.0, z = +26.7), rSPL (x = -24.8, y = +62.7, z = +59.9), and lSPL (x = +38.7, y = +48.0, z = +62.5). Follow-up tests were run for each cluster. These tests revealed that HbO concentration was significantly greater than HbR concentration in the lMFG ($t(169) = 2.69$, $p = .008$) and rSPL ($t(169) = 3.67$, $p < .001$) – see *Figure 3.6*. There were no significant findings for lSPL. These results indicate that infants activated the lMFG and rSPL during the task.

There was also a significant interaction between chromophore and infant SR score in one region i.e. rSPL (x = -23.5, y = +62.5, z = +61.2). Follow-up tests were run for each chromophore separately. These tests revealed that lower infant SR scores were associated with increasing HbO concentration in the rSPL ($p = .039$, $\eta p^2 = .05$) – see *Figure 3.7* (b). This effect remained unchanged when infant age was included as a factor. These findings indicate that infants with lower SR scores, had greater activation in the rSPL during the task.

Table 3.8 Significant clusters showing chromophore main effect and interactions between chromophore and looking measures in the infant brain data. * Indicates significant results after follow-up tests. Of these, † indicates significant follow-up results including infant age.

Effect	Cluster	Size (mm^3)	MNI coordinates		
			Centre of Mass		
			x	y	z
Chromophore	Left middle frontal gyrus (lMFG)*	822	40.4	-37.0	26.7
	Right superior parietal lobule (rSPL)*	504	-24.8	62.7	59.9
	Left superior parietal lobule (lSPL)	397	38.7	48.0	62.5
Interaction between chromophore x infant SR score	Right superior parietal lobule (rSPL)*	301	-23.5	62.5	61.2
Interaction between chromophore, load, infant SR score and infant CP score.	Right superior parietal lobule (rSPL)*†	494	-40.2	54.2	56.1
	Left inferior parietal lobule (lIPL)	339	45.4	48.0	57.0
Interaction between chromophore x caregiver CP score	Left superior parietal lobule (lSPL)*†	282	36.3	49.2	64.4

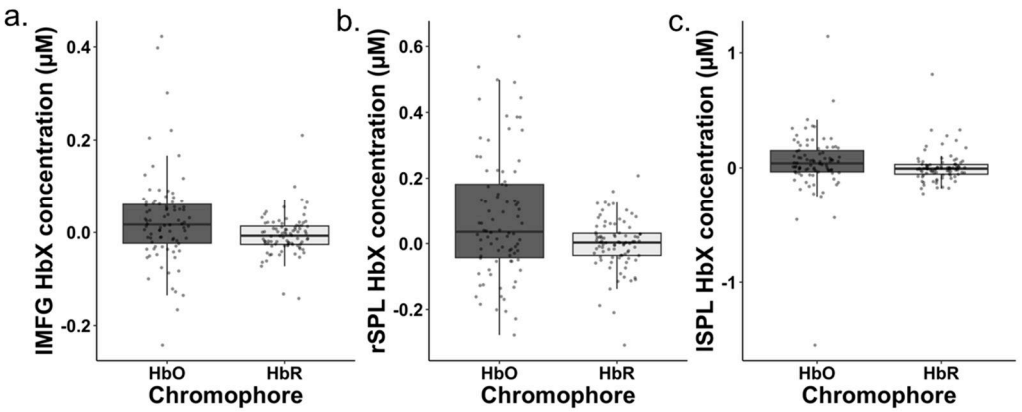


Figure 3.6 Main effect of chromophore from infant brain analyses in (a) lMFG, (b) rSPL, and (c) lSPL. HbO concentration is shown in black and HbR concentration is shown in grey.

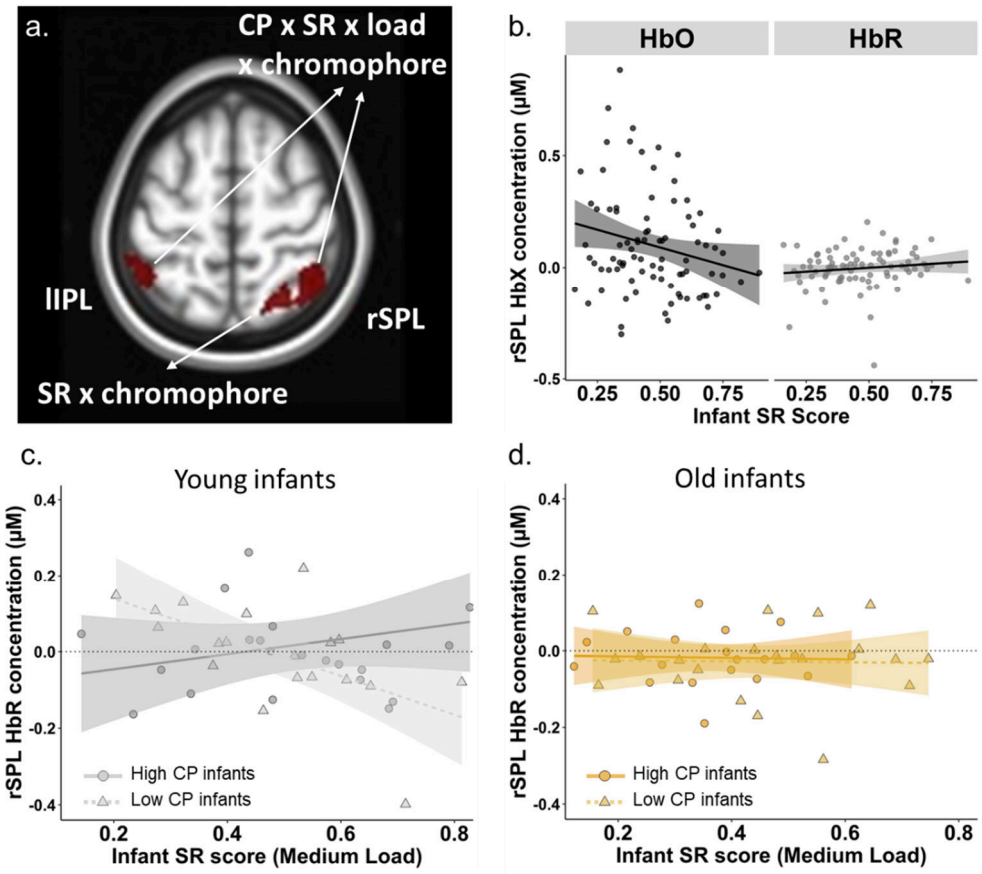


Figure 3.7 (a) Clusters showing two-way interaction between infant SR score and chromophore, and a four-way interaction between infant SR score, infant CP score, load, and chromophore in rSPL. (b) Follow-up of the two-way interaction showed that lower infant SR scores were associated with greater rSPL HbO concentration. HbO concentration is shown in black and HbR concentration is shown in grey. (c) Follow-up tests of the four-way interaction revealed that in young infants with high CP scores, lower SR scores were associated with greater rSPL activation (reduced HbR concentration), compared to old infants.

Furthermore, there was a significant interaction between chromophore, load, infant SR score, and infant CP score in two regions i.e. rSPL (x = -40.2, y = +54.2, z = +56.1) and lIPL (x = +45.4, y = +48.0, z = +57.0). Follow-up tests were run for each chromophore and load separately. These tests revealed that there was a significant interaction between infant CP score and infant SR score, on HbR concentration in the rSPL at the medium load only. When infant age was added as a factor, there was a significant interaction between infant CP score, infant SR score and infant age on rSPL HbR concentration at the medium load. To investigate SR-related age effects, infants were divided into two groups: young and old infants (median age = 8.51 months). The interaction between infant CP score and infant SR score on rSPL HbR concentration at the medium load, was only significant for young infants ($p < .001$, $\eta p^2 = .26$). To visualize multiple continuous variables, CP score was split into low and high groups in *Figure 3.7* (c-d). In young infants with high CP scores, lower SR scores were associated with greater rSPL activation (reduced HbR concentration), compared to young infants with low CP scores, who showed reducing rSPL activation with lower SR scores. Old infants did not demonstrate these differences. This finding indicates that young infants who have better CP scores, show reduced switching and greater activation in the rSPL.

Finally, there was a significant interaction between chromophore and caregiver CP score in one region i.e. lSPL (x = +36.3, y = +49.2, z = +64.4). Follow-up tests were run for each chromophore separately. These tests revealed that higher caregiver CP scores were associated with increasing HbO concentration in the lSPL in infants ($p < .001$, $\eta p^2 = .15$). When infant age was included as a factor, there was a significant interaction between caregiver CP score, infant age and chromophore. To examine this further, infants were divided into two groups: young and old infants (median age = 8.51 months). Higher caregiver CP scores were associated with increasing HbO concentration in the lSPL in young infants only ($p = .002$, $\eta p^2 = .23$) – see *Figure 3.8* (b). This finding indicates that earlier in infancy, infants who showed greater activation of the lSPL had caregivers with greater ability to detect the change, however, later in infancy, this effect is no longer present.

Finally, the spatial overlap in load- and performance-dependent fronto-parietal regions in caregivers and infants was examined (using *3dcalc* and *3dBrickStat* functions in AFNI). The rSMG cluster from the caregiver brain data (with a link to

caregiver CP score) was examined for a spatial overlap with the rSPL cluster from the infant brain data (with a link to infant CP sore, infant SR score and load). There was spatial overlap between the two clusters (4 voxels; Euclidian distance between centres of mass = 26.95 mm) – see *Figure 3.8* (c). Critically, both caregivers and infants also showed similar performance-dependent associations; caregivers showed increasing activation with increasing CP scores, and high CP infants showed increasing activation with decreasing SR scores.

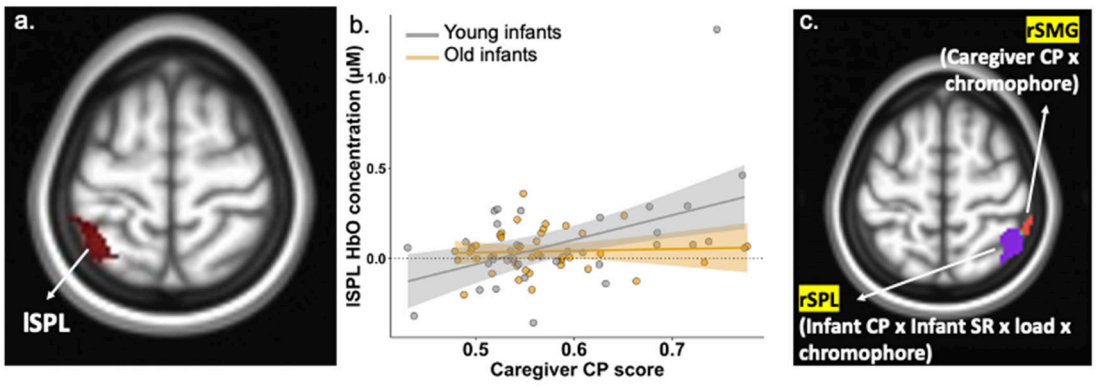


Figure 3.8 (a) Cluster showing a two-way interaction between caregiver CP score and chromophore in lSPL. (b) Follow-up of this two-way interaction showed that higher caregiver CP scores were associated with increasing lSPL HbO concentration in young infants only. (c) Spatial overlap (cyan cluster) between the rSMG cluster in caregivers (red cluster) and rSPL cluster in infants (purple cluster).

3.4.2.3 ROI brain analyses

Secondary brain analyses were run, focusing on ROIs from adult VWM literature (Wijeakumar, Magnotta, et al., 2015). These ROIs were overlayed with the caregiver and infant mask. For caregivers, there was an overlap between the caregiver mask and 5 ROIs: rTPJ, rMFG, rDLPFC, lTPJ, and lDLPFC. For each of these clusters, regression models were run with load, chromophore, and caregiver CP as predictors for each ROI. Here, there were no significant effects.

For infants, there was an overlap between the infant group mask and 7 ROIs: rTPJ, rsIPS, rMFG, rDLPFC, lIPS, lDLPFC, and laIPS. For these regions, regression models were run with load, chromophore, caregiver CP, infant CP, and infant SR as predictors for each ROI. Here again, there were no significant effects.

3.5 Discussion

The over-arching aim of this chapter was to investigate whether caregiver looking behaviours are associated with infant looking behaviours. To this end, caregivers and infants were individually presented with age-appropriate variants of a preferential looking task (Ross-Sheehy et al., 2003). Looking measures were extracted from video recordings, including CP score, a measure of the subject's ability to detect change; SR score, a measure of how frequently the subject switched between the two displays; and TLD score, a measure of the amount of time the subject explored the displays. fNIRS was also used to measure brain function across frontal, temporal, and parietal regions. Both a whole brain approach, and a secondary ROI-based approach were used to analyse the data.

This chapter had three research objectives. The first research objective was to investigate whether caregiver looking behaviours were associated with infant looking behaviours. Both caregivers and infants showed load-dependent modulation of CP scores. Notably, there were trends of both load-dependent and age-dependent modulation of SR score. Importantly, regression models revealed that greater CP scores in caregivers were associated with greater CP scores in infants at the low load. The second research objective was to examine whether caregiver behaviours were linked to infant brain function. Infants with lower SR scores showed greater activation the rSPL. Further, young infants with higher CP scores had lower SR scores and greater activation in the rSPL. Interestingly, caregiver CP scores were associated with increasing lSPL activation in young infants. The final research objective was to investigate whether there was any spatial and functional overlap in brain areas associated with looking behaviours in caregivers and infants. There was a spatial overlap between rSMG, which was linked to better CP scores in caregivers, and rSPL, which was linked to reduced SR scores in high CP young infants. These results are discussed below.

3.5.1 Association between caregiver and infant looking behaviours

The first research objective was to investigate whether caregiver looking behaviours were associated with infant looking behaviours. Across the task, caregivers and infants did not show load-modulation of TLD or SR scores. This task has not previously been used in adults; however, the absence of load-modulation suggests that

caregivers may adopt consistent exploration strategies across all load demands, resulting in stable TLD and SR scores. Previously, TLD score and SR score findings in children completing the preferential looking task have been inconsistent. One study found that infant SR score was modulated by load, but that TLD scores were not (Delgado Reyes et al., 2020), and another study reported that TLD score was modulated by load, but that SR score wasn't (Wijeakumar et al., 2019). It is possible that across different studies, which vary in age range, infants have relied on different strategies in completion of the preferential looking task, resulting in mixed findings. This suggestion also aligns with the finding here that with age, SR scores decrease.

Notably, CP scores showed consistent load effects in both caregivers and infants. This finding indicated that both caregivers and infants showed decreasing ability to detect and sustain attention towards the changing side, with increasing load. This result replicates previous findings in infants showing load-dependent changes in CP scores. Specifically, infants showed decreasing CP and SR scores with increasing load, consistent with previous work with infants in the first year of life (Delgado Reyes et al., 2020; Ross-Sheehy et al., 2003). Similarly, in caregivers, CP scores were significantly higher at the low load (four items) compared to medium and high loads, consistent with previous performance-based capacity estimates of three to five items from conventional VWM tasks (Cowan, 2001; Luck & Vogel, 1997).

There was also an association between caregiver and infant CP scores. Specifically, at the low load, higher CP scores in caregivers were associated with higher scores in infants, suggesting that better VWM in caregivers is linked to better VWM in infants. In general, this finding aligns with previous work on caregiver-child EF associations. For example, Cuevas, Deater-Deckard, Kim-Spoon, Watson, et al. (2014) examined associations between maternal EF and caregiving and child EF. Findings reported that by 24 months of age, mother and child EF was moderately correlated, and by 36 months of age, mother and child EF were robustly correlated. This finding also aligns with dyadic interaction studies that have found associations between caregiver gaze and attention on child development (Monroy et al., 2021; Schatz et al., 2022; Yu et al., 2019; Yu & Smith, 2016, 2017). For instance, (Yu & Smith, 2016) investigated how caregivers and infants co-ordinate attention during interactions with objects. Here, they found that joint attention, in which caregivers and infants jointly attend to the same object, was linked to infant subsequent sustained

attention. Specifically, almost two thirds of sustained attention periods in infants coincided with joint attention from the caregiver. Critically, the duration of joint attention predicted the duration of sustained attention, highlighting the caregiver's role in supporting and extending their infants sustained attention. Similarly, Monroy et al. (2021) also examined attention sharing behaviours between caregivers and infants, finding that infants predict their caregivers' actions, and that this anticipatory behaviour was also associated with increased infant-led joint attention. Building on these findings, infants of caregivers who demonstrate more complex input during object interactions, such as touching and verbalising around objects, also exhibit longer play bout durations (Schatz et al., 2022). Generally, these findings suggest that caregiver attention influences the attention of their infant. Collectively, this literature, and findings here, support the self-regulatory framework, which posits that attentional control, working memory, and flexibility processes must be self-regulated in the caregiver, as well as regulated between the caregiver and child during interactions (Calkins, 2011). Ultimately, this allows the caregiver to respond appropriately to their infants' cues. The findings of this chapter are novel, in the demonstration of a caregiver-infant association using comparable, but independent experimental paradigms.

More broadly, this afore-mentioned finding also contributes to literature suggesting that visual cognition is heritable (Chen et al., 2018; Constantino et al., 2017; Quinn et al., 2022). For example, one study extracted how often participants switched interpretations of two competing stimuli, otherwise known as perceptual rivalry, with genomic analyses estimating heritability to be 25% (Chen et al., 2018). Another study used a series of eye-tracking experiments in monozygotic and dizygotic twins. Here, monozygotic twins, who share close to 100% of their genetics, showed greater similarity in visual behaviours in comparison to dizygotic twins (Constantino et al., 2017). Similarly, another study reported moderate heritability in relation to visual-search performance (Quinn et al., 2022). Generally, these findings support that visual cognition is influenced by genetic factors.

3.5.2 Brain function in infants

The second research objective was to examine whether caregiver behaviours were linked to infant brain function. Better caregiver CP scores were associated with greater left-lateralized superior parietal engagement in infants. More generally, the

link between left parietal engagement and looking behaviour is in line with previous literature. This region is purported to be involved in visuo-spatial attention and working memory in children and adults. For example, in a recent study, infants of caregivers with lower inhibitory control demonstrated decreasing left parietal activation with increasing CP scores in the preferential looking task. These findings of left parietal engagement in infants are also in agreement with findings from cross-cultural samples (Delgado Reyes et al., 2020; Wijeakumar et al., 2023). Delgado-Reyes et al. showed load-dependent modulation of the lIPS from a small sample of U.S. infants and toddlers engaging with an adapted version of the same task. In a recent study conducted in 6- and 9-month-old infants in low-resource settings in rural India, age, load, and stunting status differentially modulated the laIPS (Wijeakumar et al., 2023). This region has also been linked to VWM processing in older children. For instance, McKay et al. (2021) showed that individual differences in VWM capacity was linked to individual differences in left parietal activation in pre-school children. More recent work has shown that children with early exposure to formal schooling showed greater engagement in the left parietal cortex, associated with greater improvement in non-symbolic numeracy abilities, compared to children who were enrolled in school later (Davidson, Shing, et al., 2023). In pre-school children, VWM-modulated left parietal activation has also been associated with household cognitive enrichment (Davidson, Caes, et al., 2023).

In the current study, interestingly, the association between caregiver looking behaviour and left parietal engagement in infants was observed in young, but not older infants, providing further support for the heritability of general visual cognition mechanisms (Chen et al., 2018; Constantino et al., 2017; Quinn et al., 2022). It is possible that very early on, there may only be a general heritability-related association between caregiver visual cognition and brain function in young infants. As the infant ages and becomes more mobile, it is possible that this association might become more shaped by social and environmental factors, eventually leading to load-dependent and behavioural performance related links reported in studies in older children.

3.5.3 Spatio-functional overlap between caregiver and infant brain regions

The final research objective was to investigate whether there was any spatial and functional overlap in brain areas associated with looking behaviours in caregivers and infants. Caregivers recruited large parts of the canonical visual cognition network

across the fronto-parieto-temporal cortices. Specifically, they showed increased activation in rIFG, lMOG, rIPL, and rSOG. The rIFG has been implicated in both attentional switching (Cools et al., 2002; Dove et al., 2000) and the detection of visual cues (Hampshire et al., 2010). Activation in the bilateral occipital cortex has also been associated with encoding (Pessoa et al., 2002) and consolidation (Makovski & Lavidor, 2014). Further, activation in the rIPL has been associated with both processing of spatial information (Köhler et al., 1995) and shifts of visuo-spatial attention (Corbetta et al., 1993; Nobre et al., 1997). It is possible that caregivers engage these regions during attentional shifting and item consolidation, as they switch between the two displays and process the items during the task.

Furthermore, caregivers showed decreased activation in the lSFG, rIPL, lIPL, and lSTG. Decreased activation has been observed in the bilateral posterior IPL in association with internal attention processes (Benedek et al., 2016). Further, decreased activation in the lSFG (Mayer et al., 2009; Tomasi et al., 2006) and lSTG (Mayer et al., 2009) has also been observed during attention and VWM tasks, thought to reflect the reallocation of cognitive resources from task-irrelevant to task relevant processes. Given that the caregivers were also given no instruction during the task, it is possible that these patterns of activation, occur because of switches between both externally directed and internally directed attention processes.

Caregivers also demonstrated performance-related activation in two regions. Specifically, increasing CP scores were associated with right-lateralized SMG activation and left-lateralized MFG suppression. Previous work has shown rSMG engagement is associated with allocating visuo-spatial attention and maintaining items in working memory (Berryhill & Olson, 2008; Corbetta et al., 2000; Corbetta & Shulman, 2002; Pisella, 2017; Ren et al., 2019). For instance, increased activation in the right parietal cortex has been observed when subjects direct attention to targets at specific locations during a detection task (Corbetta et al., 2000). Further, findings have reported impairments on VWM tasks as a result of right parietal lobe damage (Berryhill & Olson, 2008). In infants, left frontal engagement has been associated with poorer CP scores in infants, albeit in a sample of infants in rural settings in India (Wijeakumar et al., 2019). Specifically, they found that lDLPFC suppression was negatively correlated with CP scores – indicative of early distractor suppression. The authors speculated that children with greater abilities to detect the change might

suppress this region to reduce distraction to the unchanging side. This hypothesis is in line with other research that implicates the frontal cortex in suppression of distracting information (Cosman et al., 2018; Yamasaki et al., 2002). Taken together, these findings suggest that caregivers with better CP scores might have efficiently allocated visuo-spatial attention and regulated inhibitory control to suppress distraction, thus, detecting change and sustaining attention towards the changing side – leading to better VWM performance.

Given that both caregivers and infants show performance-related fronto-parietal engagement, spatial overlap between significant clusters were quantified. There was a spatial overlap between the rSMG cluster in caregivers and rSPL cluster in infants. While caregiver looking behaviour did not directly impact activation in this region in infants, there was an indirect alignment in its functional role in both caregivers and young infants. Importantly, in both caregivers and young infants, greater activation was linked to better performance estimates. This is consistent with findings that have associated activation in these regions with attentional control and EFs in both infancy (Delgado Reyes et al., 2020; Wijeakumar et al., 2019) and adulthood (Berryhill & Olson, 2008; Corbetta & Shulman, 2002; Coull & Frith, 1998; Pisella, 2017; Ren et al., 2019; Wang et al., 2015; Zago & Tzourio-Mazoyer, 2002). Although direct cross-age spatial comparisons are limited, the recurring engagement of parietal regions in both caregivers and infants during the same task suggests an early emerging functional specialisation in this region. Albeit in a different context, complementary evidence from inter-brain synchrony studies also supports alignment in the parietal cortex in caregivers and older children (Nguyen et al., 2020; Papoutselou et al., 2024; Piazza et al., 2020). It is possible that later in development, caregivers might more directly impact infant brain function, leading to more evident behavioural outcomes.

It is important to consider why brain findings in caregivers were not modulated by load, as expected from previous reports (Ambrose et al., 2016; Todd & Marois, 2004). This lack of load modulation in the brain results is surprising when considered alongside the interaction with CP score. Concretely, brain function was related to CP score, but in the behavioural results, CP score was modulated by load. It is possible that in adults engaging with this paradigm, changes in brain function are more representative of exploratory behaviours (allocating and re-orienting attention)

important for working memory processing, rather than a quantifiable increase in number of items consolidated in VWM. This view is consistent with the finding that other exploratory looking measures such as TLD and SR scores, did not show a significant change with increasing load. It is also possible that differences in experimental design can account for the differences in these findings. Specifically, in the preferential looking task, trial duration is longer, there is no explicit instruction to prepare for effort needed to meet challenging goals (with increasing load) and outcome estimates are derived from looking behaviours (as opposed to a decision of same/different or correct/wrong), compared to conventional experimental paradigms in adults.

3.6 Conclusions

The over-arching objective of the current study was to investigate whether caregiver looking behaviours are associated with infant looking behaviours. To this end, looking behaviours and brain function were measured from both caregivers and infants as they independently engaged with age-appropriate variants of a preferential looking task with a load manipulation. In the first finding, both caregivers and infants showed load-dependent modulation of looking behaviours. Importantly, better ability to detect in caregivers was associated with better ability to detect change in infants at the low load. In the second finding, better caregiver ability to detect change was directly associated with increasing left parietal activation in young infants. In the third finding, there was a spatial overlap in regions in the right parietal cortex associated with looking behaviours in caregivers and infants. These findings provide first evidence of a visual neurocognitive association between caregivers and their children in the first year of life.

3.7 Motivations for the Next Chapter

This chapter found associations between caregiver and infant visual neurocognition during an experimental preferential looking task. Specifically, better caregiver visual cognition was associated with better infant visual cognition at the low load. Further, caregiver visual cognition was associated with increasing activation in the left parietal cortex in infants. These findings suggest that there is a visual neurocognitive association between caregivers and infants in the first year of life. However, further investigation is required, to allow for a better understanding of how

caregivers' own visual cognitive abilities during naturalistic interactions influence their infants' visual cognition development. The next chapter in this thesis therefore aims to investigate how caregiver and infant behaviours and brain function during different types of object engagement during play interactions, influences infant visual cognition during the preferential looking task.

Chapter 4:

Modality-based differences during object engagement in caregiver-infant interactions

A version of this chapter is in preparation for publication

Theyer, A. & Wijeakumar, S. (in prep). Brain function underlying object engagement during caregiver-infant interactions.

4.1 Introduction

Over the first year of life, four key attentional functions are believed to develop: alertness, spatial orienting, attention to object features, and endogenous attention (Colombo, 2001). During this period, infants begin to explore their environments through brief, frequent, and varied play bouts with objects (Herzberg et al., 2022). As engagement and exploration increase, numerous opportunities arise for shared experiences with social partners, who can offer relevant context and guidance (Bruner, 1975; Vygotsky, 1997). Over the first few years, these interactions increase in complexity, as infants' play becomes more coordinated with their caregivers (Tamis-LeMonda & Bornstein, 1991). Importantly, developmental changes in dyadic play are influenced by independent developmental processes in each partner, as well as by the dynamic interactions between them (Tamis-LeMonda & Bornstein, 1991). Therefore, interactions between infants, objects, and knowledgeable social partners, are thought to play a key role in the development of object knowledge, motor skills, and increases in cognitive, social, and language abilities.

4.1.1 Modality-based differences in caregivers during object interactions

Research has demonstrated that caregiver attention plays a unique role in shaping infant attention (Farroni et al., 2000; Hood et al., 1998; Lansink et al., 2000; Scaife & Bruner, 1975; Yu & Smith, 2016). Furthermore, observations of caregiver-infant play have frequently highlighted gestural and verbal cues as important for shaping and scaffolding infant attention. For instance, moment-to-moment eye-tracking data has found that one-year-old toddlers were less likely to look towards their caregivers' face and more likely to attend to objects that they or their caregiver held (Yu & Smith, 2013). Further, caregivers' own hand-eye co-ordination was predictive of the proportion of time spent in joint attention with their infant. The authors proposed that early attention sharing may begin with gaze-following behaviours, but that in more complex interactions, infants may also rely on hand-following to coordinate visual attention (Yu & Smith, 2013). Along a similar vein, infants showed a preference for looking at their caregivers' physically handling objects, as opposed to static objects, their caregiver's body, or their own body (Deák et al., 2014). Further, when infants looked at the caregiver whilst they were looking at their own hands, the infant often directed their next eye movement towards the object that the caregiver was handling. The authors proposed that the link between

caregiver's gaze direction and interesting objects, such as toys, may reinforce the development of infants' abilities to follow hand- and eye-movements. This theory is further supported by research that has found that 9-month-old infants begin to anticipate their caregivers' actions during play interactions (Monroy et al., 2021). Critically, the frequency at which they do so was associated with increased bouts of child-led joint attention, in which attention was initiated by the infant and proceeded by the caregiver. Collectively, these findings emphasise the importance of caregiver manual engagement, on infants' abilities to learn to follow visual and manual cues.

Another critical and well-emphasized component of caregiver engagement is the use of speech during dyadic interactions. Alongside manual handling of objects, caregiver verbalisations have also been associated with prolonged sustained attention in infants. For example, in a recent study, 13-, 18-, and 23-month-old infants and their caregivers were recorded during everyday activities in their homes to investigate variations in infant object engagement alongside different levels of caregiver engagement (Schatz et al., 2022). The authors found that 'multimodal' input, referring to the combination of caregiver touch/gestures and verbalisations, was associated with play bouts lasting 7.5 times longer than play bouts in the absence of caregiver input. Further, object-specific verbalisations were also associated with longer play durations. An eye-tracking study in 12- to 24-month-olds has also investigated the relationship between the duration of infant attention bouts both with and without caregiver speech (Schroer & Yu, 2022). They found that infant visual attention, joint attention, and sustained attention periods were all significantly longer when accompanied by caregiver speech compared to without caregiver speech. Collectively, these findings indicate that multimodal caregiver engagement combining gaze, object-associated manipulation, and verbalisations impacts infant engagement during interactions.

4.1.2 Modality-based differences in children during object interactions

Developmental changes in dyadic play are thought to be influenced by both independent developmental processes and by dynamic interactions between each partner (Tamis-LeMonda & Bornstein, 1991). To better understand the reciprocal nature of these interactions, it is critical to also consider the nature of infant engagement behaviours. While research has shown that caregivers rapidly shift attention between their infants and objects, reflecting their goals of monitoring both, infants spend more time attending to objects, aligning with their primary focus of

exploring toys (Yu & Smith, 2016). During this exploration, infants frequently hold and manipulate objects (Yu et al., 2009; Yu & Smith, 2013, 2017). This exploratory behaviour is thought to support infants' processing of objects by enabling them to learn about object properties (Needham, 2000; Palmer, 1989). In early development, infant interactions with objects progress from basic exploration to object-specific actions, such as twisting or pulling on lids (Rachwani et al., 2020). Critically, manual exploration has been linked to later cognitive development (Ruff et al., 1984). These findings highlight the importance of infants' combined visual and manual engagement in learning how to interact with everyday objects.

In addition to manual engagement, research has also explored the significance of infant vocalisations within caregiver-infant interactions. For example, studies have highlighted the importance of infant vocalisations during interactions with partners for later play and language development. In one study, caregiver-infant dyads were observed once every two weeks between the ages of 6 and 18 months (Orr & Geva, 2015). The onset and frequency of early, simple symbolic play was linked to the onset and frequency of later-emerging, complex symbolic behaviours, and vocalisations, such as babbling, speech, and multi-object play. In another study, the authors investigated the link between infant vocalisations and gestures, caregiver responses, and later vocabulary development (Donnellan et al., 2020). Gaze-coordinated vocalisations at 12 months, proposed to be indicative of intentional communication, predicted vocabulary size at 24 months. Notably, caregivers were more likely to respond to gaze-coordinated behaviours, and the combination of gaze-coordinated vocalisations and caregiver responses was the strongest predictor of vocabulary size at 24 months. While some studies highlight the importance of infant vocalisations, others suggest that this may not be driven by social interactions with caregivers. For example, infants have been shown to produce more vocalisations during low-social contexts, such as when caregivers are present but silent (Oller et al., 2013) or when playing alone with toys rather than during social engagement (Harold & Barlow, 2013). Thus, whether infant vocalisations emerge independently of caregiver engagement, and what role these play within interactions, remains unclear.

4.1.3 Brain function underlying modality differences during object interactions

Despite a wealth of research examining caregiver-infant engagement during object-based interactions, the neural mechanisms underlying these social interactions

remain unclear. Furthermore, neuroimaging research that focuses upon brain activation in both caregiver's and infants during dyadic interactions is limited (Michel et al., 2024; Wass, Noreika, et al., 2018). Thus far, research has highlighted that caregiver input during dyadic play is associated with variations in infant brain activity associated with attention and learning. For instance, research using EEG has identified differences in neural activity when caregivers joined their infants during play (Wass, Noreika, et al., 2018). Here, infant theta power lesser predicted visual attention in joint play in comparison to solo play, suggesting that during solo play, infants had greater endogenous control over attention. Furthermore, caregiver input, such as the use of ostensive signals, has also been shown to influence infant neural activity (Michel et al., 2024). Here, during social interactions between caregivers and infants, infant theta activity synchronised. Further, increased infant theta activity during encoding also predicted object encoding abilities. While these findings underscore the importance of understanding how caregiver input might shape the neural processes underlying infant attention and learning, there remains a gap in our understanding of how varying levels of caregiver engagement shape infant neural activity during social interactions. Critically, despite research highlighting that multimodal engagement scaffolds infant play durations and complexity (Schatz et al., 2022; Schroer & Yu, 2022; Suarez-Rivera et al., 2019), to current knowledge, no study has directly compared brain function underlying modality differences during caregiver-infant interactions.

4.2 Research Objectives

Previous research has highlighted the importance of caregiver object manipulation (Deák et al., 2008, 2014; Yu & Smith, 2013) and speech (Schroer & Yu, 2022) on infant attention during dyadic interactions. Critically, the combination of gaze, physical manipulation, and verbalisations, otherwise known as 'multimodal engagement' has been shown to lead to play bouts lasting significantly longer in comparison to those without (Schatz et al., 2022). Whilst there is a wealth of research that has examined caregiver-infant behaviours in the later infancy/toddlerhood period (Herzberg et al., 2022; Rachwani et al., 2020; Schatz et al., 2022; Schroer & Yu, 2022; Suarez-Rivera et al., 2019; Tamis-LeMonda & Bornstein, 1991; Yu & Smith, 2013, 2016), there is less work examining dyadic interactions between 6 and 10 months (Michel et al., 2024; Monroy et al., 2021), a key transitional phase for visual cognitive

development. Moreover, neuroimaging research that focuses on brain activation in both caregivers and infants during dyadic interactions is limited (Michel et al., 2024).

To address these gaps, this chapter aims to examine duration of, and brain function underlying different types of object engagement in caregivers and infants. The chapter focusses on three types of behaviours - unimodal (look only), bimodal (look and touch), and multimodal (look, touch, and verbalisations/vocalisations) engagement in both partners. Following this, it examines whether the duration of, and underlying brain function during these behaviours are predictive of infant VWM (Chapter 3). To this end, video recordings and brain function data were collected from caregivers and infants while they naturalistically engaged each other with objects. Further, VWM in infants was measured through eye movements as they engaged with an experimental preferential looking task – see Chapter 3 (also Theyer et al., 2024).

This chapter had four key research objectives. The first objective was to examine whether there was a difference in the duration of unimodal, bimodal, and multimodal engagement in infants and caregivers. In line with existing literature (Yu et al., 2009; Yu & Smith, 2013, 2017), it was expected that caregivers and infants would show longer durations of bimodal compared to unimodal and multimodal engagement. The second objective was to identify key brain regions engaged in caregivers and infants during each modality. To current knowledge, no study has directly examined brain function underlying modality differences during caregiver-infant interactions, thus limiting the generation of strong predictions here. More generally findings have reported caregiver input shapes infant brain activity during interactions (Michel et al., 2024; Wass, Noreika, et al., 2018). Here, it was therefore speculated that both caregivers and infants would show increasing bilateral fronto-parietal activation with increasing complexity of modality (unimodal to multimodal engagement). The third objective was to examine whether there were any behaviour-brain associations i.e. between duration of modality engagement and fronto-parietal activation in caregivers and infants. The final research objective was to examine whether afore-mentioned caregiver-infant behaviours and brain function was associated with infant VWM. An exploratory approach was taken for addressing the third and fourth objectives due to the absence of related evidence to drive predictions.

4.3 Materials and Methods

4.3.1 Participants

This chapter is part of a larger longitudinal project. Please refer to Chapter 3, Section 3.3.1 *Participants*, for details on recruitment criteria. For this study, the final sample consisted of 90 families (90 caregivers: 89 female and 1 non-binary, mean age: 33.50 ± 4.45, age range: 22 – 46 years; 91 infants: 46 female, mean age: 8.26 ± 1.15 months, age range: 6.08 – 10.45 months, including one pair of twins).

Demographic and SES information is provided in *Table 4.1*. Caregivers provided written informed consent prior to participation in the study and received £10 following each visit. Data collection was carried out at the University of Nottingham. Ethics approval was provided by the Research Ethics Committee at the University of Nottingham (Ethics Approval Number: F1338).

Table 4.1 Socioeconomic and demographic information was collected via questionnaire after the family visited the research facility.

Family Member	Measure	N	Mean	± SD
Infant	**Age (months)**	91	8.26	1.15
Primary Caregiver	**Age (years)**	90	33.50	4.45
	Education (years)	78	16.23	2.34
	Income	71	£27,638	£13,349
Secondary Caregiver	**Education (years)**	77	13.83	4.32
	Income	51	£31,504	£11,669
Primary Caregiver	**Ethnicity**	**N**	**%**	
	Arab	1	1%	
	Asian	5	6%	
	Mixed	4	4%	
	White British	67	74%	
	Other White	1	1%	
	Did not answer	12	13%	

4.3.2 Caregiver-infant dyadic interactions

Caregivers were asked to naturalistically engage their infants with a selection of 6 objects (butterfly, car, gears, teething ring, cup, and worm) – see *Figure 4.1*. These toys were selected because they were appropriate for infants between the ages of 6 and 10 months and are used routinely in home settings (based on popularity on sales websites). The play interaction lasted for a maximum of 7 minutes. However, some

interactions were terminated earlier if the infant became fussy. To be included in analyses, the families had to have a minimum of 5 minutes of interaction time. As a result, five families were excluded from analyses due to the interaction time being too short. Further, two more families were excluded due to experimenter error. This resulted in 84 families contributing play interaction data (82 families: 7 minutes; 1 family: 6 minute 15 seconds; 1 family: 5 minutes 20 seconds).

Two video cameras were used to record the interaction. One video camera was placed closer to the dyad and offered a better view of the objects on the table, and another video camera was placed further away from the dyad to capture the full scene. These recordings were captured using Bandicam (https://www.bandicam.com/) and Movavi programs (https://www.movavi.com/mac/) and presented in real-time to the experimenter so that they could monitor the interactions. In addition, when possible, caregivers wore a head-mounted camera (Kassner et al., 2014). This video was used as a third angle to confirm details that were not evident from the other two video recordings. PsychoPy software (v2021.2.3) was used to generate a flash and an audio tone on a TV to indicate the start and end of the interaction.

fNIRS data was collected from both caregivers and infants during dyadic interactions using the NIRScout System (wavelengths 760 nm and 850 nm). The probe geometry consisted of 8 sources and 8 detectors each for caregivers and infants, creating 10 channels overlaying the frontal, temporal, and parietal cortices – see *Figure 4.1* (c-d). Multiple cap sizes were used to accommodate for the varying head sizes (caregivers: 54 cm, 56 cm, and 58 cm and infants: 42 cm, 44 cm, 46 cm, 48 cm, 50 cm, and 52 cm). Source-detector separation was scaled according to cap size (e.g., 48 cm: 2.4 cm, 50 cm: 2.5 cm, 52 cm: 2.6 cm, 54 cm: 2.7 cm, 56 cm: 2.8 cm, 58 cm: 2.9 cm).

4.3.3 Infant preferential looking task

To measure VWM, infants were presented with the preferential looking task (Ross-Sheehy et al., 2003). This task is described in detail in Chapter 3, Section 3.3.2 *Infant and caregiver preferential looking tasks*.

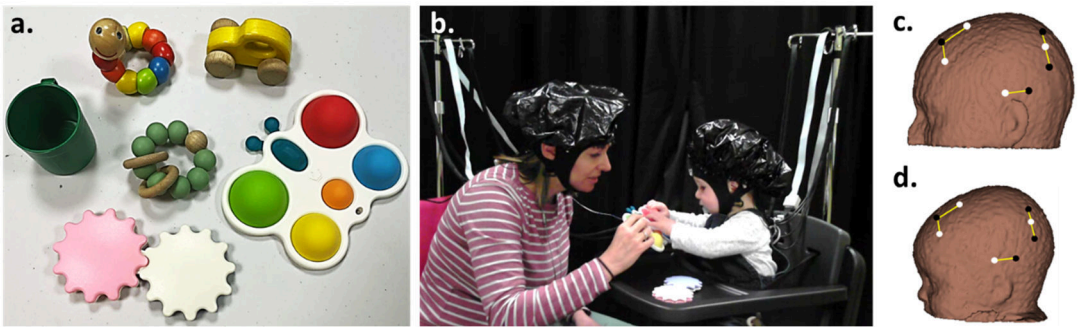


Figure 4.1 (a) Butterfly, car, gears, teething ring, cup, and worm toys used in dyadic interaction and (b) example of caregiver-infant dyadic interaction. fNIRS probe geometry with channels covering frontal, temporal, and parietal regions used for (c) caregivers and (d) infants during the dyadic interactions. White dots indicate sources, black dots indicate detectors, and yellow connections indicate channels.

4.3.4 Procedure

Data collection procedures for the infant preferential looking task are described in detail in Chapter 3, Section 3.3.4 *Procedure*. For the dyadic interaction, caregivers were then seated on a chair next to a table where the objects were placed and infants were either seated in a highchair with a tray attachment opposite their caregivers or on their caregiver's lap, if they were fussy. The experimenters then placed the fNIRS cap onto the caregivers' head. Following this, the experimenters then placed the fNIRS cap onto the infants' head and commenced the interaction. During the interaction, caregivers were asked to engage their infants with the given objects as they normally would. Throughout, one experimenter was responsible for presenting the task and monitoring the interaction using the video recordings and the other experimenter monitored the fNIRS signals.

In most cases, the infant preferential looking task was presented first, the caregiver preferential looking task second, followed by the dyadic interactions. However, this was worked around caregivers' preference and infant fussiness/fatigue. For example, if during the preferential looking task, the infants became fussy, or tired, and/or the caregiver wanted to try another day, this data was collected at another closely spaced visit, as per the caregivers' convenience. Families received £10 for each additional visit.

4.3.5 Data analyses

4.3.5.1 Modality coding scheme

Caregiver and infant engagement during the play interactions were coded using DataVyu software (https://datavyu.org/). Two coders were trained to code the interaction data. One coder coded all participants, and another coder coded 23% of the data. Reliability was computed using Cohen's Kappa, a statistic that looks at percent agreement across categories normed by the base rate of each category. The formula for Cohen's Kappa and statistics with corresponding agreement levels are described in Chapter 3, Section 3.3.5 *Behavioural analyses* (see *Formula 3.1* and *Table 3.2*). For caregiver data, the mean Kappa value was 0.96 and for infant data, the mean Kappa value was 0.96. The Kappa value for both caregiver and infant data therefore indicated near perfect agreement (0.81 to 0.99). Each play interaction was divided into 5-second epochs.

For the Modality analyses, looks, touches, and verbalisations/vocalisations were coded. Each epoch was coded into one of 9 engagement categories for each infant and caregiver separately (see *Table 4.2*). If the infant/caregiver gazed towards an object during the epoch, it was classed as a look (code 'L'). If the infant/caregiver touched an object during the epoch, it was classed as a touch (code 'T'). Touch was identified as any intentional manual contact made with the object(s) during the epoch. If the caregivers made any object-specific verbalisations during the epoch, it was classed as a verbalisation (code 'V'). Examples include caregivers naming the object (e.g., "look at the butterfly"), describing the object properties (e.g., "can you point towards the green one?"), describing actions that could be completed with the object (e.g. "these can spin around"), or providing a narrative associated with the object (e.g., "we were driving earlier" when engaging with the object car). If the infant vocalised whilst engaging with the objects during the epoch, it was classed as a vocalisation (code 'V'). Vocalisations could include sounds or babbling made by the infant as they engaged with an object. Vocalisations did not include general noises such as sighing, crying, or laughing. If more than one category applied, this was represented either as codes 'LV', 'LT', 'TV' or 'LTV' depending on the combination of behaviour codes. Finally, epochs that could not be coded were classed as 'X', referring to no engagement behaviour being present (e.g., no interaction with any objects, looking around the room), or as 'N', referring to non-codable data (e.g., researcher interrupts

during the epoch, infant distracted by fNIRS cap/wires or fussy for greater than half of the epoch).

For each dyad, the duration of engagement for each category was extracted in seconds for caregivers and infants. To convert epochs into seconds, the total number of epochs was multiplied by 5 (as each epoch length was 5 seconds). For infants, L accounted for 12.2%, LT for 80.3%, and LTV for 3.5% of the interactions, and for caregivers, L accounted for 15%, LT for 61.6%, and LTV for 20.9% of the interactions. For both infants and caregivers, all other categories (LV, T, TV, and V) each accounted for less than 2.4% of the interactions. Therefore, only L (referred to as unimodal engagement), LT (referred to as bimodal engagement), and LTV (referred to as multimodal engagement) codes were focused on for further analyses.

In addition to engagement categories, the object(s) that caregivers and infants interacted with during each epoch (butterfly: code ‘B’, car: code ‘C’, gears: code ‘G’, teething ring: code ‘R’, cup: code ‘S’, and worm: code ‘W’) were coded. If infants interacted with more than one object, this epoch was coded as a combination of the codes (e.g., BC). Note that it was possible for caregivers to interact with a maximum of all 6 toys in one epoch (e.g. BCGRSW). This object-coding was only relevant for later analyses in Chapter 5.

Table 4.2 Behaviour codes and their descriptions. * Indicate unimodal (code L), bimodal (code LT), and multimodal (code LTV) engagement periods used in further analyses.

Code	Description
L*	**Look:** Caregiver/infant gazes towards the object during the epoch.
T	**Touch:** Caregiver/infant makes any intentional manual contact with the object during the epoch.
V	**Verbalisation** (caregivers only): The caregiver makes any object-specific verbalisations during the epoch - naming the object, describing object properties, describing actions that could be completed with the object, or providing a narrative associated with the object (e.g. "look at the butterfly", "can you point towards the green one?", "these can spin around", "we were driving earlier today").
	Vocalisation (infants only)**:** The infant vocalises or babbles whilst engaging with the object (e.g. "ah", "ooh"). This does not include general noises such as sighing, crying, or laughing.
LT*	Caregiver/infant demonstrated both **look** and **touch** behaviours during the epoch.
LV	Caregiver/infant demonstrated both **look** and **verbalisation/vocalisation** behaviours during the epoch.
TV	Caregiver/infant demonstrated both **touch** and **verbalisation/vocalisation** behaviours during the epoch.
LTV*	Caregiver/infant demonstrated **look**, **touch,** and **verbalisation/vocalisation** behaviours during the epoch
X	Exclusion: Caregiver/infant does not show any look, touch, or verbalisation/vocalisation behaviours with any object during the interaction.
N	Exclusion: Other reasons such as experimenter interrupts during the epoch, infant is distracted by cap/wires or fussy for greater than half of the epoch.

4.3.5.2 Infant looking behaviour analyses

Behavioural analyses for the infant preferential looking task are described in detail in Chapter 3, Section 3.3.5 *Behavioural analyses*. Previous work (Delgado Reyes et al., 2020; Ross-Sheehy et al., 2003; Wijeakumar et al., 2019, 2023) has demonstrated that CP scores scale by memory load. Similarly, in Chapter 3, infants had higher CP scores at the low, in comparison to the medium and high loads. Further, there was an association between caregiver and infant CP score at the low load. These observations suggest that CP scores at the low load are a key indicator of infant perceptual and cognitive abilities. Thus, in this chapter, infant CP scores at the low load were used for further analyses. Note that as only CP scores were used for further analyses, the term VWM is used in this context.

4.3.6 fNIRS data analyses

4.3.6.1 Pre-processing

Onsets of unimodal, bimodal, and multimodal engagement periods that lasted for two epochs or more (at least 10 s) were inserted into caregiver and infant fNIRS data. *Table 4.3* provides details regarding the number of instances and duration of each engagement category (following the initial epoch onset). To remove noise, artefacts and other confounding signals, all fNIRS data was pre-processed in *EasyNIRS* using Homer2. Raw data was pruned to remove noisy channels (dRange = 0.03–2.0; SNRthresh = 2; caregiver SDrange = 2.5–4.5 and infant SDrange = 2-3). 0.62 % of the infants' and 0.48 % of the caregivers' channels were pruned. Raw intensity values were converted to optical density units. Targeted principal component analyses were used to detect and remove motion artifacts (tMotion = 1, tMask = 1, STDEVthresh = 50, AMPthresh = 0.5, nSV = 0.97, maxIter = 5). The data were then scanned again for remaining motion artifacts (tMotion = 1, tMask = 1, STDEVthresh = 50, AMPthresh = 0.5). The StimRejection function was used to reject uncorrected motion artifacts (tRange = -1–18). The data were then band pass filtered (hpf = 0.016, lpf = 0.5). Pre-processed optical density time-series data were then used for image reconstruction described below.

Following pre-processing, the percentage of infant data lost was 6.63% for unimodal, 3.89% for bimodal, and 1.72% for multimodal engagement. The percentage of caregiver data lost was 0.41% for unimodal, 0.90% for bimodal, and 0.64% for multimodal engagement. 69 caregivers contributed unimodal fNIRS data, 84 caregivers contributed bimodal fNIRS data, and 78 caregivers contributed multimodal fNIRS data. Further, 61 infants contributed unimodal fNIRS data, 81 infants contributed bimodal fNIRS data, and 22 infants contributed multimodal fNIRS data. Overall, caregivers contributed an average of 4 events for unimodal, 9 events for bimodal, and 4 events for multimodal engagement, and infants contributed an average of 3 events for unimodal, 7 events for bimodal, and 3 events for multimodal engagement.

Table 4.3 Summary statistics for the number of instances and duration of engagement across each category for caregivers and infants.

Engagement category	**Count**	**Minimum**		**Maximum**		**Median**		**Mean**		**Mode**	
	N	*Epochs*	*Seconds*	*Epochs*	*Seconds*	*Epochs*	*Seconds*	*Epochs*	*Seconds*	*Epochs*	*Seconds*
Caregiver unimodal	244	2	10	11	55	2	10	3.09	15.47	2	10
Caregiver bimodal	775	2	10	36	180	4	20	5.11	25.55	2	10
Caregiver multimodal	311	2	10	12	60	2	10	3.09	15.47	2	10
Infant unimodal	180	2	10	25	125	3	15	3.31	16.55	2	10
Infant bimodal	565	2	10	84	420	6	30	11.5	57.52	2	10
Infant multimodal	58	2	10	8	40	2	10	2.68	13.41	2	10
All modalities	2133	2	10	84	420	3	15	4.8	24	2	10

4.3.6.2 fNIRS image reconstruction

Channel-based fNIRS data was converted to voxel-wise fNIRS data using the same image reconstruction pipeline outlined in Chapter 3, Section 3.3.6.2 *fNIRS image reconstruction*. A general linear model with three regressors (unimodal, bimodal, and multimodal engagement) was separately run for each chromophore and each infant/caregiver. Each trial was modelled with a 10 s boxcar using a hemodynamic response function derived from diffuse optical imaging (Eggebrecht et al., 2014). Note that 10 seconds was also the most frequent duration for each engagement category (see Modal values – *Table 4.3*). This step generated beta coefficient images for each condition, chromophore, and infant/caregiver. Resulting beta coefficient maps were registered to the MNI space and used in the whole brain analyses described below.

4.3.6.3 Whole brain analyses

To standardise across multiple participants, a group mask was calculated separately for caregivers and infants. This was done by masking and summing beta maps representative of each age-specific atlas and extracting voxels that contained data from at least 65% of the participants. Only data from these voxels were used for the whole brain analyses.

To identify key brain regions engaged in caregivers and infants across different modalities, separate linear mixed effects models were run for caregivers and infants (in AFNI using *3dLME)*. Here, interaction effects that included chromophore were examined. Resultant images were thresholded at a cluster-wise threshold (10 voxels) and a voxel-wise p-value of <.05 (using *3dClustSim* in AFNI) to identify localized, significant brain regions. Average HbO and HbR concentration was extracted from voxels in these regions (using *3dROIstats* in AFNI) and followed up using regression models described in Section 4.3.7 *Statistical analyses* to meet proposed objectives.

4.3.7 Statistical analyses

Statistical analyses were run using RStudio (v2023.03.0).

For duration of modality engagement and brain data, values that fell outside of ± 3 SDs from the mean were identified as outliers and removed prior to statistical analyses. After outlier corrections, 84 caregivers contributed data for unimodal, 84 caregivers contributed data for bimodal, and 84 caregivers contributed data for

multimodal engagement. 82 infants contributed data for unimodal, 82 infants contributed data for bimodal, and 82 infants contributed data for multimodal engagement. Number of caregivers and infants contributing brain data varied by HbO/HbR concentration, clusters, and modality periods. Across these factors, the average number of caregivers/infants contributing brain data was 63 (range: 21-83). For infant CP score, 86 infants contributed data for the low load.

To examine differences between durations of engagement categories, ANCOVAs were run separately for caregivers and infants, with engagement category as a within-subjects factor and infant age as a covariate. Following this, ANCOVAs were also run separately with infant engagement category categorised by the caregiver engagement category as a within-subjects factor and infant age as a covariate. Following this, to investigate the link between caregiver and infant engagement, regression models were run, with infant engagement duration as the outcome, caregiver engagement duration and engagement category as predictors, and infant age as a covariate.

Next, to examine key brain regions engaged in caregivers and infants across different modalities, separate linear mixed effects models were run for caregivers and infants in AFNI. Each model contained modality (unimodal, bimodal, and multimodal) and chromophore (HbO and HbR) as multi-level factors. Average HbO and HbR concentration was then extracted from voxels in these clusters (see Section 4.3.6.3 *Whole brain analyses*). Significant clusters were followed up to examine whether effects survived at the cluster level (as opposed to the voxel-level). Clusters showing a chromophore main effect were followed up using pairwise comparisons. Clusters showing an interaction effect were followed up using regression models. To examine associations between caregiver and infant engagement and fronto-parietal activation, regression models were run. Similarly, to examine associations in frontal and parietal activation in infants, regression models were run.

Finally, to examine whether caregiver-infant behaviours and brain function predicted infant VWM, regression models were run to examine caregiver-infant brain-behaviour associations in relevant clusters. The number of caregivers and infants included in each analysis is presented in *Table 4.4*.

Table 4.4 Number of caregivers and infants contributing to each category.

Section	Variables	Caregiver	Infant
Behaviour data	Unimodal	84	82
	Bimodal	84	82
	Multimodal	84	82
Brain data	Unimodal	69	61
	Bimodal	84	81
	Multimodal	78	22
Preferential looking task	Low load		86

4.4 Results

4.4.1 Difference between duration in engagement categories

The first research objective was to examine whether there was a difference in the duration of unimodal, bimodal, and multimodal engagement in infants and caregivers. To investigate this, an ANCOVA with engagement category as a within-subjects factor and infant age as a covariate was run for caregivers and infants separately.

For caregivers, there was a main effect of engagement category ($F_{(2,248)}$ = 352.23, $p < .001$). Post-hoc tests revealed that duration of bimodal engagement was significantly greater than duration of multimodal ($p < .001$) and unimodal ($p < .001$) engagement, and duration of multimodal engagement was significantly greater than duration of unimodal engagement ($p = .009$) – see *Figure 4.2* (a). For infants, there was a main effect of engagement category ($F_{(2,244)} = 1062.96$, $p < .001$). Post-hoc tests revealed that duration of bimodal engagement was significantly greater than duration of unimodal ($p < .001$) and multimodal ($p < .001$) engagement, and duration of unimodal engagement was significantly greater than duration of multimodal engagement ($p < .001$) – see *Figure 4.2* (b). Caregivers and infants therefore spent the greatest amount of time both looking at and touching the objects.

Next, to examine whether the duration of time infants spent in each engagement category varied depending on the concurrent caregiver engagement category, infant engagement durations were compared across periods of caregiver unimodal, bimodal, and multimodal interactions. To do this, infant engagement durations were therefore grouped according to the concurrent caregiver engagement

category. Separate ANCOVAs with infant engagement category as a within-subjects factor and infant age as a covariate were run for caregiver unimodal, bimodal, and multimodal engagement. For caregiver unimodal engagement, there was a main effect of infant engagement category ($F_{(2,243)} = 146.64$, $p < .001$) – see *Figure 4.2* (c). During caregiver unimodal engagement, the duration of infant bimodal engagement was greater than multimodal ($p < .001$) and unimodal ($p < .001$) engagement. For caregiver bimodal engagement, there was a main effect of infant engagement category ($F_{(2,245)} = 437.58$, $p < .001$) – see *Figure 4.2* (d). During caregiver bimodal engagement, the duration of infant bimodal engagement was greater than unimodal ($p < .001$) and multimodal ($p < .001$) engagement. Further, the duration of infant unimodal engagement was greater than multimodal engagement ($p < .001$). For caregiver multimodal engagement, there was a main effect of infant engagement category on infant duration ($F_{(2,243)} = 190.04$, $p < .001$) – see *Figure 4.2* (e). During caregiver multimodal engagement, the duration of infant bimodal engagement was greater than unimodal ($p < .001$) and multimodal ($p < .001$) engagement. To summarise, regardless of caregiver engagement category, infants showed greater bimodal compared to unimodal or multimodal engagement.

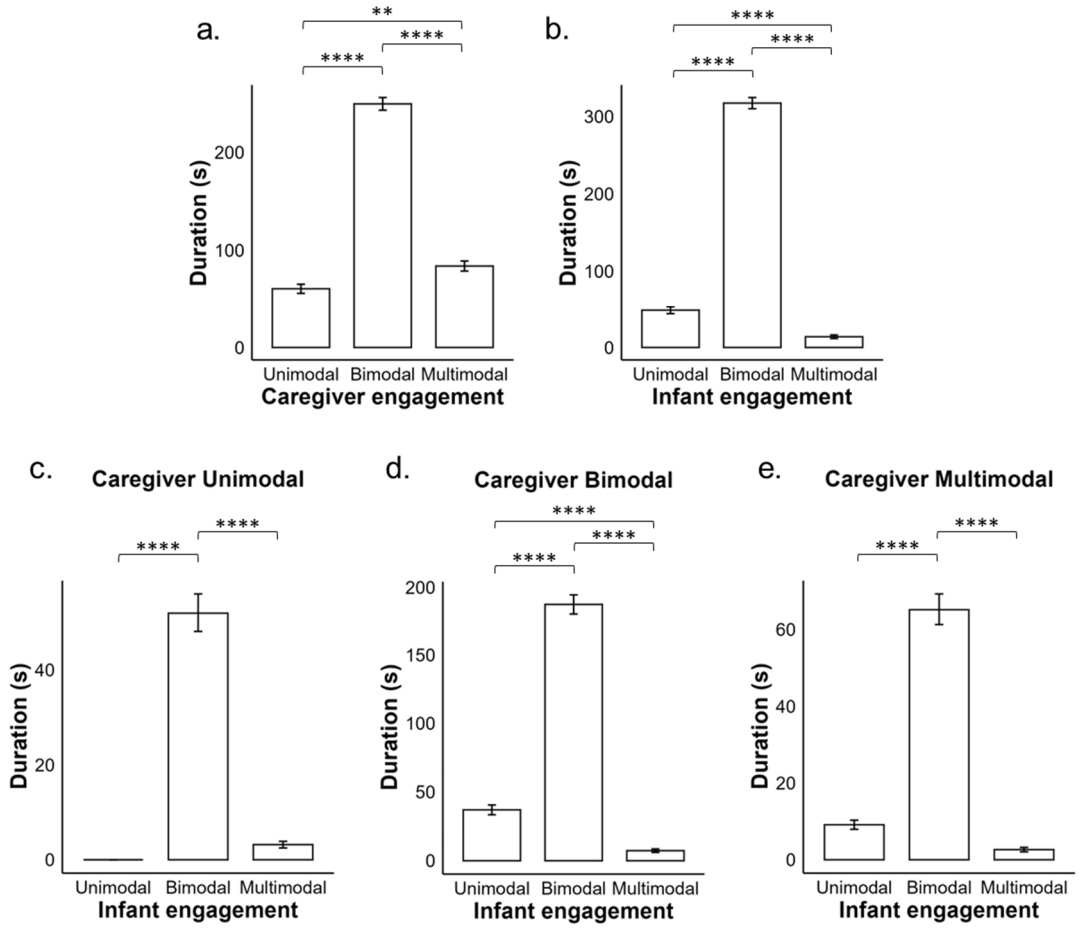


Figure 4.2 Duration of unimodal, bimodal, and multimodal engagement for (a) caregivers and (b) infants. (c-e) Infants engagement categorized by caregiver engagement category. ** $p < .01$, **** $p < .0001$.

4.4.2 Differences in brain function during engagement categories

The second research objective was to examine key brain regions engaged in different engagement categories in caregivers and infants. To do this, separate linear mixed effects models were run to investigate the main effects of and interaction between engagement category and chromophore, for caregivers and infants. Each model had engagement category (unimodal, bimodal, and multimodal) and chromophore (HbO and HbR) as multi-level factors. Here, the main effect of chromophore (indicative of common activation across engagement categories) and interaction between chromophore and engagement category (indicative of differences in activation between engagement categories) were the foci of interest. Cluster information for all effects from both models are shown in *Table 4.5*.

Table 4.5 Significant clusters in the caregiver and infant brain models. * Indicates effects that yielded significant results after follow-up tests, whilst controlling for infant age.

Model	Effect	Cluster	Size (mm^3)	MNI coordinates		
				Centre of Mass		
				x	y	z
Caregiver	Chromophore	Right angular gyrus (rAG)*	41	-48.3	+64.2	+45.6
Infant	Chromophore	Left superior parietal lobule (lSPL)	163	+28.3	+65.1	+57.5
		Right angular gyrus (rAG)	133	-40.3	+65.2	+47.8
		Left middle frontal gyrus (lMFG)	13	+31.4	-35.8	+44.3
	Chromophore x Modality	Right middle frontal gyrus (rMFG)*	598	-27.2	-39.4	+42.8
		Right angular gyrus (rAG)*	143	-36.6	+64.9	+51.8
		Left superior parietal lobule (lSPL)	68	+30.0	+67.8	+53.7

In caregivers, there was a main effect of chromophore in one cluster in the rAG. The follow-up test revealed greater HbO concentration compared to HbR concentration in this region ($t(161) = 2.52$, $p = .013$) – see *Figure 4.3* (a). This finding indicated that across all modalities, caregivers engaged the rAG.

In infants, there was a main effect of chromophore in three clusters. i.e. lSPL, rAG, and lMFG. However, follow-up tests did not reveal significant chromophore differences in any of the regions.

For infants, there was also a significant interaction between chromophore and engagement category in three clusters, rMFG, rAG, and lSPL. Follow-up tests were run on the average HbO/HbR concentration across voxels. First, each cluster was checked to ensure that the interaction was still significant for averaged HbX concentration across voxels in each cluster. The interaction was significant only for the rAG ($F_{(4,314)} = 3.71$, $p = .003$, $\eta^2 = .03$) and rMFG ($F_{(4,317)} = 3.68$, $p = .013$, $\eta^2 = .02$) – see *Figure 4.3* (b-c). Next, the difference between HbO and HbR concentration was examined for each engagement category for each cluster. Only for multimodal engagement, HbO concentration was significantly greater than HbR concentration (*p*

= .040, η^2= .10) in the rMFG, HbR was marginally greater than HbO concentration, with a trend towards statistical significance in the rAG (p = .054, η^2= .09). Then, differences between engagement category were examined for each chromophore for each cluster. There were differences between engagement categories only in the rMFG. Specifically, HbO concentration during multimodal engagement was significantly greater than HbO concentration during unimodal ($t(15) = -2.72$, p = .047) and bimodal engagement ($t(20) = -2.71$, p = .040).

To summarise, in caregivers, all engagement categories elicited rAG activation, and in infants, there was greater activation in the rMFG and a trend towards greater suppression in the rAG, during multimodal engagement, compared to other engagement categories. Given that significant effects were consistently observed for HbO concentration across relevant comparisons, subsequent analyses focused on this chromophore only.

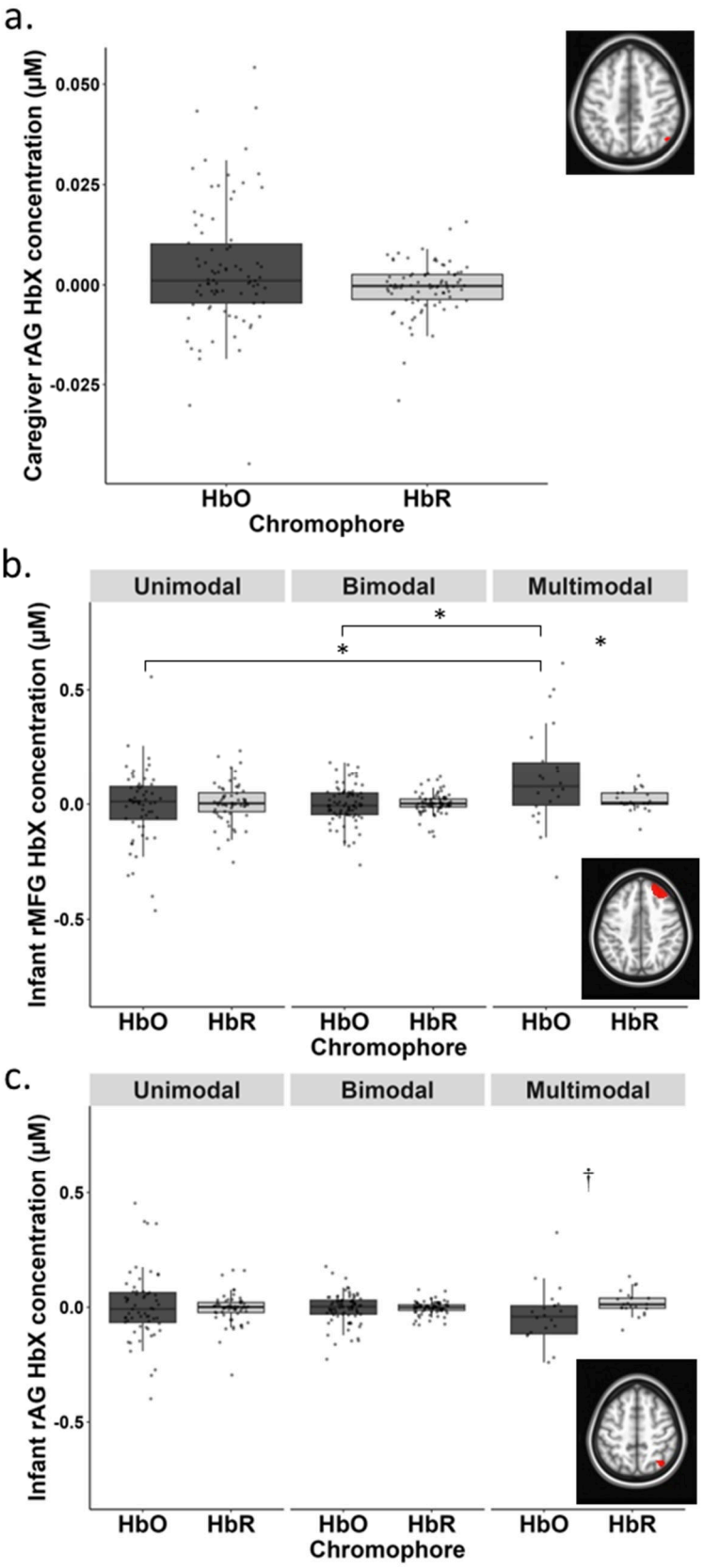


Figure 4.3 (a) Main effect of chromophore in rAG in caregivers. Interaction between engagement category and chromophore in (b) rMFG and (c) rAG in infants. * $p < .05$. † p value trending towards significance.

Since infants demonstrated opposing effects in rMFG and rAG i.e. activation in rMFG and a trend towards suppression in rAG, the association between both regions and engagement categories were examined. There was a negative association between rMFG HbO concentration and rAG HbO concentration across engagement categories ($F_{(6,152)} = 16.69$, $p < .001$, $\eta^2 = .10$) – see *Figure 4.4*.

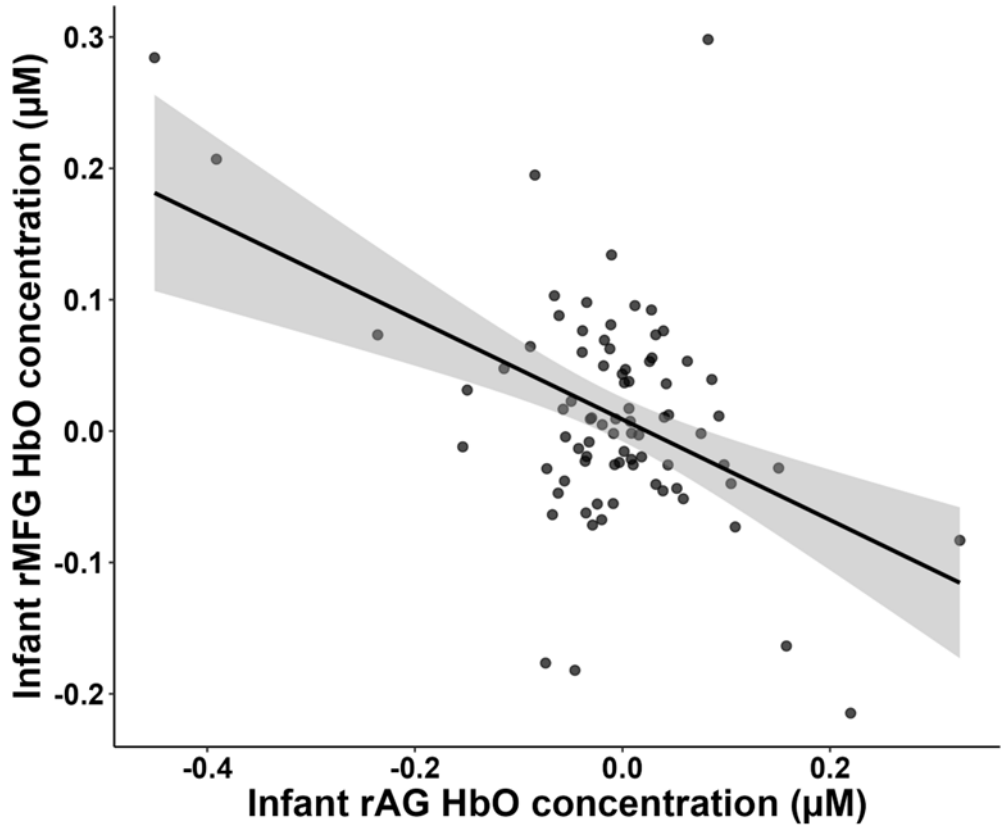


Figure 4.4 Greater rAG suppression was associated with greater rMFG activation.

4.4.3 Brain-behaviour associations in caregivers and infants

The third objective was to look at behavioural and brain associations between caregivers and infants.

First, the association between caregiver engagement and infant engagement was examined. There were no significant effects.

Next, the association between brain function in caregivers and brain function in infants was examined. Three key clusters were considered i.e. (i) the rAG cluster showing a chromophore main effect in the caregiver model, and (ii) the rAG and (iii) rMFG clusters showing an interaction between chromophore and engagement category in the infant model. For the first cluster in the rAG, the association between

overall HbO concentration in caregivers and overall HbO concentration in infants was examined, after controlling for infant age. Here, greater HbO concentration in caregivers was associated with reduced/suppressed HbO concentration in infants (p = .040, η^2= .05) – see *Figure 4.5* (a). Next, for the rMFG and rAG clusters that showed an interaction between chromophore and modality in the infant model, HbO concentration was extracted for each engagement category for each caregiver and infant. The association between HbO concentration in infants, HbO concentration in caregivers and engagement category was examined for each cluster. There was only one significant association. For unimodal engagement, greater rMFG HbO concentration in caregivers was associated with greater rMFG HbO concentration in infants (p = .024, η2= .11) – see *Figure 4.5* (b).

After examining caregiver-infant brain function associations, the next step was to investigate whether there were any associations between brain function and duration of engagement. No models were run for caregiver data, as only a chromophore main effect was observed, and it was not meaningful to link this to overall duration of engagement i.e. in most dyads, the duration of the full interaction. For infants, two clusters were considered i.e. rMFG and rAG from the interaction between modality and chromophore from the infant model. The association between engagement duration, HbO concentration and engagement category was examined for each cluster. There were no significant brain-behaviour associations for infants.

To summarise, greater overall rAG activation in caregivers was associated with greater overall rAG suppression in their infants. In rMFG, greater activation in caregivers was associated with greater activation in infants, only during unimodal engagement.

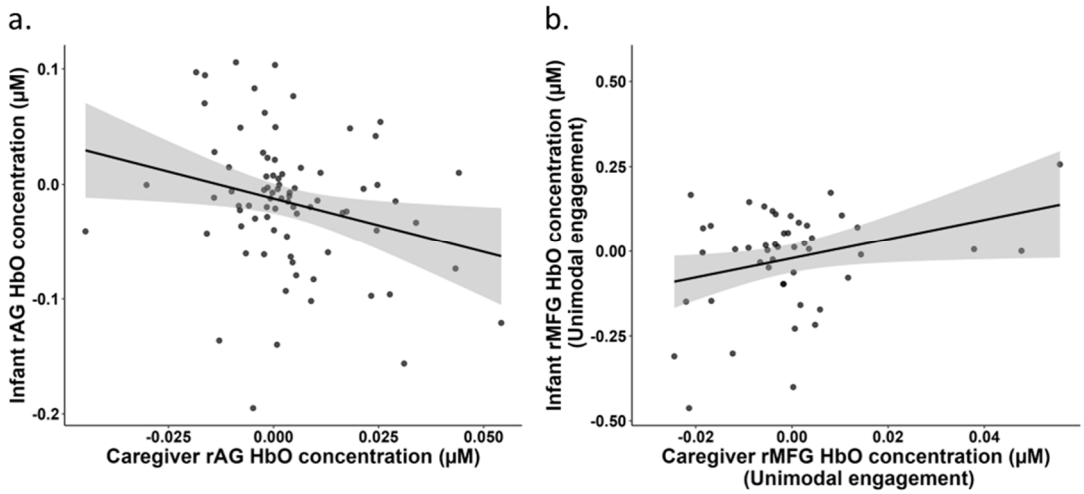


Figure 4.5 (a) Greater rAG activation in caregivers was associated with greater rAG suppression in infants and (b) greater rMFG activation in caregivers was associated with greater rMFG activation in infants during unimodal engagement.

4.4.4 Associations between engagement categories and infant CP score at the low load

The fourth research objective was to examine whether key afore-mentioned caregiver-infant behaviours and brain function during dyadic interactions predicted infant CP score at the low load.

First, the association between duration of engagement and infant CP score was examined. There were no significant effects.

Next, the link between brain function and infant CP score was examined. Three clusters were considered i.e. (i) the rAG cluster showing a chromophore main effect in the caregiver model, and (ii) the rAG and (iii) rMFG clusters showing an interaction between chromophore and engagement category in the infant model. For the rAG cluster from the caregiver model, the association between overall HbO concentration and infant CP at the low load was examined. This association was not significant. For the rAG/rMFG clusters that showed an interaction between chromophore and modality in the infant model, the association between infant CP score at the low load, HbO concentration and engagement category was examined for each cluster. There were no significant effects for either cluster.

4.5 Discussion

The over-arching objective of this chapter was to examine duration of, and brain function underlying different types of object engagement (unimodal, bimodal, and multimodal) in caregivers and infants. Following this, this chapter aimed to examine whether these behaviour and brain measures were associated with infant VWM. To this end, video recordings and brain function data were collected from caregivers and infants while they naturalistically engaged each other with toys. VWM was assessed in infants using the preferential looking task – see Chapter 3 (also Theyer et al., 2024).

This chapter had four research objectives. The first research objective was to examine whether there was a difference in the duration of unimodal, bimodal, and multimodal engagement in infants and caregivers. Both caregivers and infants showed greater proportion of bimodal compared to unimodal and multimodal engagement during the dyadic interactions. The second research objective was to examine key brain regions engaged in different engagement categories in caregivers and infants. Here, caregivers showed comparable rAG recruitment across engagement categories. On the other hand, infants showed greater rMFG activation and a trend towards greater rAG suppression during multimodal engagement compared to unimodal and bimodal engagement. Further, there was an inverse association between rMFG and rAG across all engagement categories; greater rMFG activation was associated with greater rAG suppression. The third research objective was to examine behavioural and brain associations between caregivers and infants. There were no associations between caregiver duration of engagement and infant duration of engagement. However, there were brain-related associations. Specifically, greater rAG activation in caregivers was linked to reduced rAG activation/greater rAG suppression in infants across all engagement categories. Further, greater rMFG activation in caregivers was associated with greater rMFG activation in infants during unimodal engagement only. The final research objective was to examine whether afore-mentioned caregiver-infant behaviours and brain function during dyadic interactions would predict infant VWM assessed using a preferential looking task. There were no associations. These findings are expanded upon below.

4.5.1 Difference between duration in engagement categories

The first research objective was to examine whether there was a difference in the duration of unimodal, bimodal, and multimodal engagement in infants and caregivers. Both infants and caregivers spent more time looking at and touching objects of interest, compared to only looking or looking, touching, and verbalising/vocalising about the objects. The effects were preserved even after infant engagement was sorted by type of caregiver engagement. This finding is in line with previous work in similar settings (Yu et al., 2009; Yu & Smith, 2013, 2017). For example, Yu & Smith (2013) examined moment-by-moment eye-tracking data, as caregivers and their 1-year-old infants engaged in joint play with toys. Dyads played with two sets of toys, each for 2 minutes, resulting in up to 4-minutes of play interaction data. Here, they found that neither caregivers nor infants dominated their interaction, instead, they both individually held objects for 25% of the interaction, and jointly held objects for 43% of the interaction. Similar findings have also been reported in toddlerhood. Yu et al. (2009) collected head-camera data from play interactions with caregivers and their 21-month-old toddlers. Each dyad completed between 2 and 6 play interactions with toys, each lasting 1-minute. Here, at least one member of the dyad held at least one object for 86% of the interaction (Yu et al., 2009). Collectively, the findings from the current study demonstrate that the physical manipulation of objects by both caregivers and children is also a prominent feature of play interactions in infants as young as 6 to 10 months of age.

4.5.2 Differences in brain function during engagement categories

The second research objective was to examine key brain regions engaged during the different engagement categories in caregivers and infants. While caregivers showed comparable rAG activation across engagement categories, infants showed greater rMFG activation and a trend towards greater rAG suppression during multimodal compared to unimodal or bimodal engagement.

The rAG is purported to be involved in attentional re-orienting (Perry & Zeki, 2000; Singh-Curry & Husain, 2009), encoding of salient events (Corbetta et al., 2000; Singh-Curry & Husain, 2009), and even inhibition of responses (Gottlieb, 2007). For instance, one study used fMRI to examine attentional shifts in adults. Here, subjects completed 'target' trials, in which they shifted their gaze towards a peripheral stimulus,

and ‘non-target’ trials, in which they stayed fixated on a central cross. Findings revealed temporo-parietal activation during saccades to peripheral stimuli, supporting the role of this region in attentional re-orienting (Perry & Zeki, 2000). In another study, adults were presented with task in which they were required to shift their attention to a target stimulus (Corbetta et al., 2000). During each trial, a cue appeared indicating the likely location of the upcoming target. During valid trials, the target appeared at the cued location, whereas during invalid trials, it appeared at an uncued location. Here, right temporo-parietal activation was stronger when targets appeared at the uncued location. The rMFG has a related role, however, more heavily steeped in control and flexible modulation (Japee et al., 2015). Here, surgical removal of tissue in the rMFG was found to disrupt switching between exogenous and endogenous attention strategies during a cueing task. Critically, previous work has suggested that this region might be a site of convergence between the dorsal and ventral attention networks, thus, serving as a ‘circuit-breaker’, responsible for interrupting ongoing processes and re-orienting attention to another stimulus (Japee et al., 2015).

In the current study, in caregivers, although there were differences in duration for each engagement category, there were no differences in rAG engagement, or other parts of the fronto-temporo-parietal network that was measured. It is possible that despite differences in ‘outcome behaviours’ such as looking, or object handling between the three modalities, caregivers might be coping with similar intrinsic cognitive demands. For example, when caregivers were coded as only looking at an object during unimodal interactions, it is possible that they might also be inhibiting prepotent responses, orienting and re-orienting to their infant’s actions or lack thereof, or planning subsequent actions – eliciting rAG activation comparable to what they might elicit during multimodal interactions. Infants, on the other hand, are not yet be capable of demonstrating such proactive, planned, and anticipatory internal states of cognition (Gonthier et al., 2019). For instance, researchers have suggested that age-related improvements in cognitive control can be described as a shift from reactive control, which entails responding to a control-demanding event as it occurs, to proactive cognitive control, which involves actively maintaining goal-relevant information in memory to orient behaviour (Braver, 2012; Braver et al., 2007; Gonthier et al., 2019). One study presented children with a cognitive control task and calculated indices based upon performance (i.e. error and reaction times) that reflected

proactive control (Gonthier et al., 2019). In this study, children younger than 5 years exhibited a high reliance on reactive control. During interactions, infants might simply engage brain regions in a manner commensurate with the attentional demands of the different modalities. In line with this interpretation, infants might need to differentially elicit activation in brain regions such as rMFG. For example, during multimodal engagement, infants are required to co-ordinate visual attention with physical manipulation of the object (such as reaching for it or shaking it), while simultaneously vocalising (attempting to communicate through sounds or babbling). Thus, they might greater regulate rMFG to shift between visual attention, physical object manipulation, and vocalisations, compared to bimodal or unimodal engagement.

Albeit weak, why is there a trend for suppression in the rAG in infants? To address this finding, the inverse association between the rAG and rMFG was examined – greater rMFG activation was associated with greater rAG suppression. Robust and reciprocal ties between the frontal and parietal cortices have been reported in previous literature, albeit in older adults. In that literature, this association is referred to as a posterior to anterior shift in activation i.e. greater activation in frontal regions compared to sensory posterior regions (Ansado et al., 2012; Davis et al., 2008; Grady et al., 1994; Wijeakumar, Magnotta, et al., 2017; Zhang et al., 2017). For example, Davis et al. (2008) matched younger and older participants on performance during episodic memory and visual perceptions tasks, and found that increased frontal activity in older adults was both positively associated with task performance and negatively associated with posterior activity. In older adults, this phenomenon is thought to reflect a compensatory mechanism involved in sensory decline, whereby increased recruitment of frontal regions offsets processing deficits in posterior regions (Davis et al., 2008; Grady et al., 1994). Similar patterns of activation have been observed in early life. For example, one study examined EEG coherence, thought to be a marker of frontal connectivity, in infants between the ages of 5 and 10 months (Cuevas & Bell, 2011). Here, increased EEG coherence was observed with age between frontal-posterior electrode pairs. Similarly, in another study, better performance on a working memory task was associated with increased fronto-parietal EEG coherence in 8-month-old infants (Bell, 2012). In the first year of life, it is possible that these inverse posterior-anterior associations during dyadic interactions may represent evolving context-dependent connectivity between the frontal and parietal cortices.

4.5.3 Brain-behaviour associations in caregivers and infants

The third objective was to examine whether there were any behaviour and/or brain associations between caregivers and infants. There were caregiver-infant associations only at the brain level. First, greater rMFG activation in caregivers was associated with greater rMFG activation in infants during unimodal engagement only. In general, given lower cognitive demands for both infants and caregivers during unimodal engagement, this positive link is not entirely surprising. This finding suggests that caregivers and infants might engage similar attentional mechanisms when visually exploring the same objects together. This interpretation aligns, albeit only generally, with previous work examining brain-behaviour dynamics during joint/solo play in caregivers and infants (Wass, Clackson, et al., 2018; Wass, Noreika, et al., 2018). For instance, during joint play, caregiver theta power has been shown to closely track changes in infant attention (Wass, Noreika, et al., 2018). It is possible that these associations do not yet exist for more complex modalities for infants in the first year of life. For example, there are differences in how caregivers hold and manipulate objects versus how infants hold and manipulate objects, even if they are the same objects. For instance, in infancy, children tend to interact with objects by shaking, banging and rotating them (Rachwani et al., 2020). In contrast, caregivers engage behaviours which facilitate learning (Lockman & Tamis-LeMonda, 2021), such as the use of exaggerated motion (Brand et al., 2002) and guiding infants hand movements to object features (Lockman & McHale, 1989). Similarly, caregivers, or indeed adults, mostly engage in verbalisations with infants similar in age as those in the current study (Schatz et al., 2022), while infants mostly engaged in vocalisations (Bigelow et al., 2004; Nathani et al., 2006; Oller et al., 2021).

Interestingly, greater rAG activation in caregivers was associated with greater rAG suppression in infants, across all engagement categories. This finding can be aligned with two afore-mentioned results. Concretely, it was speculated that comparable activation levels across engagement categories in adults might be reflective of intrinsic cognitive demands that are not 'visible' to observers. This ability is likely absent in infants. Further, in infants, rAG suppression, in line with rMFG activation, was observed across all engagement categories. Given these different neural mechanisms in caregivers and infants, it is not surprising that the nature of the link is inverse. It is possible that with increasing age, more spatially- and functionally-

aligned caregiver-infant associations emerge and become evident – during dyadic interactions. There is some evidence for alignment in the parietal cortex from inter-brain synchrony research in older infants and children. For instance, one study examined inter-brain synchrony in caregivers and their 9- to 15-month-old infants during a book reading task and found increased synchrony in the parietal cortex during joint book reading (Piazza et al., 2020). Although the principles of the analyses between what was conducted in the current study, and what is conducted in interbrain synchrony studies might be different, these findings from inter-brain synchrony research imply that more aligned activation between caregivers and children may emerge later in development.

It is important to consider how these caregiver-infant associations from dyadic interactions align with caregiver-infant associations from experimental studies (reported in Chapter 3). These findings do not align; in Chapter 3, there was a positive association in looking behaviours and spatio-functional correspondence in right parietal engagement between caregivers and infants, while here, an inverse association is reported in the rAG. While there is limited research directly comparing experimental tasks to dyadic interactions, there is evidence for differences in activation patterns during different contexts – for example, social contexts during dyadic interactions and non-social contexts during experimental tasks. Relatedly, one study collected EEG data from 6- and 12-month-old infants in the viewing of social vs non-social stimuli (Jones et al., 2015). Here, theta power, which is thought to be sensitive to social interaction, was stronger and more widespread during live action social stimuli (more closely resembling dyadic interactions) in comparison to non-social stimuli. It is speculated that these brain-behaviour differences must stem from contextual differences i.e. solo engagement during the experimental task (albeit, visual in nature), and engagement of a joint nature during dyadic interactions. More research is required in this direction to directly examine differences between dyadic interactions and experimental tasks within the same cohort, and thus, better capture contextual variation in brain function.

4.5.4 Association between caregiver-infant brain-behaviour measures during dyadic interactions and infant visual cognition

The final research objective was to examine whether afore-mentioned caregiver-infant behaviours and brain function during dyadic interactions were linked

to infant VWM during a preferential looking task. Contrasting predictions, there were no links between caregiver-infant behaviours or brain function and infant VWM. This finding was unexpected, given that existing literature has reported associations between caregiver/infant engagement during play and infant cognition (Bernier et al., 2010; Brandes-Aitken et al., 2020; Lawson & Ruff, 2004; Lugo-Gil & Tamis-LeMonda, 2008; Ruff et al., 1990). In one study, caregiver behaviours during play were linked to child cognitive abilities at 14, 24, and 36 months (Lugo-Gil & Tamis-LeMonda, 2008). Similarly, findings have also linked caregiver behaviours during play interactions with their infants at 12 to 15 months with child EF at 18 to 26 months (Bernier et al., 2010). Furthermore, caregiver behaviours during play at 15 months have been positively associated with child EF at 48 months (Brandes-Aitken et al., 2020). Further, joint attention at 24 months was shown to partially mediate this relationship. In line with this, previous research has demonstrated that caregiver input that occurs *within* joint attention periods, is associated with extended infant sustained attention periods (Schatz et al., 2022; Schroer & Yu, 2022; Suarez-Rivera et al., 2019; Yu & Smith, 2016). Based on these findings, it is possible that significant associations might exist between attentional episodes, such as joint attention or subsequent continued attention in infants, and infant cognition.

4.6 Conclusions

The current chapter examined the duration of, and brain function underlying different types of object engagement in caregivers and infants. Furthermore, this chapter examined whether the duration of, and underlying brain function during these behaviours was predictive of infant looking behaviours. Both caregivers and infants showed greater proportion of bimodal compared to unimodal and multimodal engagement. While caregivers showed comparable right-lateralised recruitment across all engagement categories, infants showed modality-specific changes in right-lateralized fronto-parietal cortex suggesting a role in actively shifting between attentional demands. Interestingly across engagement categories, greater right parietal activation in caregivers was linked to greater right parietal suppression in infants. It was proposed that differences in activation patterns reflected variation in the complexity of cognitive processing demands between caregivers and infants. Furthermore, greater right frontal activation in caregivers was associated with greater right frontal activation in infants during unimodal engagement only. It was speculated

that caregivers and infants might engage similar mechanisms in the frontal cortex during unimodal engagement, but that such alignment might not yet extend to more complex engagement categories. Contrasting predictions, there were no links between behaviour and brain function during dyadic interactions and infant VWM during the preferential looking task. These findings provide novel contributions to the understanding of the cortical mechanisms underlying different types of object engagement.

4.7 Motivations for Next Chapter

The third chapter in this thesis found associations between caregiver and infant looking behaviours and brain function during an experimental preferential looking task. Interestingly, the current chapter reported caregiver-infant brain associations during dyadic interactions. However, contrasting predictions, there were no associations between caregiver-infant behaviours or brain function and infant VWM during the preferential looking task. In the current chapter, it was suggested that this lack of association may be attributable to the current coding scheme, which focussed on episodes of unimodal, bimodal, and multimodal engagement for caregivers and infants. It is possible that concrete associations may exist between joint attention during these interactions and infant VWM. Keeping this in mind, the next chapter in this thesis aims to examine duration of joint and continued engagement during dyadic interactions.

Chapter 5:

Brain-behaviour associations underlying joint and continued attention during caregiver-infant interactions

A version of this chapter is in review in Infancy as

Theyer, A. & Wijeakumar, S. (in review). Brain-behaviour associations underlying object engagement during caregiver-infant interactions.

5.1 Introduction

5.1.1 Joint and sustained attention in caregivers and infants

The ability to sustain attention undergoes rapid change over the first few years of life. For instance, casual attention, referring to brief momentary shifts of attention, has been shown to decrease with age, while sustained attention, referring to focused attention on a task or object, has been shown to increase with age (Ruff & Capozzoli, 2003). In early life, these developmental changes are thought to support infants' exploration of their surroundings (Colombo, 2001; Herzberg et al., 2022). For instance, as infants explore, they are able to extract information, and learn about objects and their environments (Needham, 2000; Palmer, 1989). Following this, the ability to sustain attention steadily increases throughout childhood (Kannass et al., 2006; Ruff et al., 1998; Ruff & Lawson, 1990), and has been linked to academic achievement (Gallen et al., 2023), distractibility (Kannass et al., 2006), language (Brooks & Meltzoff, 2008) and cognitive development (Lawson & Ruff, 2004; Reck & Hund, 2011). It is therefore important to understand the factors that might influence the development of sustained attention in early life.

There is a wealth of evidence demonstrating the role of caregiver input on infant object engagement (Hoehl et al., 2012; Michel et al., 2024; Wass, Clackson, et al., 2018) and attention (D'Entremont, 2000; Farroni et al., 2000; Hood et al., 1998) in the first year of life. For example, joint visual attention between caregivers and infants when interacting with an object is related to the duration of sustained visual attention that infants subsequently paid to the same object (Yu & Smith, 2016). In addition to mutual gaze, caregivers and infants show attention-sharing during object manipulation (Deák et al., 2014; Yu & Smith, 2013) and related verbalisations (Schroer & Yu, 2022). This type of 'multimodal' input, referring to the combination of caregiver touch, gesturing and verbalisations is associated with longer play bouts in infants (Schatz et al., 2022). Collectively, these findings indicate that caregiver engagement, particularly combining gaze, object-associated manipulation, and verbalisations, impacts infant engagement durations during interactions.

Current theories on the neural basis of joint attention rely primarily on findings from adult studies (Bristow et al., 2007; Materna et al., 2008; Morris et al., 2005; Redcay et al., 2012; Schilbach et al., 2006; Williams et al., 2005). These findings

suggest that joint attention occurs as an outcome of two interacting attentional systems: the anterior attention system, responsible for the initiation of joint attention, and the posterior attention system, responsible for responding to joint attention (Mundy et al., 2000; Mundy & Newell, 2007; Posner & Rothbart, 2007). The posterior attention system is thought to develop in the first few months of life and be mostly involuntary, prioritising attention to biologically relevant stimuli. This system is supported by parietal and superior temporal regions, such as the AG, STG, somatosensory association cortex, and auditory cortex, which are thought to play key roles in representations, imitations, and perceptions of others (such as eye and head orientations), as well as spatial relationships between oneself, others, and the environment (Mundy & Newell, 2007). On the other hand, the anterior attention system is thought to develop later and be involved in goal-directed attentional allocation. This system involves the FEFs, DLPFC, orbitofrontal area, pars orbitalis, and anterior cingulate cortex. To some extent, limited but nonetheless, existing neuroimaging evidence does point towards the recruitment of regions in these networks in infants during dyadic interactions. For example, in 5-month-old infants engaging in joint attention, left prefrontal activation has been associated with the detection of a social partner following their gaze (Grossmann et al., 2013; Grossmann & Johnson, 2010). In addition, findings in 7- to 12-month-old infants have reported that right-lateralized prefrontal activation is associated with initiation and response to joint attention (Naoi et al., 2022). Together, integrated activity between the anterior and posterior systems are purported to support joint attention (Mundy, 2003; Mundy et al., 2000; Mundy & Newell, 2007; Williams et al., 2005).

Neuroimaging studies in caregivers and infants engaging in episodes of joint attention have emphasized temporally predictive behaviour-brain links. For example, research using EEG has found that infant theta power lesser predicted visual attention in joint play in comparison to solo play, suggesting that during solo play, infants had greater endogenous control over attention (Wass, Noreika, et al., 2018). This finding is in line with research reporting that increased theta power is associated with infant sustained attention (Xie et al., 2018). In this study, infants were also more attentive during joint play, and caregiver theta power tracked infant attentional changes, with greater neural responsivity associated with increased sustained attention (Wass, Noreika, et al., 2018). Further, consistent with the anterior-posterior model of attention

(Mundy & Newell, 2007; Posner & Petersen, 1990), EEG data from toddlers has also revealed that left frontal, and left and right central cortical activity was associated with initiating joint attention bids, and that left parietal activation and right parietal deactivation was associated with responding to joint attention bids (Mundy et al., 2000). Moreover, caregiver input, such as the use of ostensive signals, has also been shown to influence infant neural activity (Michel et al., 2024). Here, during social interactions between caregivers and infants, infant theta activity synchronised. Further, increased infant theta activity during encoding also predicted object encoding abilities. Another fNIRS study has also explored the neural mechanisms underlying joint attention during interactions between adults (Dravida et al., 2020). Here, adults engaged in a joint attention task, in which they either directed each other's attention towards targets (social task) or in which they followed a cue (non-social task). They found increased right temporal-parietal activity in the social joint attention task in comparison to the non-social task. Additionally, the frequency of eye-contact between partners also modulated neural activity, with increased eye-contact associated with increased bilateral activity in the temporal regions. Collectively, these studies demonstrate that investigating brain function during dyadic interactions might provide unique mechanistic insight into attentional pathways in both partners.

5.1.2 Impact of caregiver-child joint attention on cognitive development

Joint attention has been shown to play a critical role in early cognitive and social development. Specifically, joint attention enhances object processing in younger infants (Striano, Chen, et al., 2006) and is linked to gestural abilities (Carpenter et al., 1998), language development (Carpenter et al., 1998; Morales et al., 2000), and individual differences in IQ, self-regulation, and social abilities (Mundy & Newell, 2007). Previous work has also examined the impact of caregiver object naming during joint attention and sustained attention periods in infancy on word learning in later toddlerhood (Yu et al., 2019). Here, sustained attention taken within the context of joint attention yielded stronger predictions, compared to joint attention by itself. Beyond language development, sustained attention in late infancy has also been shown to predict developmental outcomes, with early deficits serving as indicators of diagnoses of later developmental disorders (Barkley, 1997). Finally, sustained attention has also been shown to support object exploration, language acquisition, and problem-solving (Ruff & Rothbart, 1996). These findings suggest that

characterising joint and sustained attentional pathways during caregiver-infant interactions is important for cognitive functions in infancy and for later cognitive development.

5.2 Research Objectives

There is a wealth of evidence demonstrating the importance of caregiver-infant joint attention on subsequent infant attention (Deák et al., 2014; Schatz et al., 2022; Schroer & Yu, 2022; Yu & Smith, 2013, 2016). However, much less is understood about changes in underlying brain function in either partner. Neuroimaging research in adults suggests that joint attention arises from the interaction between the anterior and posterior attention system (Morales et al., 2000; Mundy & Newell, 2007; Posner & Rothbart, 2007). To a degree, literature in children supports this characterization (Grossmann et al., 2013; Mundy et al., 2000; Naoi et al., 2022), however, research that focuses upon brain activation in both caregivers and infants during dyadic interactions is limited (Michel et al., 2024; Wass, Noreika, et al., 2018) and associations with concurrent infant cognition remain unclear.

To address these gaps, this chapter utilizes data and findings from Chapter 4 to examine periods of joint attention between caregivers and infants (referred to as 'joint attention' from here on) and periods of infant attention subsequently following joint attention (referred to as 'continued attention' from here on). Following this, it examines whether the duration of joint and continued attention and underlying brain function during these attentional episodes are predictive of infant VWM (Chapter 3). To this end, video recordings and brain function data were collected from caregivers and infants while they naturalistically engaged each other with toys – see Chapter 4. Further, VWM in infants was measured through eye movements as they engaged with an experimental preferential looking task – see Chapter 3 (also Theyer et al., 2024).

This chapter had five key research objectives. The first objective was to examine whether duration of joint attention was associated with duration of continued attention in infants. Here, in line with existing research (Yu & Smith, 2016), it was expected that joint attention length would be positively associated with continued attention length. The second objective was to identify key brain regions engaged in caregivers and infants during periods of joint and continued attention. Again, based on previous findings (Mundy et al., 2000), both caregivers and infants were predicted to

show increasing bilateral fronto-parietal activation during periods of joint and continued attention. The third objective was to examine whether there was an association between brain function in caregivers and brain function in infants during joint attention and how these brain function measures were linked to duration of joint attention. No study has examined whether there is spatio-functional correspondence in brain regions involved in joint attention. Based on EEG evidence from dyadic interactions (Mundy et al., 2000), it was speculated that there would be spatio-functional correspondence in the fronto-parietal cortex during caregiver-infant joint attention. The fourth objective was to examine whether the duration of continued attention in infants, was associated with brain function in infants during continued attention, brain function in infants during joint attention, and brain function in caregivers during joint attention. Similarly, no study has examined whether there is spatio-functional correspondence in brain regions involved in joint and continued attention. However, EEG research has suggested that caregiver neural responsivity is linked to greater infant sustained attention (Wass, Noreika, et al., 2018). Thus, it was also speculated that there would be spatio-functional correspondence in the fronto-parietal cortex during caregiver-infant joint attention and infant continued attention.

The final research objective was to examine whether afore-mentioned caregiver-infant behaviours and brain function during dyadic interactions would predict infant VWM measured using preferential looking task. In line with evidence linking both caregiver-infant joint attention and infant continued attention to general infant cognition (Carpenter et al., 1998; Morales et al., 2000; Mundy et al., 2000), an interaction between caregiver and infant behaviours and fronto-parietal engagement was generally speculated to predict infant looking behaviours. However, due to the lack of studies in this direction, an exploratory analysis approach was followed, gradually building on findings from meeting previous objectives.

5.3 Materials and Methods

5.3.1 Participants

This chapter is part of a larger longitudinal project. Please refer to Chapter 3, Section 3.3.1 *Participants*, for details on recruitment criteria. Please refer to Chapter 4, Section 4.3.1 *Participants*, for details on sample size related to the dyadic interactions. Demographic and SES information for the dyadic interactions is also

provided in Chapter 4, *Table 4.1*. Data collection was carried out at the University of Nottingham. Ethics approval was provided by the Research Ethics Committee at the University of Nottingham (Ethics Approval Number: F1338).

5.3.2 Caregiver-infant dyadic interactions

Please refer to Chapter 4, Section 4.3.2 *Caregiver-infant dyadic interactions*, for details on caregiver-infant dyadic interactions with toys. Here, the same dyadic interactions were examined, to extract measures of joint and continued attention.

5.3.3 Infant preferential looking task

To measure VWM, infants were presented with the preferential looking task (Ross-Sheehy et al., 2003). This task is described in detail in Chapter 3, Section 3.3.2 *Infant and caregiver preferential looking tasks*.

5.3.4 Procedure

Data collection procedures for the infant preferential looking task are described in detail in Chapter 3, Section 3.3.4 *Procedure*. Data collection procedures for the dyadic interactions are described in detail in Chapter 4, Section 4.3.4 *Procedure*.

5.3.5 Data analyses

5.3.5.1 Joint and continued attention coding scheme

Caregiver and infant engagement during the play interactions were coded as described in Chapter 4, Section 4.3.5.1 *Modality coding scheme*. For the joint/continued attention analyses, periods in which caregivers were showing multimodal engagement whilst interacting with the same object as their infant (joint attention), and periods in which the infant continued to interact with that same object after caregiver multimodal engagement ended (continued attention) were then identified – see *Table 5.1*.

To code joint attention periods, periods during which caregivers showed multimodal engagement with one object for at least two consecutive epochs and infants showed unimodal, bimodal, or multimodal engagement with the same object were identified – see *Figure 5.1* (a-b). Here, multimodal engagement was considered across two consecutive epochs for two reasons. Firstly, multimodal engagement is thought to scaffold infant play durations and complexity (Schatz et al., 2022; Suarez-Rivera et al., 2019, 2022). Secondly, since caregivers could jointly attend with their

infants in several ways across all modalities, it was necessary to define determinate distinguishable periods. Here, a criterion was therefore set of at least 2 consecutive epochs (or 10 s) for specifying a joint attention period for the purpose of examining underlying brain function during this period. This criterion was drawn from experimental fNIRS studies which typically use trial windows of 5-10 s to capture the hemodynamic response. Note that for infants, epochs where they showed some engagement with another object were also included, so long as they were still interacting with the object of interest. The joint attention period ended if the caregiver switched to a different type of engagement for more than one epoch and/or if the infant did not unimodally, bimodally, or multimodally engage with the same object anymore.

A 'continued attention' period was defined as epochs after caregiver engagement had ended, during which the infant continued to unimodally, bimodally, or multimodally engage with the same object they had interacted with during joint attention – see *Figure 5.1* (a-b). Epochs during which infants showed some engagement with another object were included, so long as they were still interacting with the object of interest. The continued attention period ended if the infant no longer showed unimodal, bimodal, or multimodal engagement with the object from the preceding joint attention period and/or a third object was introduced, and/or if the caregiver re-joined the interaction with multimodal engagement such that a new joint attention period began. Continued attention periods following multimodal joint attention were focused upon because previous work has shown that caregiver joint attention (Yu et al., 2019; Yu & Smith, 2016), particularly multimodal input (Schatz et al., 2022; Suarez-Rivera et al., 2019, 2022), is associated with extended infant sustained attention.

For each dyad, the duration of joint attention in seconds was extracted from caregivers and infants, and the duration of continued attention in seconds was extracted from infants. To convert epochs into seconds, the total number of epochs was multiplied by 5 (as each epoch length was 5 seconds). Only one outlier was identified - for joint attention. In total, 69 caregivers and infants contributed data for caregiver-infant joint attention and 70 infants contributed data for continued attention.

Table 5.1 Summary of coding criteria for caregiver-infant joint attention and infant continued attention periods.

Attention type	**Definition**	**Criteria for coding**	**Ending conditions**
Caregiver-infant joint attention	Periods in which caregivers showed multimodal engagement whilst interacting with the same object as their infant.	Caregivers: ▪ Showed multimodal engagement with 1 object (object of interest) for at least 2 consecutive epochs. ▪ Could not show engagement with any other object. Infants: ▪ Showed unimodal, bimodal, or multimodal engagement with object of interest. ▪ Could show engagement with a maximum of 1 additional object, as long as they were still interacting with object of interest.	Caregivers: ▪ Switched to a different type of engagement (unimodal or bimodal) for > 1 epoch. ▪ Stopped interacting with object of interest. Infants: ▪ No longer showed unimodal, bimodal, or multimodal engagement with object of interest. ▪ A second additional object was introduced (third object).
Infant continued attention	Periods in which the infant continued to interact with the same object after caregiver multimodal engagement ended.	Infants: ▪ Continued to interact with object of interest following the preceding joint attention period. ▪ Could show engagement with a maximum of 1 additional object, as long as still interacting with object of interest. Note if the infant engaged with an additional object during the joint attention period, this had to be the same additional object during the continued attention period.	Infants: ▪ No longer showed unimodal, bimodal, or multimodal engagement with object of interest. ▪ A second additional object was introduced (third object). Caregivers: ▪ Re-engaged infant with multimodal input with a singular object (initiating new joint attention period).

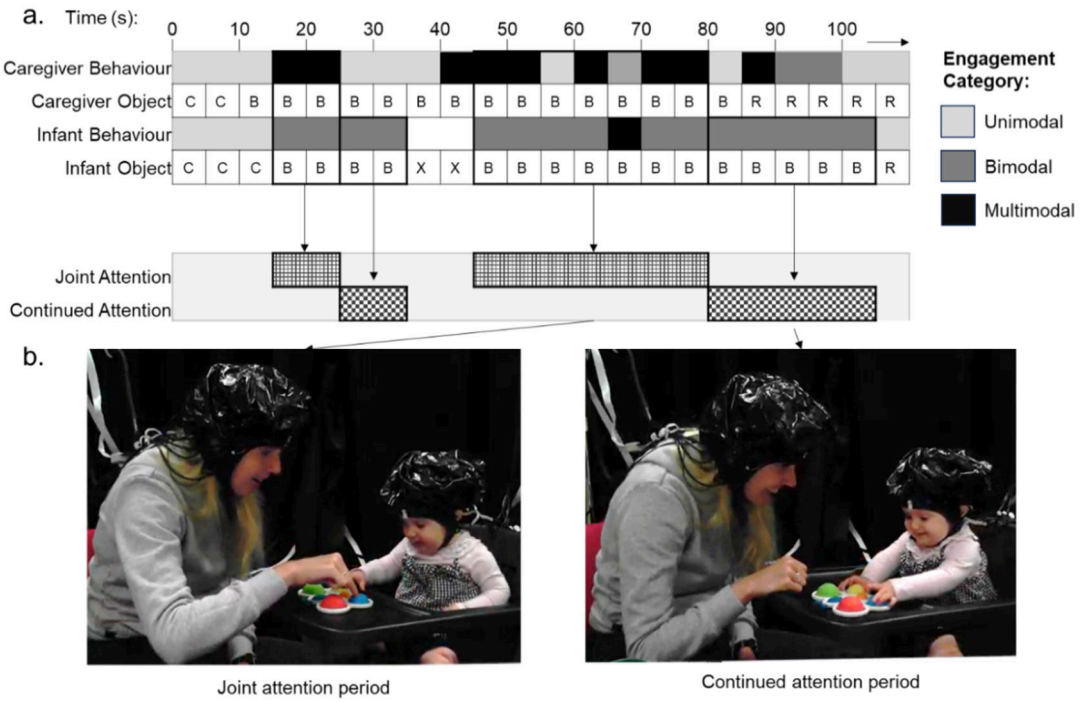


Figure 5.1 (a) Joint and continued attention periods extracted from caregiver and infant behaviours and (b) corresponding example of dyad demonstrating these behaviours.

5.3.5.2 Infant looking behaviour analyses

Behavioural analyses for the infant preferential looking task are described in detail in Chapter 3, Section 3.3.5 *Behavioural analyses*. In line with justification provided in Chapter 4, Section 4.3.5.2 *Infant looking behaviour analyses*, infant CP scores at the low load were used for further analyses in this chapter.

5.3.6 fNIRS data analyses

fNIRS data analyses for caregiver-infant dyadic interactions are presented in Chapter 4, Section 4.3.6 *fNIRS data analyses*. For joint/continued engagement analyses, fNIRS data was analysed following the same methods. Some differences are highlighted below.

Onsets of joint attention and continued attention periods were inserted into caregiver and infant fNIRS data. Note that joint attention periods always lasted for at least two epochs (at least 10 s) and continued attention periods could last for one or more epochs (at least 5 s). *Table 5.2* provides details regarding the number of instances and the overall lengths of attention periods (following the initial epoch onset). Caregivers and infants contributed an average of 3 events each for both joint attention and continued attention. To remove noise, artefacts and other confounding signals, all

fNIRS data was pre-processed in *EasyNIRS* using Homer2 – details have been described in Chapter 4, Section 4.3.6.1 *Pre-processing*.

Following pre-processing, 0.62 % of the infants' and 0.48 % of the caregivers' channels were pruned. The percentage of infant data lost was 5.47% for joint attention and 5.36% for continued attention. The percentage of caregiver data lost was 0.50% for joint attention and 2.38% for continued attention. Regarding sample sizes, 70 caregivers contributed joint attention fNIRS data, 67 infants contributed joint attention fNIRS data, and 62 infants contributed continued attention fNIRS data. Caregivers and infants contributed an average of 3 events for both joint attention and continued attention. For image reconstruction, a general linear model with two regressors (joint attention and continued attention) was separately run for each chromophore and each infant/caregiver.

To investigate joint/continued attention differences in brain function, separate t-tests were run to examine chromophore differences in caregiver joint attention data, infant joint attention data, and infant continued attention data (in AFNI using *3dttest++).* Resultant images were thresholded at a cluster-wise threshold (10 voxels) and a voxel-wise p-value of <.05 (using *3dClustSim* in AFNI) to identify localized, significant brain regions. Average HbO and HbR concentration was extracted from voxels in these regions (using *3dROIstats* in AFNI) and followed up using analyses described in Section 5.3.7 *Statistical analyses* to meet proposed objectives.

Table 5.2 Summary statistics for the number of instances and duration of engagement across each category for caregivers and infants.

Engagement category	**Count**	**Minimum**		**Maximum**		**Median**		**Mean**		**Mode**	
	N	*Epochs*	*Seconds*	*Epochs*	*Seconds*	*Epochs*	*Seconds*	*Epochs*	*Seconds*	*Epochs*	*Seconds*
Caregiver-infant joint attention	201	2	10	22	110	3	15	3.70	18.48	2	10
Infant continued attention	168	1	5	32	160	4	20	5.26	26.28	2	10

5.3.7 Statistical analyses

Statistical analyses were run using RStudio (v2023.03.0).

For duration and brain data, values that fell outside of ± 3 SDs from the mean were identified as outliers and removed prior to statistical analyses. After outlier corrections, 69 caregivers and infants contributed data for duration of joint attention and 70 infants contributed data for duration of continued attention. Between 55 and 70 caregivers and infants contributed brain data – this range represents the difference in number of outliers across regions, caregivers/infants, and attention periods. For infant CP score, 86 infants contributed data for the low load.

To examine the association between joint and continued attention, a regression model was run, with duration of joint attention as the predictor and duration of continued attention as the outcome, after controlling for age.

Next, to examine chromophore differences in caregiver joint attention data, infant joint attention data, and infant continued attention data, separate t-tests were run in AFNI (see Section 5.3.5.2). Significant clusters were followed up to examine whether effects survived at the cluster level (as opposed to the voxel-level). Clusters showing a chromophore effect were re-examined using pairwise comparisons. Further regression models were run to examine caregiver-infant brain-behaviour associations in relevant clusters.

Finally, to examine whether caregiver-infant behaviours and brain function during dyadic interactions predicted infant VWM, regression models were run to examine caregiver-infant brain-behaviour associations in relevant clusters. The number of caregivers and infants included in each analysis is presented in *Table 5.3*.

Table 5.3 Number of caregivers and infants contributing to each section.

Section	Variables	Caregiver	Infant
Joint/continued attention behaviour	Joint attention	69	69
	Continued attention	70	70
Joint/continued attention brain	Joint attention	70	67
	Continued attention	65	62
Preferential looking task	Low load		86

5.4 Results

5.4.1 Association between joint and continued attention in caregivers and infants

The first research objective was to examine whether duration of caregiver-infant joint attention predicted duration of infant continued attention, whilst controlling for age. There was a significant positive association; greater duration of caregiver-infant joint attention was associated with greater duration of infant continued attention ($F_{(2,66)} = 5.08$, $p = .003$, $\eta^2 = .13$) – see *Figure 5.2*.

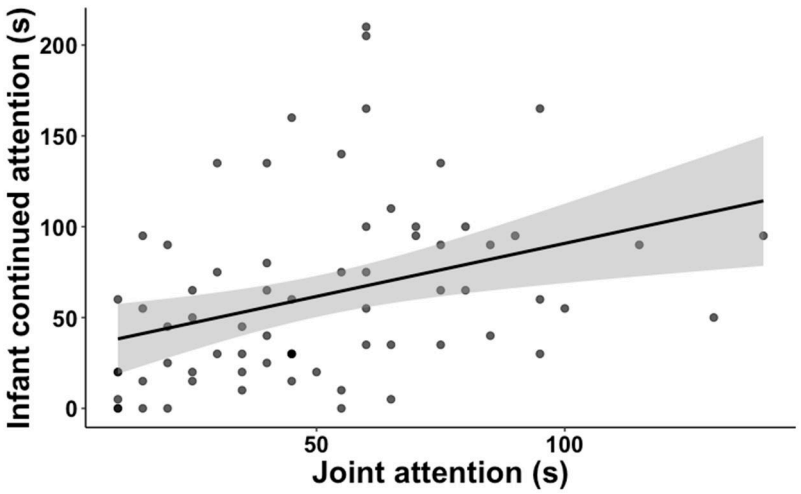


Figure 5.2 Association between caregiver-infant joint attention and duration of infant continued attention.

5.4.2 Brain function in caregivers and infants

5.4.2.1 Brain regions engaged during joint attention in caregivers and infants, and continued attention in infants

The second research objective was to identify key brain regions engaged in caregivers and infants during periods of joint and continued attention. Separate voxel-wise t-tests were run to examine whether was there a difference between HbO and HbR concentration for caregiver joint attention, infant joint attention, and infant continued attention brain data. Significant clusters were only observed for joint attention in infants. Specifically, there was a difference between HbO and HbR concentration in the rSTG, lSTG, and lSPL – see *Table 5.4*. Here, follow-up tests conducted to examine the difference between averaged HbO and HbR concentration from these clusters revealed a significant effect in all three clusters. In the lSTG and rSTG, HbO concentration was significantly greater than HbR concentration (rSTG: p = .048; lSTG: p = .030) – see *Figure 5.3* (a-b). In the lSPL, HbR concentration was significantly greater than HbO concentration (p = .025) – see *Figure 5.3* (c). There were no significant clusters for joint attention in caregivers and continued attention in infants.

For meeting the third, fourth and fifth objectives of the study, HbO concentration was extracted from these regions for joint attention in caregivers and continued attention in infants (as well as joint attention in infants).

Table 5.4 Significant clusters showing chromophore-related differences in infant joint attention brain data. * Indicates effects that yielded significant results after follow-up tests, whilst controlling for infant age.

Model	Effect	Cluster	Size (mm^3)	MNI coordinates		
				Centre of Mass		
				x	y	z
Infant joint attention	Chromophore	Right superior temporal gyrus (rSTG)*	381	-62.4	+38.5	+21.3
		Left superior temporal gyrus (lSTG)*	212	+62.1	+36.0	+15.3
		Left superior parietal lobule (lSPL)*	117	+27.1	+65.2	+58.1

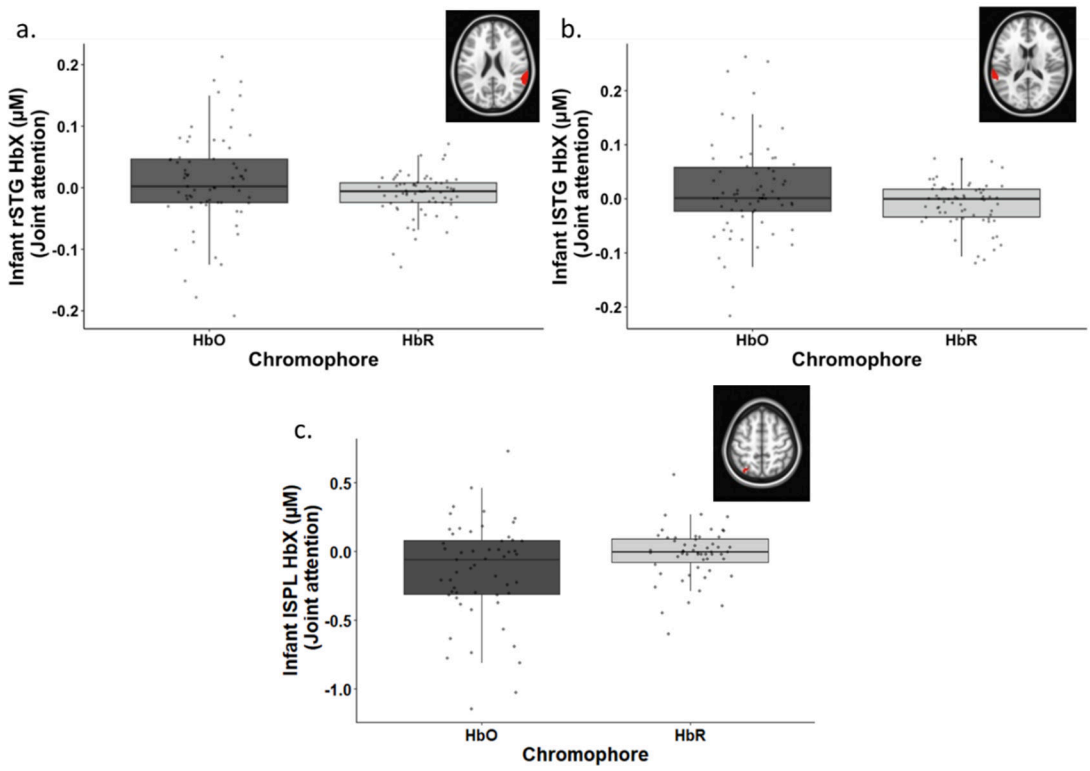


Figure 5.3 Activation in (a) rSTG and (b) lSTG, and suppression in (c) lSPL during joint attention in infants.

5.4.2.2 Brain-behaviour associations between joint and continued attention in caregivers and infants

The third research objective was to examine whether there was an association between brain function in caregivers and brain function in infants during joint attention, and whether this brain function was related to duration of joint attention. To do this, three regression models were run each for lSTG HbO concentration, rSTG HbO concentration, and lSPL HbO concentration. These models examined three associations: (1) between HbO concentration in caregivers during joint attention and HbO concentration in infants during joint attention, (2) between HbO concentration in caregivers during joint attention and duration of joint attention, and (3) between HbO concentration in infants during joint attention and duration of joint attention. Significant associations were found only for the lSTG cluster. Specifically, reduced lSTG HbO concentration in caregivers during joint attention was associated with reduced lSTG HbO concentration in infants during joint attention ($F_{(2,63)} = 3.54$, $p = .037$, $\eta^2 = .07$) – see *Figure 5.4* (a). Further, reduced lSTG HbO concentration in caregivers during joint attention was associated with longer duration of joint attention ($F_{(2,65)} = 2.65$, $p = .038$, $\eta^2 = .06$) – see *Figure 5.4* (b).

The fourth research objective was to examine whether duration of continued attention in infants was associated with brain function in infants during continued attention, brain function in caregivers during joint attention and brain function in infants during joint attention. To do this, three regression models were run each for lSTG HbO concentration, rSTG HbO concentration, and lSPL HbO concentration. These models examined three associations: (1) between the duration of continued attention in infants and HbO concentration in infants during continued attention, (2) between the duration of continued attention in infants and HbO concentration in infants during joint attention, and (3) between the duration of continued attention in infants and HbO concentration in caregivers during joint attention. There was only one significant association in the lSTG. Specifically, longer duration of continued attention in infants was associated with reduced lSTG HbO concentration in caregivers during joint attention ($F_{(2,66)} = 3.03$, $p = .023$, $\eta^2 = .08$) – see *Figure 5.4* (c).

5.4.3 Association between joint and continued attention and infant CP score at the low load

The fifth research objective was to examine whether afore-mentioned caregiver-infant behaviours and brain function during dyadic interactions predicted infant looking behaviours. Four key measures were used as predictors based on significant effects in objectives 1-4 i.e. duration of joint attention, duration of continued attention, lSTG HbO concentration in caregivers during joint attention, and lSTG HbO concentration in infants during joint attention. Thus, four models were run. The first model included duration of joint attention as the predictor and infant CP score as the outcome. The second model included duration of continued attention as the predictor and infant CP score as the outcome. The third model included lSTG HbO concentration in caregivers during joint attention as the predictor and infant CP score as the outcome. The fourth model included lSTG HbO concentration in infants during joint attention as the predictor and infant CP score as the outcome. Note that these measures were not included in the same model as most of them were related to each other (see previous sections). There was only one significant association. Specifically, reduced lSTG HbO concentration in caregivers during joint attention was associated with a higher infant CP scores ($F_{(2,61)} = 6.12$, $p = .001$, $\eta^2 = .16$) – see *Figure 5.4* (d).

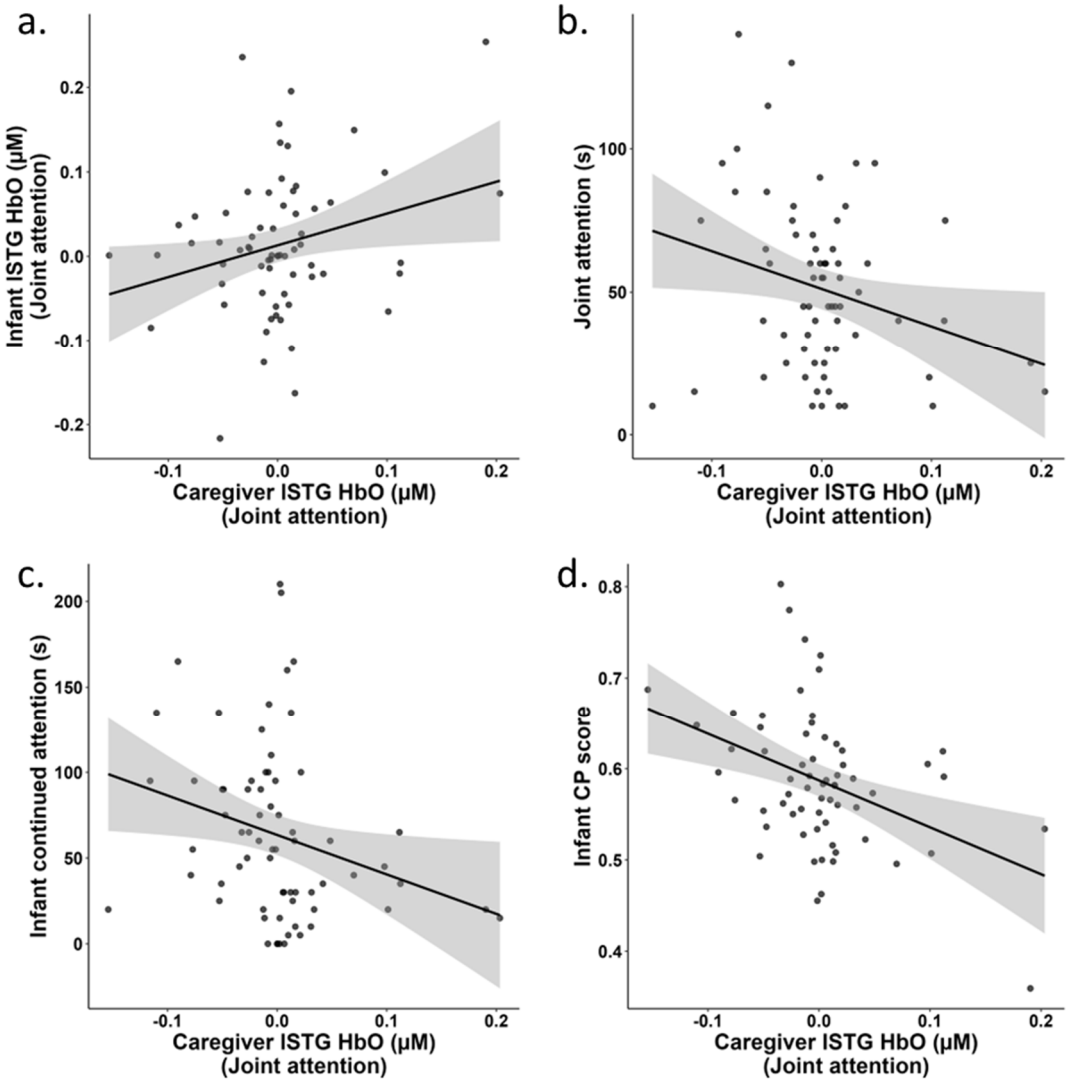


Figure 5.4 Reduced lSTG HbO concentration in caregivers during joint attention was associated with (a) reduced lSTG HbO concentration in infants during joint attention, (b) longer duration of joint attention, (c) longer duration of continued attention in infants, and (d) higher CP scores in infants.

5.5 Discussion

The over-arching objective of this chapter was to examine duration of, and brain function underlying periods of joint and continued attention in caregivers and infants. Following this, this chapter aimed to examine whether these behaviour and brain measures were associated with infant VWM. To this end, video recordings and brain function data were collected from caregivers and infants while they naturalistically engaged each other with toys. VWM was assessed in infants using the preferential looking task – see Chapter 3 (also Theyer et al., 2024).

This chapter had five research objectives. The first objective was to examine whether duration of joint attention was associated with duration of continued attention in infants. Duration of caregiver-infant joint attention was positively associated with duration of infant continued attention. The second objective was to identify key brain regions engaged in caregivers and infants during periods of joint and continued attention. Infants showed bilateral activation in the STG and suppression in the lSPL during joint attention. The third objective was to examine whether there was an association between brain function in caregivers and brain function in infants during joint attention and, how these brain function measures were linked to duration of joint attention. Reduced lSTG activation in caregivers during joint attention was associated with longer duration of joint attention and reduced lSTG HbO concentration in infants during joint attention. The fourth objective was to examine whether the duration of continued attention in infants, was associated with brain function in infants during continued attention, brain function in infants during joint attention, and brain function in caregivers during joint attention. Reduced lSTG activation in caregivers during joint attention was associated with longer duration of continued attention in infants. The final research objective was to examine whether afore-mentioned caregiver-infant behaviours and brain function during dyadic interactions would predict VWM measured using preferential looking task. Here, reduced lSTG HbO concentration in caregivers during joint attention was associated with a higher infant CP scores. These findings are expanded upon below.

5.5.1 Association between duration of joint and continued attention

The first objective was to investigate whether duration of joint attention was associated with duration of continued attention in infants. Here, duration of caregiver-

infant joint attention was positively associated with duration of infant continued attention. These findings are in line with previous work investigating caregiver-child interactions in the later-infancy/toddlerhood period (Michel et al., 2024; Schatz et al., 2022; Schroer & Yu, 2022; Wass, Noreika, et al., 2018; Yu & Smith, 2016). For example, head-mounted eye-tracking used to observe free-play interactions with objects in infants aged 1 year, found that instances of sustained attention that occurred alongside caregiver joint attention were significantly longer than those that occurred without joint attention (Yu & Smith, 2016). Further, in similar settings, infants aged 1 year exhibited longer look durations along with fewer and shorter periods of inattentiveness, during joint play in comparison to solo play (Wass, Noreika, et al., 2018). Similarly, in another study observing caregiver-child interactions with objects in homes, play bouts with the presence of caregiver joint engagement were longer compared to bouts without caregiver input (Schatz et al., 2022). Furthermore, additional caregiver input, such as caregiver ostensive signals, has been associated with increased infants' attention and object encoding in infants aged 9 and 10 months (Michel et al., 2024). These behavioural links demonstrate that caregiver-infant joint attention is associated with continued attention in infants as young as 6 to 10 months and set the precedence for exploring underlying brain function.

5.5.2 Brain function underlying joint and continued attention

The second objective was to identify key brain regions engaged in caregivers and infants during periods of joint and continued attention. Activation in the bilateral STG and suppression in the lSPL was observed in infants during joint attention. The STG has been implicated in several aspects of social cognition and perception (Deen et al., 2015), including perception of speech and sound (Belin et al., 2000; Noppeney et al., 2008), perception of motion (Allison et al., 2000; Bonda et al., 1996; Carter & Pelphrey, 2006; Grossman et al., 2004; Grossman & Blake, 2002; Morris et al., 2005), visual attention to salient events (Corbetta & Shulman, 2002), theory of mind (Ciaramidaro et al., 2007; Gallagher et al., 2000; Saxe & Kanwisher, 2003; Saxe & Powell, 2006), and understanding actions of others, such as gaze shifts (Hoffman & Haxby, 2000; Pelphrey et al., 2003; Puce et al., 1998) and reaching (Pelphrey et al., 2004; Vander Wyk et al., 2012). Temporal activation has also been reported during joint attention in other similar fMRI studies requiring adults to interact with the gaze behaviour of a partner presented on a monitor (Materna et al., 2008; Redcay et al.,

2012; Schilbach et al., 2010). Further, the superior temporal cortex has also been associated with communication abilities later in toddlerhood (Smith et al., 2023). This finding is also consistent with research suggesting that joint attention relies on integrated activity between the anterior and posterior attention systems (Mundy et al., 2000; Mundy & Newell, 2007; Posner & Rothbart, 2007). The STG is among other regions supporting the posterior attention system. The posterior attention system is thought to develop within the first few months of life, is thought to be mostly involuntary, prioritising attention to biologically relevant stimuli (Mundy & Newell, 2007). This system is thought to be involved in responding to joint attention bids, which requires the ability to follow another person's gaze or gestures, in order to reach shared focus. It is possible that at this stage in infancy, infants recruit the STG, primarily in responding to joint attention bids of their caregiver. In another study, eye-tracking and fMRI were used with children and adolescents to examine brain activation while they either initiated or responded to gaze interactions with a partner presented on a screen. The authors also reported joint attention related activation in a cluster which extended to the left temporal lobe (Oberwelland et al., 2016).

Interestingly, infants also showed suppression in the parietal cortex during joint attention. Opposing temporo-parietal patterns have been reported in experimental studies of attention and VWM in adults and infants. For instance, one study found increasing parietal activation and temporal suppression with increasing VWM demands in adults (Todd & Marois, 2004). In another study, infants demonstrated parietal activation and temporal suppression when engaging with a preferential looking task (Wijeakumar et al., 2023). Taken together, infants seem to demonstrate parietal activation and temporal suppression in response to attention and VWM demands in the absence of a social partner but elicit temporal activation and parietal suppression during joint attention with a social partner. Future work should seek to elucidate the exact nature of the mechanism(s) involved in this temporo-parietal engagement.

Whilst there were significant effects in infants that align with findings in older children, there were no significant clusters of activation during joint attention in caregivers and continued attention in infants. Absence of these effects does not align with previous work in adults. For example, left temporal activation has been reported when adults jointly engage with gaze behaviours of a partner presented on a monitor

in fMRI studies (Redcay et al., 2012; Schilbach et al., 2010). In this study, it is possible that the fNIRS channels did not directly overlap key regions in the temporal cortex involved in joint attention in adults or continued attention in infants. However, activation extracted from the lSTG region (activated during joint attention in infants) during joint attention in caregivers and continued attention in infants yielded significant associations suggesting that these areas are, nonetheless, important for dyadic interactions – these findings are discussed in the section below.

5.5.3 Brain associations during joint and continued attention in caregivers and infants

The third objective was to examine whether there was an association between brain function in caregivers and brain function in infants during joint attention, and how these brain function measures were linked to duration of joint attention. Further, the fourth objective was to examine whether duration of continued attention in infants was associated with brain function in infants during continued attention, brain function in infants during joint attention, and brain function in caregivers during joint attention. Findings revealed caregiver-infant links in the left lateralised lSTG. Here, caregivers who showed reduced lSTG activation also had infants who showed reduced lSTG activation during joint attention. Spatio-functional lSTG alignment in caregivers and their infants' might shed light on the heritable nature of brain function. For example, findings from twin studies have demonstrated structural heritability in the temporal cortex in children (Lenroot et al., 2009; van der Meulen et al., 2020). The TPJ also demonstrates additional shared environmental influences, suggesting that this region is also sensitive to social experiences (van der Meulen et al., 2020). Along a similar vein, studies have reported pronounced neural synchrony in the temporal cortex between caregivers and children during cooperative interactions (Jiang et al., 2012; Miller et al., 2019; Nguyen et al., 2020).

Interestingly, there were also links between lSTG activation in caregivers and duration of joint and continued attention periods. Critically, caregivers with reduced lSTG activation during joint attention engaged in longer periods of joint attention with their infants and had infants who also demonstrated longer periods of continued attention. To maintain longer bouts of joint or continued attention, social partners need to efficiently maintain and update items/goals/actions in working memory while suppressing distractions and irrelevant stimuli. It is possible that reduced activation or

suppression of the temporal cortex is necessary for enhancing engagement in fronto-parietal regions linked to critical cognitive functions, which then impacts the duration of joint and continued attention. This interpretation partially aligns with evidence from experimental neuroimaging studies in adults and infants showing that suppression in the temporal cortex and activation in the parietal cortex is linked to attention and working memory processing in adults (Todd et al., 2005; Todd & Marois, 2004) and infants (Wijeakumar et al., 2023). This interpretation is particularly relevant to the final research objective discussed below.

5.5.4 Association between caregiver-infant brain-behaviour measures during joint and continued attention and infant visual cognition

The final research objective was to examine whether afore-mentioned caregiver-infant behaviours and brain function during dyadic interactions would predict infant VWM measured using preferential looking task. Findings revealed that there were no links between caregiver-infant behaviours and infant VWM. The lack of behavioural associations was unexpected, given that joint attention has previously been associated with child EF (Brandes-Aitken et al., 2020), social abilities (Carpenter et al., 1998), language development (Carpenter et al., 1998; Morales et al., 2000), and IQ (Smith & Ulvund, 2003). For example, one study examined the association between caregiver-infant behaviours and social communication in infants aged 9 to 15 months (Carpenter et al., 1998). Here, caregiver-infant joint engagement and caregivers use of language were both associated with early communication abilities. In another study in pre-term children, the relationship between joint attention at 13 months and IQ at 8 years was examined (Smith & Ulvund, 2003). Here, initiation of joint attention was associated with later IQ, regardless of early health or developmental factors. Moreover, another study investigated the relationship between attuned caregiving behaviours during play at 15 months, joint attention at 24 months, and child EF at 48 months (Brandes-Aitken et al., 2020). Here, joint attention at 24 months partially mediated the positive association between attuned caregiving behaviours in toddlerhood and later child EF. Whilst there were no links between caregiver-infant behaviours and infant looking behaviours, there was an association between reduced lSTG activation in caregivers during joint attention and higher CP scores in infants. It is possible that caregivers who are better at suppressing lSTG during play interactions, can more promptly pick up on cues, and guide and shape their infants' cognitive

abilities resulting in longer bouts of joint attention and continued attention – eventually, improving infants' VWM. This interpretation partially aligns with evidence from studies reporting left temporal engagement in visual and verbal working memory studies in children, adolescents, and adults (Brahmbhatt et al., 2008; Delgado Reyes et al., 2020). For instance, one study administered the preferential looking task to children aged 4 months, 1 year, and 2 years (Delgado Reyes et al., 2020). Across all ages, children similarly activated a cluster in the lSTG in completion of the task. In another study, verbal working memory was examined using an "n-back" task in adolescents and adults. During the task, both adolescents and adults similarly activated a cluster in the lSTG (Brahmbhatt et al., 2008). In contrast, these studies reported lSTG activation during visual and verbal working memory tasks, however, findings here suggest that this region must be suppressed during social interactions. Further research is required to better compare contextual variation in brain function across dyadic interactions and experimental tasks.

5.6 Conclusions

The over-arching objective of the current chapter was to examine brain function in infants and caregivers during critical attention periods in dyadic interactions, and whether extent of engagement and brain function during these periods were associated with VWM in infants. In line with previous findings, duration of joint attention between caregivers and infants was linked to duration of continued attention in infants. Importantly, reduced lSTG activation in caregivers during joint attention was associated with reduced lSTG activation in infants during joint activation, longer duration of joint and continued attention, and better VWM in infants. The current findings contribute to the understanding of cortical mechanisms engaged during attention periods in caregiver-infant interactions, and importantly, how these mechanisms might be linked to visual cognition in infants.

5.7 Motivations for the Next Chapter

The third chapter in this thesis found associations between caregiver and infant visual neurocognition during an experimental preferential looking task. The fourth chapter in this thesis also found caregiver-infant brain associations during dyadic interactions. However, in the fourth chapter, there were no associations between caregiver-infant behaviours or brain function and infant VWM during the preferential

looking task. In this chapter there was a positive association between joint and continued attention durations during dyadic interactions. Importantly, reduced temporal activation in caregivers was also associated with reduced temporal activation in infants, longer duration of joint and continued attention, as well as better VWM in infants. Whilst these findings highlight a potential mechanism for how behaviour and brain function during play interactions might influence visual cognition in infancy, further examination is required to establish whether early brain-behaviour associations observed during play interactions stabilise or shift over time, and whether these changes predict later visual cognitive abilities. The next chapter in this thesis therefore aims to investigate longitudinal associations between infant and toddler visual neurocognition and the impact of caregiver influences on these associations.

Chapter 6:

Longitudinal changes in visual neurocognition from infancy to toddlerhood

A version of this chapter is in preparation for publication

Theyer, A., Dabholkar, A., Spencer, J. & Wijeakumar, S. (in prep). Longitudinal changes in visual neurocognition from infancy to toddlerhood

6.1 Introduction

Visual cognition undergoes significant changes after infancy – with considerable impact on both academic (Alloway & Alloway, 2010; Bull & Scerif, 2001; Conway et al., 2003; Fukuda et al., 2010; Gathercole et al., 2004; Leather & Henry, 1994; Swanson & Beebe-Frankenberger, 2004) and social (de Wilde et al., 2016; McQuade et al., 2013) outcomes. Importantly, these abilities are receptive to intervention (Lakes & Hoyt, 2004; Lillard & Else-Quest, 2006; Raver et al., 2008, 2011), highlighting the malleability of this system in early childhood. Understanding the development of this system may provide support for existing theoretical frameworks, identify critical periods of change or stability, and identify windows for interventions to maximise developmental outcomes.

6.1.1 Visual neurocognition across early childhood – evidence from cross-sectional studies

Most previous research has shown developmental changes in visual neurocognition using cross-sectional samples of children. For example, Kaldy et al. (2016) used the delayed match retrieval paradigm in infants, which examines location binding, and reported that while 10-month-olds were able to store object location information for two items, 8-month-olds did not show this ability. Children show similar task performance in toddlerhood, with older toddlers demonstrating better ability to store object information under complex conditions (Cheng et al., 2019a, 2019b, 2020). For instance, while both 20-month-old and 25-month-old toddlers could track items while they were static, only the older group could maintain items within VWM when motion was added (Cheng et al., 2019b). Similar increases in working memory performance have been observed in adaptations of the Spin-the-Pots task (Morra et al., 2021). As described in previous chapters, the preferential looking paradigm (Ross-Sheehy et al., 2003) has also been used to examine developmental changes in VWM from infancy to toddlerhood. For instance, Delgado Reyes et al. (2020) used variations of the preferential looking task to examine capacity limits in children aged 4 months, 1 year, and 2 years of age. In this study, children aged 4 months were presented with a load manipulation of one, two, and three items, and children aged 1 and 2 years were presented with a load manipulation of two, four, and six items. The authors reported that at 4 months, children showed robust change preference at a load of one item only. They also began to show above chance looking

towards the changing side for two items around the middle of the trial, and for three items towards the end of the trial. At 1 year, children showed robust change preference abilities at a load of two items. They also began to show above chance looking at the higher loads by around 7 seconds. Finally, at 2 years, above-chance performance was observed at the highest load (six items) by 2-4 seconds. These results indicate that the latency to robust change preference abilities at higher loads improves from infancy to toddlerhood. However, the factors that might influence this developmental trajectory remain unclear.

There are significant shifts in visual cognitive abilities from infancy to toddlerhood, however, it is critical to understand what mechanisms drive these early changes. One approach to understanding underlying mechanisms is to examine brain function alongside behaviour during paradigms used in infants and toddlers – this is especially valuable given the difficulties of conducting longitudinal studies during the early developmental period. Early neuroimaging studies in infancy and childhood have implicated both frontal and posterior parietal regions in the development of visual cognition (Bell & Fox, 1992; Fox & Bell, 1990). Some research has indicated that the frontal cortex plays a key role in infant visual cognition. For example, Delgado Reyes et al. (2020) used fNIRS to record brain function, and found that 4-month-old infants showed increased activation in the MFG compared to 1-year-old infants. The authors also found that the rDLPFC showed an early association with look duration, hypothesised to reflect the emergence of early looking abilities, such as shifting between displays, controlling consolidation, and releasing from fixation (Perone et al., 2011; Perone & Spencer, 2013). Children also began to show load-dependent modulation in parts of the parietal cortex, such as the laIPS. Here, as load demand increased, activation also increased, until capacity was surpassed, after which this activation plateaued. Finally, in the raIPS, the authors also found quantitative increases in activation between 1 and 2 years of age. At 2 years, increased activation in this region was also associated with lower switch rates. This finding was thought to represent the refinement of visual cognition processes anchored in parietal regions. In another study, fMRI data was collected from awake infants, aged 3 to 12 months, completing a cueing task (Ellis et al., 2021). Here, infants showed engagement of frontal regions from adult attention networks, such as the MFG and IFG. Interestingly, both behavioural and brain findings were consistent across the ages, suggesting that

there were no developmental changes in stimulus-driven attention in this period. To summarise, visual cognitive abilities continue to undergo significant changes from infancy to toddlerhood. Neuroimaging studies have linked these behavioural changes to maturation in both frontal and parietal brain regions. The emergence of specialised regions appears to support improvements in capacity, precision and attentional control over development. While cross-sectional studies have identified regions contributing to visual cognition at various timepoints, longitudinal research is needed, to better understand the trajectory of the emergence and refinement of this fronto-parietal network over development.

6.1.2 Visual neurocognition across early childhood – evidence from longitudinal studies

Longitudinal research provides researchers with a more accurate understanding of developmental changes as they tap into how behaviours and specific brain regions engaged during one developmental time-point changes/shifts at the next developmental point. For example, one study examined the emergence of object permanence between the ages of 5 and 12 months, conducting assessments at 4-week intervals (Baird et al., 2002). While the age at which children reached object permanence varied, the emergence of this behaviour was consistently associated with increases in frontal cortex activation. Importantly, while some children demonstrated reaching behaviours at earlier time-points, increased frontal activation only occurred when object permanence was achieved, suggesting that this activation pattern is specific to the cognitive shift associated with the emergence of this behaviour. This finding supports the engagement of frontal regions in association with specific visual cognitive behaviours in early infancy. Another study examined EEG in infants between 5 and 10 months of age, both at baseline and as they engaged in a looking A-not-B working memory task (Cuevas & Bell, 2011). At baseline, age-related increases in EEG power were found in most regions, with the exception of the frontal pole and lateral frontal areas, aligning with evidence for the protracted development of the frontal cortex (Casey et al., 2005; Chugani, 1994; Collin & Den Heuvel, 2013; Huttenlocher, 1990; Huttenlocher & Dabholkar, 1997; Matsuzawa et al., 2001). Additionally, younger infants showed greater engagement of parietal regions compared to older infants. Further, age-related increases in EEG coherence, thought to be a marker of functional connectivity, were observed between frontal and frontal-

posterior electrode pairs. These findings suggested a shift from early parietal engagement to increased integration of frontal-posterior VWM brain regions across the second half of the first year. In another study, EEG power and coherence was examined from infancy to early childhood during completion of the looking A-not-B task (Bell & Wolfe, 2007). Here, infants were first examined at 8 months and then followed up at 4.5 years. In infancy, VWM was associated with widespread cortical changes in EEG power across the whole scalp, with EEG coherence changes occurring across all electrode pairs. However, later in childhood, changes in EEG power were localised to frontal regions, and coherence changes to frontal-posterior pairs. These findings suggest that early VWM processing involves more widespread cortical activation, including less mature frontal regions which may support more basic visual cognition processes. Over development, this is thought to shift to more refined and specialised engagement in childhood, supporting emerging higher-order processes.

6.1.3 Impact of caregiving on developmental changes in visual neurocognition

While previous studies have examined the development of behaviour and brain function underlying visual cognition across childhood, the contributing roles of caregiver behaviours and caregiver EF in shaping these longitudinal changes remain unclear. There is some evidence to suggest that caregiver attentional behaviours during dyadic interactions play a critical role in early development. For instance, one study examined how joint and sustained attention at 9 months predicted language development at 12 and 15 months (Yu et al., 2019). Here, infant sustained attention within the context of caregiver-infant joint attention yielded stronger predictions, compared to joint attention by itself. Another study reported that joint attention partially mediated a positive relationship between attuned caregiving behaviours in toddlerhood and later child EF (Brandes-Aitken et al., 2020). In addition to behavioural outcomes, previous work has also linked caregiving behaviours to early brain development. For example, one study found that greater positive affect at 5 months, was associated with greater frontal EEG power at 10 and 24 months (Bernier et al., 2016). Importantly, greater positive affect was also linked to greater increases in frontal EEG power from 5 to 10 months and 10 to 24 months, implying that caregiver affect plays an ongoing role into this developmental trajectory. In contrast, a different study in older infants, aged 10 months, found contrasting results (Kraybill & Bell, 2013). Here, reduced frontal EEG power and greater positive affect were

shown to both jointly and uniquely predict child EF at both 4 and 6 years. These findings highlight that early caregiving behaviours impact developmental changes in both behaviour and brain changes.

6.2 Research Objectives

Through the use of novelty preference procedures, previous research has highlighted improvements in visual cognition over the first year, including increases in VWM capacity limits (Ross-Sheehy et al., 2003) and ability to process more complex stimuli (Mitsven et al., 2018; Oakes et al., 2013, 2017). In toddlerhood, cross-sectional research has found similar increases in visual cognition abilities (Cheng et al., 2019a, 2019b, 2020; Delgado Reyes et al., 2020; Kaldy et al., 2016). Early in life, neuroimaging studies have also implicated the frontal and posterior parietal cortex in the development of visual cognition (Baird et al., 2002; Bell & Wolfe, 2007; Cuevas, Bell, et al., 2012; Delgado Reyes et al., 2020; Ellis et al., 2021; McKay et al., 2021; Perlman et al., 2016; Perry et al., 2016; Todd & Marois, 2004, 2005; Wilcox & Biondi, 2016). However, no research has examined longitudinal changes in visual cognition behaviour and brain function in the first two years of life. Furthermore, existing studies have found that caregiver EF and/or caregiving behaviours impact child cognitive development (Bernier et al., 2010; Brandes-Aitken et al., 2020; Cuevas, Deater-Deckard, Kim-Spoon, Wang, et al., 2014; Cuevas, Deater-Deckard, Kim-Spoon, Watson, et al., 2014; Kraybill & Bell, 2013; Lugo-Gil & Tamis-LeMonda, 2008, 2008; Ribner et al., 2022; Suarez-Rivera et al., 2019). Nonetheless, it remains unclear to what extent afore-mentioned longitudinal changes in visual cognition behaviour and brain function are shaped by caregiver influences.

This chapter builds upon the current literature by examining longitudinal changes in looking behaviours and brain function from infancy to toddlerhood, and how caregiver looking behaviours and brain function and caregiver-infant dyadic behaviours impact these longitudinal changes. To achieve this, children were presented with a variant of the preferential looking task (Ross-Sheehy et al., 2003) at timepoint 1 (T1) in infancy. These findings are reported in Chapter 3. These children were then re-assessed with same task one year later - at timepoint 2 (T2). Across both timepoints, load was manipulated (T1: one, two, and three items; T2: two, four, and six items). Looking behaviours were extracted from video recordings, and brain function was recorded using fNIRS whilst the children engaged with the task.

This study had three research objectives. The first research objective was to investigate if there were longitudinal changes in behavioural performance from T1 to T2. Aligned with findings in infancy in Chapter 3, and findings in cross-sectional samples from Delgado Reyes et al. (2020), it was expected that toddler CP scores would decrease with increasing load. Specifically, Delgado Reyes et al. (2020) found that by 1 year of age, children show robust change preference at a load of two items, and by 2 years of age, children show robust change preference at loads of up to six items. Therefore, it was expected that there would be higher CP scores at T2 compared to T1. Delgado Reyes et al. (2020) also found increased visual exploratory behaviours with age. Thus, it was expected that children would demonstrate higher TLD scores at T2 in comparison to T1. Given that load-related findings are mixed for switching (Delgado Reyes et al., 2020; Wijeakumar et al., 2019), there were no clear predictions for SR, and an exploratory approach was followed.

The second research objective was to examine whether there were longitudinal changes in brain activation from T1 to T2. Previous work has reported increased activation (Buss et al., 2014) and load-dependent modulation (Buss et al., 2014; Delgado Reyes et al., 2020; Todd et al., 2005; Todd & Marois, 2004) in parietal regions across development. In addition, some of these studies and others have reported frontal activation in infancy associated with early visual cognition behaviours, such as attention-orienting and regulating shifting (Delgado Reyes et al., 2020; Ellis et al., 2021). Thus, it was expected that children would demonstrate increased activation in posterior parietal regions and decreased activation in frontal regions at T2 in comparison to T1.

The final research objective was to examine caregiver influences on longitudinal changes in behaviour and brain function. Previous studies have reported the impact of both caregiver attentional behaviours (Bernier et al., 2016; Brandes-Aitken et al., 2020; Kraybill & Bell, 2013; Yu et al., 2019) and caregiver EF (Cuevas, Deater-Deckard, Kim-Spoon, Wang, et al., 2014; Cuevas, Deater-Deckard, Kim-Spoon, Watson, et al., 2014; Ribner et al., 2022) on child cognitive development. Further, caregiver-child associations were also evident in previous studies presented in the thesis. Concretely, in Chapter 3, there was an association between caregiver looking behaviours, and infant looking behaviours and brain function providing evidence for the heritable nature of visual cognition (Theyer et al., 2024). In Chapter

5, there was evidence for caregiving-based/interaction-based influences on infant attention and looking behaviours. Specifically, there was an association between caregiver-infant joint attention and infant continued attention during dyadic interactions. Importantly, there was also an association between caregiver lSTG suppression during joint attention and infant VWM during the preferential looking task. In line with these findings, it was expected that both heritability- and caregiving-related factors would impact developmental changes in looking behaviours and brain function.

6.3 Materials and Methods

6.3.1 Participants

This chapter is part of a larger longitudinal project. Please refer to Chapter 3, Section 3.3.1 *Participants,* for details on recruitment criteria. Caregivers provided written informed consent prior to participation in the study and received £10 following each visit. Data collection was carried out at the University of Nottingham. Ethics approval was provided by the Research Ethics Committee at the University of Nottingham (Ethics Approval Number: T1: F1338; T2: F1415).

As previously detailed in Section 3.3.1 *Participants*, a total of 111 families initially expressed interest at T1 in the study. Of these, 17 families dropped out of the study before their first visit and 4 families were not included as the infant was not in the correct age range, resulting in 90 families who visited the lab (including one pair of twins). Of these, data from three families were later excluded from analyses due to a familial history of colour blindness. Further, two infants were excluded due to fussiness. The final sample at T1 consisted of a total of 86 infants (44 female, mean age: 8.24 ± 1.18 months, age range: 6.08 – 10.45 months, including one pair of twins).

At T2, 20 families (including one pair of twins) from T1 dropped out of the study. An additional eight families also expressed interest in the study. Of these eight, one more family dropped out of the study before their first visit. This resulted in 77 families who visited the lab at T2. Of these, data from two families were later excluded from analyses due to a familial history of colour blindness. The final sample at T2 therefore consisted of a total of 75 toddlers (43 female, mean age: 20.24 ± 0.84 months, age range: 18.57 – 22.02 months).

66 families were common across both T1 and T2 (36 female; T1: mean age 8.20 ± 1.14 months, age range: 6.11 – 9.96 months; T2: mean age 20.17 ± 0.78 months, age range: 18.57 – 22.02 months). A schematic representation of inclusion at T1 and T2 is shown in *Figure 6.1*. Further demographic and SES information is provided for each timepoint in *Table 6.1*.

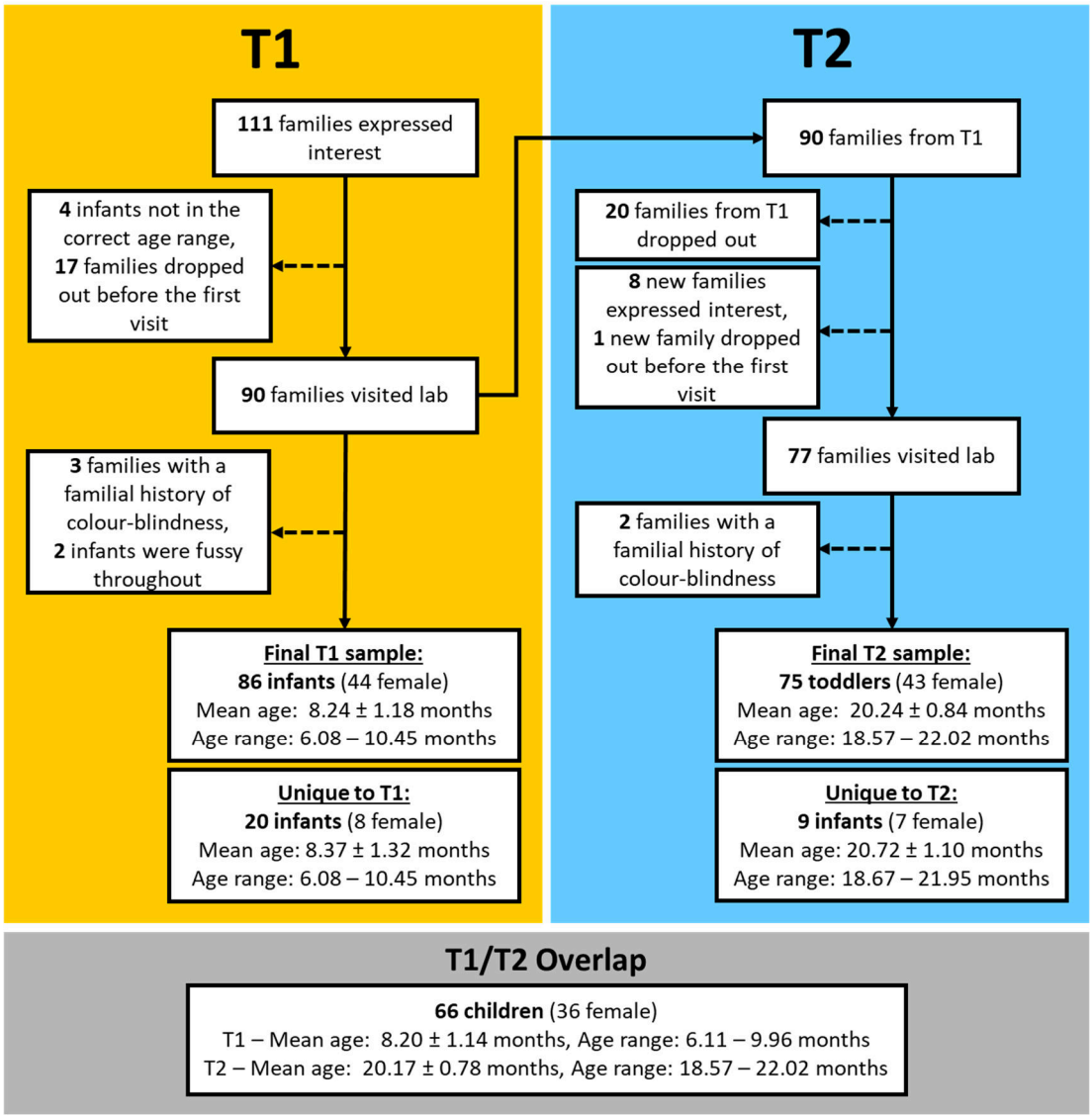


Figure 6.1 Schematic for recruitment, attrition, and exclusions across T1 and T2.

Table 6.1 Socioeconomic and demographic information was collected via questionnaire after the family visited the research facility. Details for the families who contributed data at each timepoint is presented. Longitudinal overlap refers only to subjects that provided data at both timepoints. For longitudinal overlap, ages are reported for each timepoint.

Family member	**Measure**		**T1**	**T2**	**Longitudinal Overlap**	
					T1	**T2**
Child	**Age**	N	86	75	66	66
		Mean (months)	8.24	20.24	8.20	20.17
		± SD	1.18	0.84	1.14	0.78
Primary Caregiver	**Age**	N	85	75	66	66
		Mean (years)	33.53	34.11	33.39	34.35
		± SD	4.52	4.35	4.49	4.52
	Education	N	75	67	60	
		Mean (years)	16.27	16.43	16.4	
		± SD	2.31	2.26	2.36	
	Income	N	69	62	56	
		Mean (£)	27,845	27,035	27,403	
		± SD	13,480	12,779	13,120	
	Ethnicity	Arab	0 %	1 %	0 %	
		Asian	6 %	7 %	8 %	
		Mixed	5 %	4 %	5 %	
		White British	75 %	76 %	77 %	
		Other White	1 %	1 %	2 %	
		Did not answer	13 %	11 %	9 %	
Secondary Caregiver	**Education**	N	74	67	60	
		Mean (years)	13.81	13.97	13.83	
		± SD	4.38	4.06	4.17	
	Income	N	49	45	41	
		Mean (£)	31,408	30,683	30,774	
		± SD	11.776	11,053	11,519	

6.3.2 *Children and caregiver preferential looking tasks*

Please refer to Section 3.3.2 *Infant and caregiver preferential looking tasks* for details of the preferential looking task used in infants at T1 and for caregivers. The task used at T1 was modified to be used at T2 with toddlers (both versions are shown in *Figure 6.2*). To manipulate load at T2, toddlers were presented with either two (low load), four (medium load) or six (high load) shapes on each side. At T2, toddlers completed between one and four runs of the task (mean: 2.08 ± 0.67). The number of runs/trials the child completed was dependent on the child's engagement with the task. At T2, video recordings that were used to code looking behaviours were collected as described in Chapter 3, Section 3.3.2.

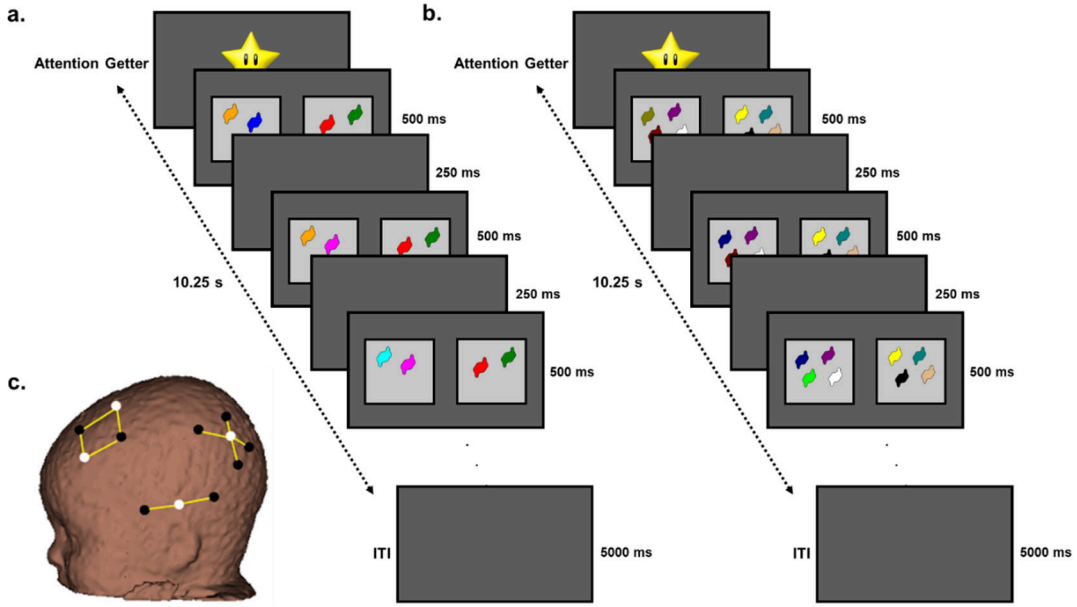


Figure 6.2 Preferential looking task used at (a) T1 and (b) T2. In both panels, the medium load is displayed with the changing side on the left. (c) fNIRS probe geometry with channels covering frontal, temporal, and parietal regions at both timepoints. White dots indicate sources, black dots indicate detectors, and yellow connections indicate channels.

6.3.3 *Dyadic interactions at T1*

Dyadic interaction procedures and analyses are described in detail in Chapter 4, Sections: 4.3.2 *Caregiver-infant dyadic interactions*, 4.3.4 *Procedure*, and 4.3.5.1 *Modality coding scheme*; and Chapter 5, Section 5.3.5.1 *Joint and continued attention coding scheme*.

6.3.4 fNIRS data collection

fNIRS data collection details have been described in Chapter 3, Section 3.3.3 *fNIRS data collection*, for T1 and caregiver preferential looking tasks. Details for fNIRS data collection for caregiver-infant dyadic interactions are described in Chapter 4, Section 4.3.2 *Caregiver-infant dyadic interactions*. At T2, fNIRS data was collected following the same methods for collecting T1 fNIRS data described in Chapter 3 – see *Figure 6.2* (c) for probe geometry.

6.3.5 Procedure

Data collection procedures are described for T1 in Chapter 3, Section 3.3.4 *Procedure*. At T2, the same procedures were followed (T2 mean number of visits: 2.13 ± 0.47).

6.3.6 Behavioural analyses

Behavioural analyses procedures are described for T1 in Chapter 3, Section 3.3.5 *Behavioural analyses*. At T2, the same procedures were followed. Two coders were trained and 22% of toddlers were coded for checking reliability. The mean Kappa value was 0.91. For T2 looking measures, 6 data points were identified as outliers and removed from the dataset (low load – SR: 1; medium load – SR: 1 and CP: 2; high load – SR: 1 and CP: 1). Behavioural analyses procedures for dyadic interactions are described in Chapter 5, Section 5.3.5.1 *Joint and continued attention coding scheme*.

6.3.7 fNIRS data analyses

fNIRS data analyses for T1 and caregiver preferential looking tasks are presented in Chapter 3, Section 3.3.6 *fNIRS data analyses*, and caregiver-infant dyadic interactions are presented in Chapter 5, Section 5.3.6 *fNIRS data analyses*. At T2, fNIRS data was analysed following the same methods for T1 fNIRS data analyses. Some differences are highlighted below.

Following pre-processing, 6.19 % of the T2 channels were pruned. Concretely, the percentage of trials lost was 10.21 % for low load, 10.22 % for medium load, and 9.83 % for high load. For image reconstruction, to account for age-specific differences in head size and shape at T2, an 18-month-old atlas was used (Richards et al., 2016). For group analyses, a group mask was created by taking the overlap between the T1 and T2 masks.

To examine longitudinal changes in brain function, a linear mixed effects model was run (in AFNI using *3dLME)*. This model contained load (low, medium, and high), chromophore (HbO and HbR), and timepoint (T1 and T2) as multi-level factors, and CP score as a quantitative variable. As this model examined both timepoints, only data from the overlap between the two masks was used. Resultant F-statistic interaction images were thresholded at an appropriate cluster-wise threshold (147 voxels) and a voxel-wise p-value of <.01 (using *3dClustSim* and *3dClusterize*). Average HbO and HbR concentration was extracted from significant clusters using *3dROIstats* for display and further analyses.

6.3.7.1 ROI analyses

ROI analyses are described for T1 in Chapter 3, Section 3.3.6.4 *ROI analyses*. Here, the same methods were followed, however, the ROIs were overlayed with the longitudinal group mask described above, to ensure that ROI analyses were restricted to the standardised group space from this chapter. Only ROIs that overlapped with this group mask were followed up for each participant (Voxel overlap – rsIPS: 192, rIPS: 27, lIPS: 16, lDLPFC: 151, rMFG: 9, rTPJ: 199) – see *Table 6.2*. From each of the overlapping regions, average HbO and HbR concentration for each load was extracted using *3dROIstats* for display and further analyses.

Table 6.2 List of ROIs that overlapped with the longitudinal group mask and were followed up in ROI-based analyses. These regions and co-ordinates are taken from a meta-analysis of VWM literature (Wijeakumar, Spencer, et al., 2015).

ROI	**Hemisphere**	**MNI coordinates**		
		x	**y**	**z**
Superior intraparietal sulcus (sIPS)	Right	25	-61	51
Intraparietal sulcus (IPS)	Right	30	-73	38
Intraparietal sulcus (IPS)	Left	-21	-65	46
Dorsolateral prefrontal cortex (DLPFC)	Left	-42	41	20
Middle frontal gyrus (MFG)	Right	49	6	31
Temporo-parietal junction (TPJ)	Right	62	-46	26

6.3.8 Statistical analyses

Statistical analyses were run using RStudio (v2023.03.0).

To examine the impact of load and timepoint on looking measures, separate two-factor ANCOVAs, with load and timepoint as within-subjects factors, and T1 age as a covariate, were run on TLD, SR, and CP scores. Next, to investigate associations between T1 and T2 looking behaviour, regression models were then run for each of the looking measures (TLD, SR, and CP scores). For each, the T2 looking measure was the outcome, and the mean-centered T1 looking measure was the predictor, whilst controlling for T1 age. Here, the T1 measures were mean-centered to account for baseline differences at T1 and increase interpretability of the data.

To examine differences in brain function from T1 to T2, a linear mixed effects model was run in AFNI, and average HbO and HbR concentration was extracted from significant clusters (see Section 6.3.7 *fNIRS data analyses*). Significant clusters were followed up to examine whether effects survived at the cluster level (as opposed to the voxel-level). Clusters showing a chromophore main effect were followed up using pairwise comparisons. Clusters showing an interaction effect were followed up using regression models. Follow-up tests included age as a covariate. Following this, to examine associations in brain function between T1 and T2 in significant whole-brain clusters, regression models with T2 HbX concentration as the outcome and mean-centered T1 HbX concentration as the predictor, and T1 age as a covariate were run.

Regarding ROI analyses, average HbO and HbR concentration for each load was extracted for each ROI (see Section 6.3.7.1. *ROI analyses*). Data from these ROIs were followed up for further analyses. To examine differences in brain function from T1 to T2 in each ROI, a regression model with chromophore, load, and CP as predictors, and T1 age as a covariate, was run, and all significant effects followed up. To examine associations in brain function between T1 and T2 in each ROI, regression models with T2 HbX concentration as the outcome and mean-centered T1 HbX concentration as the predictor, and T1 age as a covariate were run.

To examine whether longitudinal changes in behaviour and brain function are influenced by heritability-related and/or caregiving-related factors, separate moderation analyses were run in RStudio. Moderators were caregiver-infant joint attention and caregiver CP score at the low load.

Finally, spatial overlap between regions showing longitudinal changes and regions related to heritability and caregiving-related factors were quantified using *3dcalc* and *3dBrickStat* functions in AFNI. In addition, the Euclidian distance was calculated to compute distance between the clusters. Finally, to examine functional alignment in these regions, Pearson's correlations were run. *Table 6.3* presents the number of children included in each analysis.

Table 6.3 Number of infants and toddlers contributing to each analysis.

Analyses	**Variables determining number**	**Timepoint**	**Low**	**Medium**	**High**
Behavioural models	TLD	T1	86	86	86
		T2	74	74	73
	SR	T1	86	86	85
		T2	73	73	72
	CP	T1	86	83	86
		T2	74	72	72
Longitudinal brain model	CP	T1	86	86	86
		T2	62	63	62
Moderations	Brain	T1	86	86	86
		T2	62	63	62
	Caregiver CP	T1	78		
	Joint attention	T1	69		

6.4 Results

6.4.1 Longitudinal changes in looking behaviours from T1 to T2

6.4.1.1 Differences between T1 and T2 looking behaviours

To examine differences in looking behaviours between T1 and T2, separate two-way ANCOVAs with load and timepoint as within-subjects factors, and T1 age as a covariate, were run on TLD, SR, and CP scores – see *Table 6.4* for statistics. To maintain consistency with analyses in Chapter 3, age at T1 was chosen as the controlling variable. In addition, the ANCOVAs were also repeated with age difference as a covariate. There were no differences in the overall findings – see Appendix C: *Appendix Table C.2* for statistics.

For TLD score, there was a main effect of timepoint ($F_{(1,61)} = 10.27$, $p = .002$; T1: 6117.73 ± 1128.11, T2: 6790.00 ± 1395.85). Here, TLD score was significantly greater at T2 in comparison to T1, indicating that children spent a significantly longer amount of time exploring the displays at T2 in comparison to T1 – see *Figure 6.3* (a). There was no main effect of load and no interaction between load and timepoint on TLD score.

For SR score, there was a main effect of timepoint ($F_{(1,30)} = 23.80$, $p < .001$; T1: 0.47 ± 0.16, T2: 0.34 ± 0.16). Here, SR score was significantly greater at T1 in comparison to T2, indicating that children switched between the two displays at a significantly higher rate at T1 in comparison to T2 – see *Figure 6.3* (b). There was no main effect of load and no interaction between load and timepoint on SR score.

Finally, for CP score, there was a main effect of load ($F_{(2,114)} = 12.98$, $p < .001$; low: 0.58 ± 0.06, medium: 0.56 ± 0.05, high: 0.53 ± 0.07). Pairwise comparisons revealed that CP scores at the high load were significantly lower than CP scores at the medium ($p = .022$) and low ($p < .001$) loads – see *Figure 6.3* (c). These results indicate that at across both timepoints, as load increased, CP scores decreased. In addition, to assess whether CP scores were significantly greater than chance, one-sample t-tests were also run at each load. These revealed that CP scores were significantly greater than chance at the low ($t(64) = 11.56$, $p < .001$), medium ($t(59) = 8.16$, $p < .001$), and high ($t(63) = 3.41$, $p < .001$) loads. There was no main effect of timepoint and no interaction between load and timepoint on CP score.

Table 6.4 Summary of statistics, ANCOVA results and findings for looking measures across load and timepoint whilst controlling for T1 age. * p < .05, ** p < .01, and *** p < .001

Measure	Effect	F Statistic	p Value	Sig.	Timepoint	Load	Mean	± SD	Summary of results
TLD	Load x Timepoint	0.43	0.650	ns	T1	Low	6069.95	1163.35	-
						Medium	6097.72	1152.35	
						High	6185.52	1329.05	
					T2	Low	6640.97	1556.75	
						Medium	6878.98	1536.50	
						High	6844.78	1718.54	
	Load	1.01	0.366	ns	-	Low	6397.10	1098.40	-
						Medium	6509.10	1088.65	
						High	6553.09	1098.40	
	Timepoint	10.27	0.002	**	T1	-	6117.73	1128.11	T1 < T2
					T2		6790.00	1395.85	
	Age (T1)	0.64	0.426	ns	-	-	-	-	-
SR	Load x Timepoint	1.05	0.354	ns	T1	Low	0.50	0.19	-
						Medium	0.46	0.17	
						High	0.45	0.18	
					T2	Low	0.33	0.17	
						Medium	0.34	0.20	
						High	0.35	0.20	
	Load	1.10	0.338	ns	-	Low	0.41	0.12	-
						Medium	0.40	0.13	
						High	0.40	0.14	
	Timepoint	23.80	< .001	***	T1	-	0.47	0.16	T1 > T2
					T2		0.34	0.16	
	Age (T1)	0.51	0.479	ns	-	-	-	-	-
CP	Load x Timepoint	0.69	0.505	ns	T1	Low	0.59	0.08	-
						Medium	0.55	0.07	
						High	0.54	0.07	
					T2	Low	0.57	0.10	
						Medium	0.56	0.10	
						High	0.52	0.10	
	Load	12.98	< .001	***	-	Low	0.58	0.06	High < Low ***, High < Medium *
						Medium	0.56	0.06	
						High	0.53	0.07	
	Timepoint	0.16	0.690	ns	T1	-	0.56	0.04	-
					T2		0.55	0.06	
	Age (T1)	0.08	0.778	ns	-	-	-	-	-

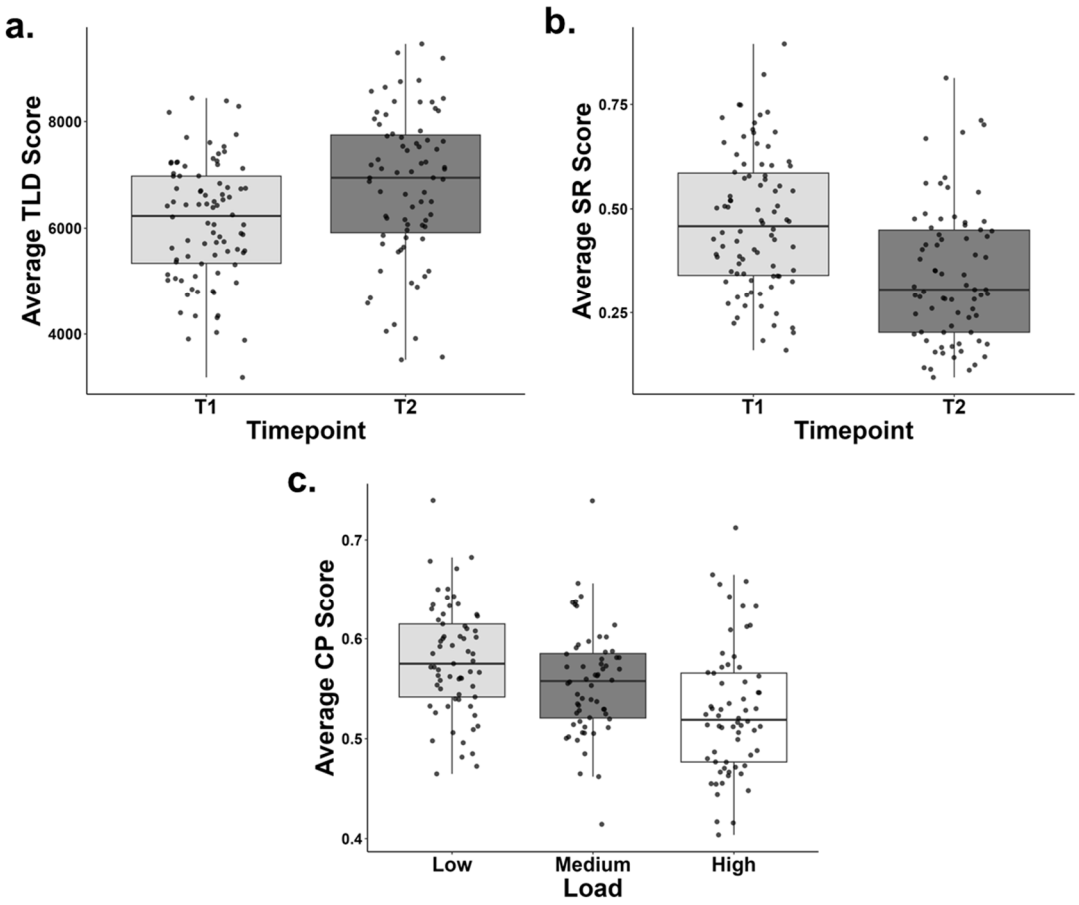


Figure 6.3 Main effect of timepoint on (a) TLD score and (b) SR score, and (c) main effect of load on CP score.

To summarise, from T1 to T2, there was a significant increase in the length of time the children spent exploring the displays, and a significant decrease in the rate at which children switched between the two displays.

Across both T1 and T2, as load increased, CP scores decreased. Across T1 and T2, children therefore showed greater ability to detect the changing side at the low load, in comparison to both the medium and high loads.

6.4.1.2 Associations between T1 and T2 looking behaviours

To investigate associations between T1 and T2 looking behaviour, separate regression models were run for each of the looking measures (TLD, SR, and CP scores). Each model had the T2 looking measure as the outcome, and the mean-centered T1 looking measure and load as the predictors, whilst controlling for T1 age. There were no significant interactions, indicating that T1 looking measures did not significantly predict T2 looking measures.

6.4.2 Longitudinal changes in brain function from T1 to T2

6.4.2.1 Differences between T1 and T2 brain function

To examine longitudinal changes in brain function, a linear mixed effects model was run – see *Table 6.5*. This model revealed a main effect of chromophore in four clusters, located in the lMFG (x = +42.8, y = -31.2, z = +30.3), rSPL (x = -31.3, y = +62.5, z = +57.7), rSFG (x = -24.9, y = -28.1, z = +53.9), and rMFG (x = -43.6, y = -24.0, z = +42.2). Here, follow-up tests were run for each chromophore, whilst controlling for T1 age. These tests revealed that HbO concentration was significantly greater than HbR concentration in the lMFG ($t(111) = 2.81$, $p = .006$), rSPL ($t(111) = 3.44$, $p < .001$), and rMFG ($t(111) = 4.06$, $p < .001$) – see *Figure 6.4*. These findings suggest that across both timepoints, children similarly activated the lMFG, rSPL, and rMFG.

Table 6.5 Significant clusters showing chromophore main effect, interaction between timepoint and chromophore, and interaction between CP score, timepoint, and chromophore.* Indicates significant results after follow-up tests. † Indicates result was trending towards significance after follow-up tests.

Effect	Cluster	Size (mm^3)	MNI coordinates		
			Centre of Mass		
			x	y	z
Chromophore main effect	Left middle frontal gyrus (lMFG)*	657	42.8	-31.2	30.3
	Right superior parietal lobule (rSPL)*	511	-31.3	62.5	57.7
	Right superior frontal gyrus (rSFG)	293	-24.9	-28.1	53.9
	Right middle frontal gyrus (rMFG)*	149	-43.6	-24.0	42.2
Interaction between timepoint and chromophore	Left middle temporal gyrus (lMTG)†	238	62.3	34.3	4.3
	Right superior parietal lobule (rSPL)*	210	-37.7	64.1	53.3
	Left middle frontal gyrus (lMFG)*	163	37.6	-40.8	27.4
Interaction between CP score, timepoint and chromophore	Left middle frontal gyrus (lMFG)*	156	37.5	-40.1	28.3

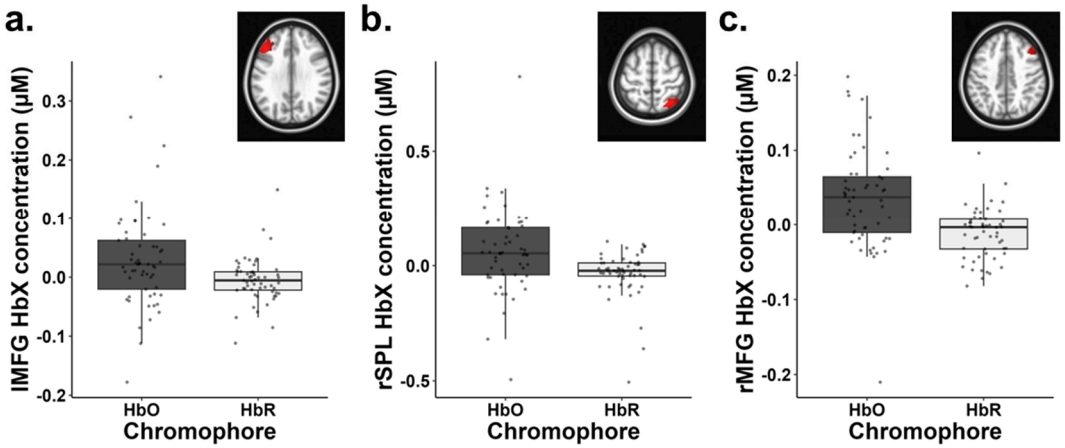


Figure 6.4 Main effect of chromophore in (a) lMFG, (b) rSPL, and (c) rMFG. In all regions, HbO was significantly greater than HbR. HbO concentration is shown in black and HbR concentration is shown in grey.

There was a significant interaction between timepoint and chromophore in three clusters - in the lMTG (x = +62.3, y = +34.3, z = +4.3), rSPL (x = -37.7, y = +64.1, z = +53.3), and lMFG (x = +37.6, y = -40.8, z = +27.4). Follow-up tests only revealed a significant interaction effect for the rSPL and lMFG clusters, and a marginally insignificant interaction effect for the lMTG cluster. In the rSPL cluster, follow-up tests revealed that HbO concentration was significantly greater than HbR concentration at T2 ($F_{(2,111)}$ = 4.01, p = .006, η^2= .07). Further, HbR concentration at T2 was significantly lower than HbR concentration at T1 ($F_{(2,140)}$ = 4.45, p = .004, η^2= .06) see *Figure 6.5* (a). In the lMFG cluster, follow-up tests revealed that HbO concentration was significantly greater than HbR concentration at T1 ($F_{(2,169)}$ = 4.01, p = .004, η^2= .05). Further, HbO concentration at T1 was significantly greater than HbO concentration at T2 ($F_{(2,140)}$ = 3.15, p = .004, η^2= .03) – see *Figure 6.5* (b). Finally, in the lMTG cluster, follow-up tests revealed that the interaction effect between chromophore and timepoint was trending towards significance ($F_{(4,281)}$ = 3.83, p = .051, η^2= .01). So, this result was followed up; HbO concentration was greater than HbR concentration, with a trend towards statistical significance at T1 only ($F_{(2,169)}$ = 3.73, p = .055, η^2= .02) – see *Figure 6.5* (c). These findings indicate that children showed greater activation in the rSPL at T2, as well as greater activation in the lMFG and a trend towards greater activation in the lMTG at T1.

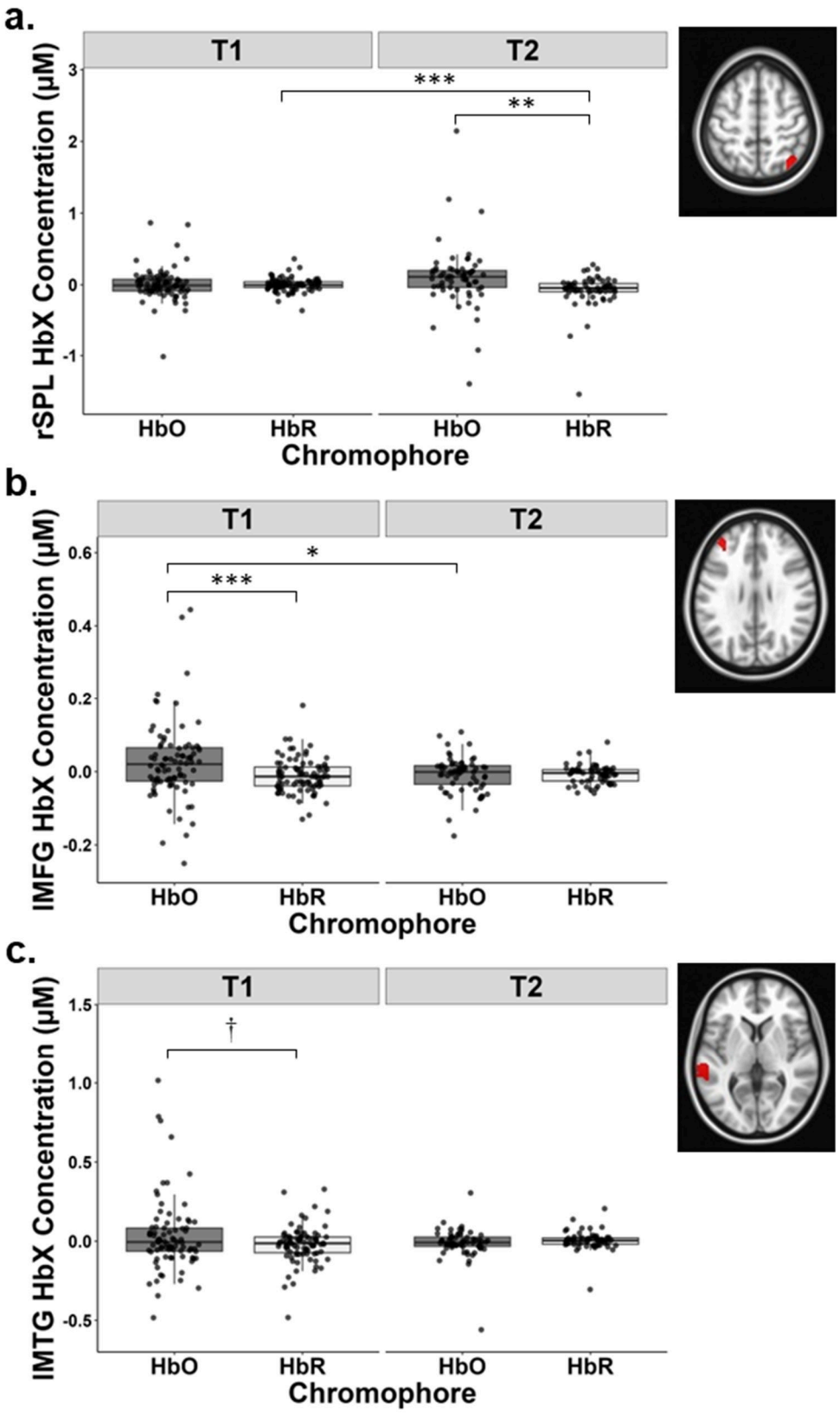


Figure 6.5 Interaction between timepoint and chromophore in (a) rSPL, (b) lMFG, and (c) lMTG. HbO concentration is shown in black and HbR concentration is shown in grey. * $p < .05$, ** $p < .01$, and *** $p < .001$. † p value trending towards significance.

Finally, there was a significant interaction between CP score, timepoint, and chromophore in the lMFG (x = +37.5, y = -40.1, z = +28.3). Follow-up tests were run for chromophore and timepoint separately. Increased CP scores were associated with increased HbO concentration at T1 only ($F_{(1,84)}$ = 5.64, p = .020, ηp^2 = .06) – see *Figure 6.5*. This finding suggests that at T1, greater ability to detect change, was associated with greater lMFG activation.

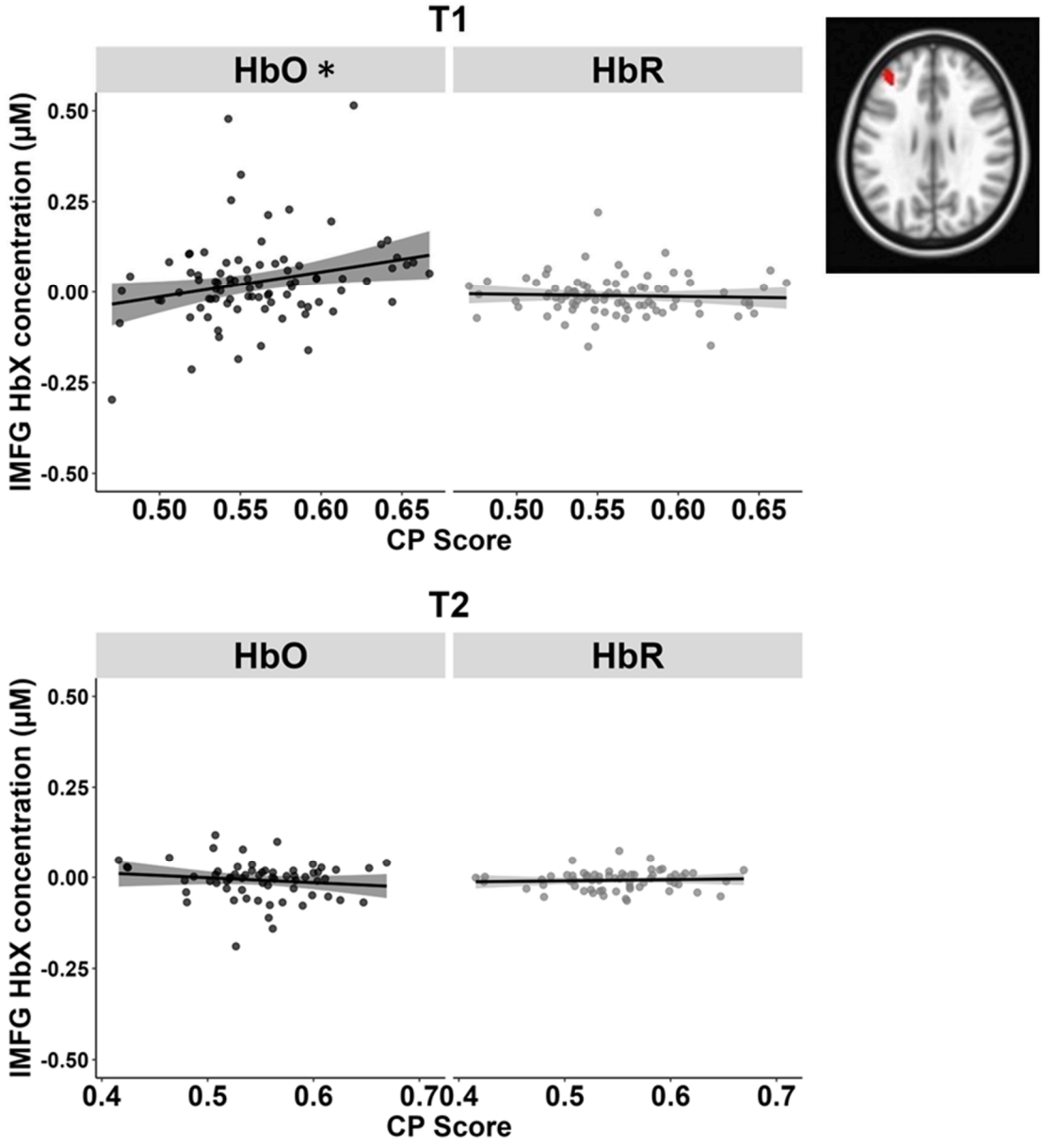


Figure 6.6 (a) Interaction between timepoint, CP, and chromophore in lMFG. Follow-up tests revealed greater CP scores were associated with greater HbO concentration at T1. HbO concentration is shown in black and HbR concentration is shown in grey. * p < .05.

To summarise the brain findings, across both infancy and toddlerhood, children activated the lMFG, rSPL, and rMFG during the task. Further, children showed greater rSPL activation, reduced lMFG activation and a trend towards greater lMTG activation at T2 compared to T1. Finally, greater ability to detect change, was associated with greater lMFG activation at T1.

6.4.2.2 Associations between T1 and T2 brain function

To investigate whether there were any associations between activation in brain regions at T1 and activation in brain regions at T2, regression models were run for each significant cluster from the whole brain results, for HbO and HbR separately. The significant clusters were lMFG, rSPL, and rMFG from the chromophore main effect, rSPL and lMFG from the timepoint x chromophore effect, and lMFG from the CP x timepoint x chromophore effect. Given that the lMTG cluster from the timepoint x chromophore effect showed a trend towards significance, this region was also included. For each cluster, a model with T2 HbX concentration as the outcome and mean-centered T1 HbX concentration as the predictor, with T1 age as a covariate, was run.

There were two significant results from these models. Firstly, in the lMTG cluster from the interaction between timepoint and chromophore, there was a negative association between lMTG HbO concentration at T1 and lMTG HbO concentration at T2 ($F_{(1,54)} = 7.30$, $p = .009$, $\eta p^2 = .12$) – see *Figure 6.7* (a). These findings indicate that greater activation in the lMTG at T1 was associated with lower activation in the lMTG at T2. Second, in the lMFG cluster from the chromophore main effect, there was a positive association between lMFG HbO concentration at T1 and lMFG HbO concentration at T2 ($F_{(1,54)} = 10.28$, $p = .002$, $\eta p^2 = .16$) – see *Figure 6.7* (b). These findings indicate that greater activation in the lMFG at T1 was associated with greater activation in the lMFG at T2 during the task. Note that this lMFG cluster (from the chromophore main effect) also overlapped with the other two lMFG clusters from the whole brain analyses (interaction between chromophore and timepoint, and interaction between chromophore, timepoint and CP score). Thus, for Section 6.4.3, this overlap is considered, and functional interpretations are derived from all three regions.

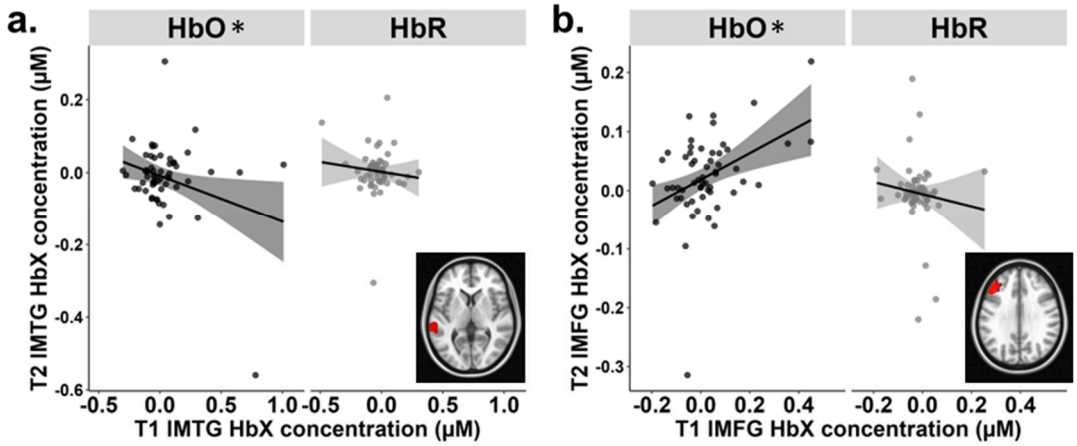


Figure 6.7 (a) Negative association between lMTG HbO concentration at T1 and T2 and (b) positive association between lMFG HbO concentration at T1 and T2. HbO concentration is shown in black and HbR concentration is shown in grey.

6.4.2.3 ROI-based differences between T1 and T2 brain function

ROI-based brain analyses were run, focusing on 21 ROIs from adult VWM literature (Wijeakumar, Magnotta, et al., 2015). The longitudinal group mask overlapped with 6 of these ROIs: rsIPS, rIPS, lIPS, lDLPFC, rMFG, and rTPJ. To examine longitudinal changes in brain function in each ROI, a regression model with chromophore, load, and CP score as predictors, and T1 age as a covariate, was run. These models revealed significant effects in two ROIs: the lIPS (x = +36.2, y = +59.8, z = +45.8) and the lDLPFC (x = +41.8, y = -39.2, z = +23.8) – see *Figure 6.8* (a-b). All significant effects were followed up.

Firstly, in the lIPS, there was one significant effect. Here, there was an interaction between CP score and chromophore ($F_{(1,819)}$ = 63.88, p = .049, ηp^2 = .005). Follow-up tests were run for each chromophore. Here, there was only a significant effect for HbO, with an increase in lIPS HbO concentration associated with a decrease in CP score (p = .040, ηp^2 = .08) – see *Figure 6.8* (c). This finding indicated that across both timepoints, increased lIPS suppression during the task was associated with increased ability to detect change.

Next, in the lDLPFC, there were three significant effects: a main effect of chromophore ($F_{(1,819)}$ = 6.36, p = .049, ηp^2 = .008), an interaction between CP score and chromophore ($F_{(1,819)}$ = 9.39, p = .002, ηp^2 = .01), and an interaction between timepoint, CP score, and chromophore ($F_{(1,819)}$ = 5.11, p = .024, ηp^2 = .006). Firstly, for the main effect of chromophore, HbO concentration was significantly greater than

HbR concentration ($t(107) = 2.95$, $p = .004$) – see *Figure 6.8* (d). This finding indicated that across both timepoints, children activated the lDLPFC during the preferential looking tasks. Secondly, for the interaction between CP score and chromophore, follow-up tests revealed no significant results. Finally, for the interaction between timepoint, chromophore, and CP score, follow-up tests revealed that increased lDLPFC HbO concentration was associated with increased CP scores at T1 only ($p = .033$, $\eta p^2 = .05$) – see *Figure 6.8* (e). This finding indicated that at T1, increased lDLPFC activation during the task was associated with increased ability to detect change.

6.4.2.4 ROI-based associations between T1 and T2 brain function

To investigate whether there were any associations between activation in ROIs at T1 and activation in ROIs at T2, regression models were run for each ROI for HbO and HbR separately. The ROIs were rsIPS, rIPS, lIPS, lDLPFC, rMFG and rTPJ. For each ROI, a model with T2 HbX concentration as the outcome and mean-centered T1 HbX concentration as the predictor, with T1 age as a covariate, was run.

There was one significant result from these models, for the lDLPFC ROI. Here, there was a positive association between lDLPFC HbO concentration at T1 and lDLPFC HbO concentration at T2 ($F_{(1,54)} = 7.30$, $p = .009$, $\eta p^2 = .12$) – see *Figure 6.8* (f). This finding indicates that greater activation in the lDLPFC at T1 during the task, is associated with greater activation in the lDLPFC at T2 during the task. There were no significant results for rsIPS, rIPS, lIPS, rMFG, or rTPJ.

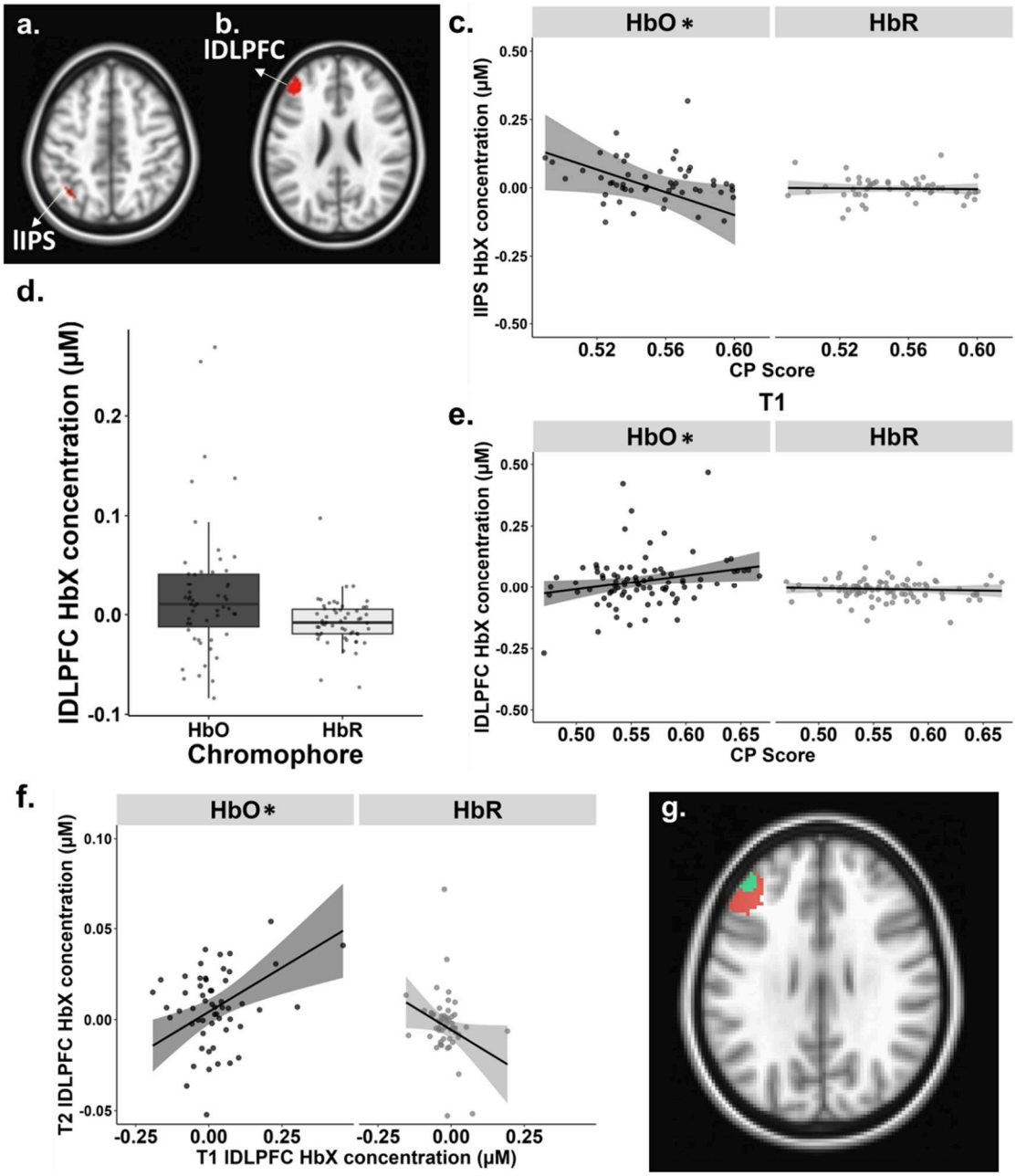


Figure 6.8 ROI clusters showing significant results in the regression model with chromophore, load, and CP as predictors: (a) lIPS and (b) lDLPFC; (c) interaction between CP and chromophore in the lIPS; (d) main effect of chromophore; and (e) interaction between CP and chromophore at T1 in the lDLPFC. (f) Interaction between T1 lDLPFC HbX concentration and T2 lDLPFC HbX concentration and (g) spatial overlap (cyan cluster) between lMFG cluster from whole brain analyses (red cluster) and lDLPFC cluster from ROI analyses (cyan cluster). Here, cyan indicates both the lDLPFC cluster and the overlap, as the entire lDLPFC cluster overlapped with the lMFG cluster. HbO concentration is shown in black and HbR concentration is shown in grey.

6.4.3 Caregiver influences on longitudinal changes from T1 to T2

6.4.3.1 Moderating effects of caregiver factors

The final research objective was to examine caregiver influences on longitudinal changes in behaviour and brain function from T1 to T2. There were no longitudinal associations in looking behaviours. However, there were longitudinal associations in brain function i.e. lMFG and lMTG from the whole-brain analyses (*Figure 6.7*) – these were included for the moderation analyses. Note that the lDLPFC cluster from ROI analyses was not included for these analyses, as it spatially overlapped with the lMFG cluster from the whole-brain analyses – see *Figure 6.8* (g).

Two models were run to examine caregiver-related influences on the association between lMFG HbO concentration at T1 and lMFG HbO concentration at T2. In one model, caregiver-infant joint attention was the moderator and in the other, caregiver CP score at the low load was the moderator. There were no significant effects.

Afore-mentioned moderation models were also run to examine influences on the association between T1 lMTG HbO concentration and T2 lMTG HbO concentration. Findings revealed a significant moderation effect of joint attention on the association between T1 lMTG HbO concentration and T2 lMTG HbO concentration (p = .007). When examined further, the simple slope of lMFG HbO concentration at T1 on HbO concentration at T2 was significant for dyads with lower (b = -.36, SE = .10, t = -3.54, p < .011) and mean (b = -.13, SE = .06, t = -2.09, p < .043) duration of joint attention – see *Figure 6.9* (a). Specifically, infants who engaged in shorter episodes of joint attention with their caregivers, showed a stronger inverse association between lMTG engagement at T1 and lMTG engagement at T2. This association was not significant for infants who engaged in longer periods of joint attention.

To summarize, only in lMTG, there was a moderating influence from a caregiving-related factor.

6.4.3.2 Spatial alignment between brain regions

The spatial overlap between brain regions involved in caregiver looking behaviours and caregiver-infant dyadic interactions, and longitudinal associations in

brain function, was examined. To summarize, the brain regions involved in caregiver looking behaviours were rSMG and lMFG (Chapter 3), the brain region involved in caregiver-infant dyadic interactions was lSTG (Chapter 5), and the regions showing longitudinal associations in brain function were lMFG and lMTG.

There were two cases with spatial overlap. First, there was an overlap between the lMFG cluster showing longitudinal associations and the lMFG cluster involved in caregiver looking behaviour (39 voxels; Euclidian distance between centres of mass = 18.84 mm) – see *Figure 6.9* (b). To examine functional alignment in these clusters, Pearson's correlations were run. Correlations were first run between caregiver CP score at the low load and both T1 lMFG HbO concentration and T2 lMFG HbO concentration. Correlations were next run between caregiver lMFG HbO concentration and both T1 lMFG HbO concentration and T2 lMFG HbO concentration. No significant results were found in any case.

Second, there was an overlap between the lMTG cluster showing longitudinal associations and the lSTG cluster involved in caregiver-infant dyadic interactions (1 voxel; Euclidian distance between centres of mass = 11.13 mm) – see *Figure 6.9* (c). To examine functional alignment in these clusters, Pearson's correlations were run between caregiver lSTG HbO concentration during joint attention and both T1 lMFG HbO concentration and T2 lMFG HbO concentration. No significant results were found.

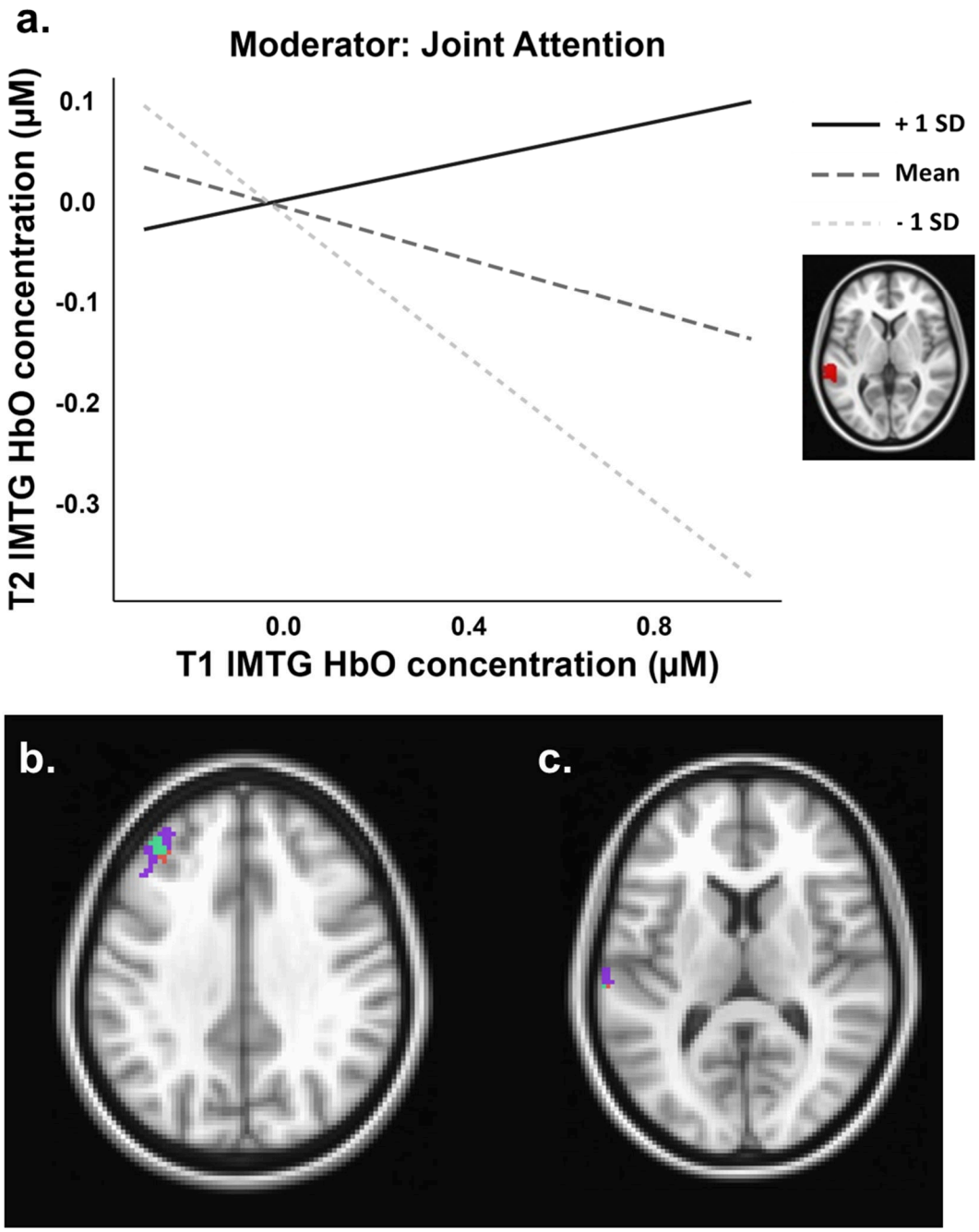


Figure 6.9 (a) Moderation effect of joint attention on the association between T1 lMTG HbO concentration and T2 lMTG HbO concentration. (b) Overlap (cyan cluster) between lMFG cluster from the longitudinal associations (red cluster) and the lMFG cluster involved in caregiver looking behaviour (purple cluster) and (c) overlap (cyan cluster) between lMTG cluster from the longitudinal associations (red cluster) and the lSTG cluster involved in caregiver-infant dyadic interactions (purple cluster).

6.5 Discussion

The over-arching aim of this chapter was to examine longitudinal changes in looking behaviours and brain function from infancy to toddlerhood, and how caregiver looking behaviours and brain function and caregiver-infant dyadic behaviours impact these longitudinal changes. To this end, children were presented with age-appropriate variants of a preferential looking task (Ross-Sheehy et al., 2003) at two timepoints: infancy (T1) and toddlerhood (T2). Looking measures were extracted from video recordings and fNIRS was used to measure brain function across frontal, temporal, and parietal regions.

This chapter had three research objectives. The first objective was to investigate if there were longitudinal changes in behavioural performance from T1 to T2. Children showed increased TLD scores and decreased SR scores from T1 to T2. Further, at both timepoints, children showed load-dependent modulation of CP scores. The second objective was to examine whether there were longitudinal changes in brain activation from T1 to T2. Findings revealed greater activation in the rSPL at T2, as well as greater activation in the lMFG and a trend towards greater activation in the lMTG at T1. Interestingly, there was a positive association between activation in the lMFG at T1 and activation in the lMFG at T2. There was also a negative association between activation in the lMTG at T1 and activation in the lMTG at T2. The final objective was to examine caregiver influences on longitudinal changes in behaviour and brain function. Findings suggested that infants who experienced shorter episodes of joint attention showed a more negative association between lMTG activation at T1 and T2. Finally, two clusters showed spatial overlap with caregiver-, and caregiving-related effects. First, between the lMFG cluster showing longitudinal associations in brain function and the lMFG cluster involved in caregiver visual cognition. Second, between the lMTG cluster showing longitudinal associations in brain function and the lSTG cluster involved in caregiver-infant dyadic interactions. These findings are discussed below.

6.5.1 Longitudinal changes in looking behaviours from T1 to T2

The first research objective was to investigate if there were longitudinal changes in behavioural performance from T1 to T2. Children showed longitudinal changes in two out of the three looking behaviours from infancy to toddlerhood.

Concretely, there was an increase in TLD scores, and a decrease in SR scores, and no difference in CP scores, from T1 to T2 – suggesting that although children explored the displays for longer and switched less frequently, they did not differ in their ability to detect and fixate on the changing side at T2, compared to T1. Observed increase in looking duration is in line with previous work using the preferential looking task (Delgado Reyes et al., 2020), which reported that from 4 months to 2 years of age, there is an increase in children's overall looking duration. However, the observed decrease in switching from T1 to T2 contrasts findings from Delgado Reyes et al. (2020), who found no age-related changes in SR. More broadly, the age-related increase in looking duration and decrease in switching, aligns with findings reporting general attentional improvements with age (Kannass & Oakes, 2008; Richards & Casey, 1992; Ruff & Capozzoli, 2003). For instance, in one study that examined attentional behaviours in children aged 10, 26 and 42 months whilst they played with toys, there was a decrease in casual attention and an increase in focused attention with age (Ruff & Capozzoli, 2003). Furthermore, children aged 10 months were more distractible than older children, even during periods of focused attention. Similarly, other research has also suggested that distractibility decreases with age as attentional control improves, with younger infants being more influenced by exogenous stimuli and toddlers' attention increasingly governed by endogenous control (Kannass & Oakes, 2008). Collectively, the changes in TLD and SR scores from T1 to T2 may therefore reflect improving visual cognition abilities in children, as they become better at sustaining attention to the task itself, and less distracted by changing side/external stimuli.

In contrast to age-related changes in TLD and SR scores, CP scores only showed load-related effects in the current study. Across both timepoints, CP scores were significantly higher at the low and medium loads, compared to the high load. Generally, this load-dependent decrease in CP scores is in line with previous work in children (Delgado Reyes et al., 2020; Ross-Sheehy et al., 2003) as well as infant and caregiver findings in Chapter 3. However, previous research has also reported age-dependent changes in load from infancy to toddlerhood, in contrast with findings or lack thereof in the current study. For instance, Delgado Reyes et al. (2020) reported that infants aged 4 months demonstrated robust change preference for one item, while infants aged 1 year demonstrated robust change preference for two items, and by 2

years, this was observed for six items. It is possible that the difference in findings between this study and Delgado Reyes et al. (2020) could be due to the difference in the ages of the cohorts and respective load manipulation. Specifically, in this study, load was manipulated between one, two, and three items between 6 and 10 months, and between two, four, and six items between 18 and 22 months, while in Delgado Reyes et al. (2020), load was manipulated between one, two, and three items for the 4-month group, and between two, four, and six items for the older groups. It is also possible that the 'blurred' age boundaries across the four-month period of the group of infants in the current study might have captured more individual differences in CP scores compared to infants in Delgado Reyes et al. (2020) – despite, controlling for T1 age.

The findings revealed that looking behaviours at T1 did not predict looking behaviours at T2. This finding was surprising given that more generally, previous research has found longitudinal associations between infant attention and later EF abilities (Cuevas & Bell, 2014; Devine et al., 2019; Kraybill et al., 2019). For instance, Kraybill et al. (2019) found that attention skills at 5 months, assessed through caregiver reports and laboratory measures, was predictive of EF at 3 years. Equally, studies have provided evidence of instability in EF from late infancy to early childhood. For instance, studies have reported mixed findings across different tasks (Broomell & Bell, 2022; Johansson et al., 2016; Miller & Marcovitch, 2015). In one of these studies, EF development was tracked across 6 timepoints i.e. 5 months, 10 months, 24 months, 36 months, 48 months, and 9 years, using a series of developmental-appropriate EF tasks (Broomell & Bell, 2022). From 24 months to 9 years, child EF was relatively stable and predictive of the next time point, however, infant EF did not show the same stability or predictability. It is possible that predictive effects are only evident from later toddlerhood to childhood, and that the transition from infancy to toddlerhood might be unstable as reliance shifts from caregiver-led visual cognition to visual cognition abilities informed by self-exploration or other environmental effects. This interpretation is supported by findings from Chapter 3 that revealed associations between caregiver CP scores and infant CP scores.

6.5.2 Longitudinal changes in brain function from T1 to T2

The second research objective was to examine whether there were longitudinal changes in brain activation from T1 to T2. Three key regions showed developmental

effects in the current study – rSPL, lMFG, and lMTG. In the rSPL, there was greater activation at T2 compared to T1. Parietal engagement has previously been associated with allocating visuo-spatial attention and working memory maintenance (Berryhill & Olson, 2008; Corbetta & Shulman, 2002; Pisella, 2017; Ren et al., 2019). Additionally, parietal regions have been associated with sustained attention processes (Ackles & Cook, 2007; Reynolds & Richards, 2005). Importantly, the current finding is in line with previous work showing increased parietal engagement across early childhood. For example, Delgado Reyes et al. (2020) reported an increase in activation in the right parietal cortex from infancy to toddlerhood. Further, Buss et al. (2014) presented 3- and 4-year-old children with a change-detection task and recorded brain function as they engaged with the task. They found that while both age groups showed activation across the frontal and parietal cortices during the task, older children showed more robust activation in parietal cortex. It is possible that the increase in activation from T1 to T2, reflects a developmental shift to more specialised VWM processes, anchored in parietal regions.

Next, an interesting, yet complex set of developmental effects were observed in the lMFG. Concretely, there was a decrease in activation from T1 to T2 in this region. However, there was a positive predictive link i.e. greater activation at T1 was associated with greater activation at T2. Lastly, there was a positive link between lMFG activation and CP scores only at T1. Across adult and child studies, the lMFG has been associated with orienting and stimulus-driven attention (Corbetta et al., 2008; Corbetta & Shulman, 2002; Doricchi et al., 2010; Ellis et al., 2021). Further, in general, the right frontal cortex has also been associated with the emergence of looking behaviours in infancy (Delgado Reyes et al., 2020). The authors suggested that this effect was due to the emergence of early looking behaviours (Perone et al., 2011; Perone & Spencer, 2013). Along a similar vein, other work suggests that frontal activation in infancy might be linked to attention-related behaviours (Cuevas, Swingler, et al., 2012; Ellis et al., 2021; Perry et al., 2016). For example, in one study, EEG was recorded from 10-month-olds whilst they completed a task designed to engage both working memory and inhibitory control processes. Here, increased frontal EEG coherence was associated with the presence of additional inhibitory control demands (Cuevas, Swingler, et al., 2012). In another study, increased attentional behaviours, extracted from the proportion of time spent attending towards an object,

were associated with greater EEG power in frontal regions in 10-month-olds (Perry et al., 2016). Attentional re-orienting has also been associated with activation in the MFG and IFG in 3- to 12-month-old infants completing a cueing task (Ellis et al., 2021).

Interestingly, there is evidence for associations between increased efficiency/reduced activation in the frontal cortex. In research in children with attention-deficit/hyperactivity disorder, increased frontal cortex activity was associated with poorer working memory performance, thought to reflect inefficient processing (Tsujimoto et al., 2013). Further, in children, cognitive training aimed to improve attentional control was linked to more efficient and focal activation in the frontal cortex (Rueda et al., 2012). While it is difficult to meaningfully interpret the reduction in activation from T1 to T2 without behavioural links to the latter, it is plausible that reduction in engagement might represent better efficiency, requiring lesser neural resources to elicit similar attentional behaviours, compared to infancy – explaining the lack of behavioural association with CP scores in toddlerhood.

Lastly, there was a negative predictive effect between T1 and T2 in the lMTG. The temporal cortex has previously been linked to visual perception (Allison et al., 2000; Bonda et al., 1996; Corbetta & Shulman, 2002; Deen et al., 2015) and the processing of socially relevant motion cues (Carter & Pelphrey, 2006; Grossman et al., 2004; Grossman & Blake, 2002; Grossmann et al., 2008; Lloyd-Fox et al., 2009; Mosconi et al., 2005; Pelphrey et al., 2003). For instance, across childhood and adulthood, activation in the temporal cortex has been linked to the observation of biological motion (Carter & Pelphrey, 2006; Grossman & Blake, 2002) and gaze shifts (Mosconi et al., 2005; Pelphrey et al., 2003). Critically, in infants aged 4 months, activity in temporal regions has been associated with mutual gaze (Grossmann et al., 2008). Further, in infants aged 5 months, greater activity in temporal regions was observed in response to dynamic social stimuli, such as faces making eye, mouth, or hand movements, over non-social stimuli, such as images of vehicles (Lloyd-Fox et al., 2009). Temporal activation has also been observed in social partners in studies of joint attention in adults (Materna et al., 2008; Redcay et al., 2012; Schilbach et al., 2010). Interestingly, left temporal activation has also been observed in EF processes, such as visual (Delgado Reyes et al., 2020) and verbal working memory tasks (Brahmbhatt et al., 2008). In the absence of behavioural associations, it is difficult to interpret what temporal activation or suppression might indicate. Nonetheless, in the

current study, the functional role of this region appears to drastically shift from T1 to T2. The following section on caregiver influences sheds more insight on the nature of this developmental shift.

6.5.3 Caregiver influences on longitudinal changes in looking behaviour and brain function

The final research objective was to examine caregiver influences on longitudinal changes in behaviour and brain function. Caregiver-related influences were observed in two regions that showed developmental effects. Critically, lMFG engagement was influenced by heritability-related factors, while lMTG engagement was influenced by caregiving interaction-related effects. Whilst functional links are discussed below, these should be interpreted with caution, due to the lack of correlational evidence.

The lMFG cluster that showed developmental effects spatially overlapped with an lMFG cluster in the caregiver brain that was inversely associated with CP scores (Chapter 3). When the functional interpretations of these regions are considered together, an interesting alignment between both effects emerge. In the developmental lMFG effect – at T1, greater HbO concentration was associated with better CP scores. Further, while there was a positive association between HbO concentration at T1 and HbO concentration at T2, there was a decrease in HbO concentration from T1 to T2. One year later, there was no association between CP scores and activation; indeed, there is an insignificant trend for a negative association. This 'developmental brain-behavioural shift' aligns with brain-behavioural effects in caregivers i.e. adults, where greater HbO concentration was associated with poorer CP scores. For instance, MRI studies in twins have indicated heritability in visual cognition-related frontal cortex activation (Blokland et al., 2008, 2011). In another study, heritability estimates of 29% in the frontal cortex were reported in association with selective attention (Park et al., 2024). Taken together, in the current study, the findings provide heritability-related evidence for a gradual shift in functionality of this region in children, towards patterns observed in caregivers.

The developmental effect observed in the lMTG showed caregiving interaction-related effects. Concretely, from findings during caregiver-infant interactions, reduced caregiver lSTG suppression/lSTG activation during joint attention was related to reduced suppression/lSTG activation in the same region in infants during joint attention, and shorter duration of joint attention (Chapter 5). Put

simply, shorter episodes of joint attention are related to reduced left temporal suppression/greater left temporal activation during joint attention in infancy. From the moderation effect, infants who showed reduced suppression/greater activation in the left temporal cortex and were also exposed to shorter durations of joint attention, demonstrated suppression in this region, a year later. On the other hand, infants who were exposed to longer durations of joint attention did not show dramatic effects in this region. Taken together, these findings suggest that exposures to episodes of joint attention with caregivers can significantly shape developmental changes in brain regions that are involved in both social cognition (Carter & Pelphrey, 2006; Grossmann et al., 2008; Lloyd-Fox et al., 2009; Mosconi et al., 2005) and EF (Brahmbhatt et al., 2008; Delgado Reyes et al., 2020) contexts.

6.6 Conclusions

The over-arching objective of this chapter was to examine longitudinal changes in looking behaviours and brain function from infancy to toddlerhood, and how caregiver looking behaviours and brain function, and caregiver-infant dyadic behaviours impact these longitudinal changes. To this end, looking behaviours and brain function were measured from children at T1 (infancy) and T2 (toddlerhood), whilst they engaged with a preferential looking task. From T1 to T2, children showed changes in looking behaviours i.e. longer looking duration and reduced shifting. Children also showed load-dependent modulation of CP scores across both timepoints, with reduced change preference abilities with increasing load. Across timepoints, three key regions showed developmental effects. Children showed greater activation in a cluster in the right superior parietal cortex at T2 compared to T1, which was suggested to represent a developmental shift to more specialised processes, such as visuospatial attention, sustained attention and VWM. Further, children showed greater activation in a left frontal cluster at T1 compared to T2, a positive association between activation at T1 and activation at T2, and positive association with CP scores only at T1 – collectively suggesting better neural efficiency over time. Interestingly, this frontal cluster overlapped with a cluster identified in the caregiver preferential looking task, providing support for heritability-related link in this region. Finally, in the left temporal cortex, children showed an inverse association between activation at T1 and activation at T2 – this association was moderated by duration of caregiver-infant joint attention during dyadic interactions, suggesting caregiving-related effects.

Importantly, this chapter offers new insight into the development of visual neurocognition across infancy and toddlerhood and highlights the importance of examining caregiver-related contributions on this developmental shift.

Chapter 7:

General discussion

7.1 Introduction

Visual cognition begins to emerge in early infancy, as children begin to develop foundational attentional and visual cognitive abilities. This system is important to study, as it is predictive of many real-world outcomes impacting quality of life, such as academic achievement, IQ, global fluid intelligence, and social abilities. Existing research has examined developmental shifts in visual cognition and associated brain function across childhood. Despite significant progress in early visual cognition research, several gaps remain. There is a gap in the literature regarding the influences of caregiver cognitive function on child visual cognition development as early as the first year of life. Previous research has primarily focussed on associations between caregiver EF and child EF later in development. Furthermore, it remains unclear what role caregiving during dyadic interactions plays on infant visual cognition. Research has instead examined the impact of these interactions on infant attention and language abilities. Additionally, there is limited understanding of longitudinal changes in visual cognition at both the behavioural and brain level. Previous research has implicated the frontal and parietal cortex in early visual cognition; however, it remains unclear how visual cognition behaviour and brain function change longitudinally during this period. Finally, the contributions of heritability and caregiving to these longitudinal changes in visual cognition remain unclear. Previous research has linked both caregiver behaviours and caregiver EF to early changes in child behaviour and brain development, suggesting that both heritability- and caregiving-related factors may contribute to these developmental changes.

The experimental studies in this thesis therefore aimed to address these gaps by investigating neurocognitive associations between caregiver visual cognition and child visual cognition development, with a focus on insights from dyadic interactions. Chapter 3 investigated associations between caregiver and infant looking behaviours using comparable experimental paradigms. Chapters 4 and 5 examined how caregiver-infant dyadic interaction behaviours impact infant VWM. Finally, Chapter 6 investigated longitudinal changes in child looking behaviours and brain function. Further, Chapter 6 explored the contributions of caregiving and heritability in shaping these developmental trajectories. The current chapter summarises each experimental study from the thesis and discusses the implications of the main findings. This chapter

also addresses the overarching strengths and limitations of the thesis and proposes possible future research directions informed by the findings.

7.2 Summary of experimental studies

7.2.1 The association between caregiver and infant visual neurocognition

The first year of life has been identified as a critical period in which visual cognitive abilities begin to emerge and develop (Delgado Reyes et al., 2020; Ross-Sheehy et al., 2003). While visual neurocognition has been examined across childhood, adolescence, and adulthood (Geier et al., 2009; Scherf et al., 2006), less is known in the infancy period. Furthermore, while there is evidence for associations between caregiver EF and child EF later in development (Cuevas, Deater-Deckard, Kim-Spoon, Wang, et al., 2014; Cuevas, Deater-Deckard, Kim-Spoon, Watson, et al., 2014; Distefano et al., 2018; Korucu et al., 2020; Ribner et al., 2022), there is a gap in the literature on the influences of caregiver cognitive function on infant visual cognition.

To address these gaps, this chapter aimed to investigate whether caregiver looking behaviours were associated with infants' looking behaviours, using comparable experimental paradigms. To this end, infants (aged 6- to 10-months) and caregivers were presented with variants of the same preferential looking task. During each trial in this task, two side-by-side flashing displays of coloured shapes were presented. On the 'unchanging' side, the colours of the shapes remained the same. On the 'changing' side, the colour of one shape changed after each flash. Load was varied by changing the number of shapes across trials (low, medium, and high loads – one, two, and three items for infants and four, six, and eight items for caregivers). To examine behavioural associations, looking dynamics were extracted from video recordings. Among these measures were CP score, a measure of the subject's ability to detect the changing side, and SR, a measure of how frequently the subject shifted between the two sides of the display. This chapter had three key research objectives. The first research objective was to investigate whether caregiver looking behaviours were associated with infant looking behaviours. The second research objective was to investigate whether caregiver behaviours were linked to infant brain function. The third research objective was to examine whether there was any spatial and functional overlap in brain areas associated with looking behaviours in caregivers and infants.

The behavioural findings revealed that CP score showed load-dependent modulation for both infants and caregivers. For both infants and caregivers, as load increased, CP scores decreased, with the greatest CP scores seen at the low load in both groups. In infants, this pattern replicated previous findings using the same task (Delgado Reyes et al., 2020; Ross-Sheehy et al., 2003). In caregivers, higher CP scores at the low load (four items) was consistent with previous performance-based capacity estimates of around three to five items from conventional VWM tasks (Cowan, 2001; Luck & Vogel, 1997). Interestingly, regarding the first research objective, there was a behavioural association between caregiver and infant CP scores. Specifically, at the low load, higher CP scores in caregivers were associated with higher CP scores in infants, suggesting that better visual cognition in caregivers is linked to better visual cognition in infants. This finding was in line with previous work on caregiver-child EF (Cuevas, Deater-Deckard, Kim-Spoon, Wang, et al., 2014; Cuevas, Deater-Deckard, Kim-Spoon, Watson, et al., 2014) and dyadic interactions showing the impact of caregiver gaze and attention on child development (Monroy et al., 2021; Schatz et al., 2022; Yu et al., 2019; Yu & Smith, 2016, 2017). More broadly, these findings contributed to literature showing that visual cognition is heritable (Constantino et al., 2017; Quinn et al., 2022).

This chapter also reported several brain findings. Concerning the second research objective, better caregiver CP scores were associated with greater left-lateralized superior parietal engagement in infants. Studies indicate that this region is involved in visuo-spatial attention and working memory in children and adults (Davidson, Caes, et al., 2023; Davidson, Shing, et al., 2023; Delgado Reyes et al., 2020; McKay et al., 2021; Wijeakumar et al., 2023). Interestingly, this association was observed in younger, but not older infants, providing further support for heritability of visual cognition mechanisms (Constantino et al., 2017; Quinn et al., 2022). In this chapter, it was suggested that very early on, there may only be a general heritability-related association between caregiver visual cognition and brain function in young infants. As the infant ages and starts to explore their environment, it is possible that this association might become more shaped by social and environmental factors, eventually leading to load and performance-related links reported in studies in older children.

Regarding the final research objective, there was a spatial overlap between the rSMG, linked to better CP scores in caregivers, and the rSPL, linked to reduced SR scores in high CP infants. These regions have previously been associated with attentional control and EFs in infancy and adulthood (Berryhill & Olson, 2008; Corbetta & Shulman, 2002; Coull & Frith, 1998; Delgado Reyes et al., 2020; Pisella, 2017; Ren et al., 2019; Wang et al., 2015; Wijeakumar et al., 2019; Zago & Tzourio-Mazoyer, 2002). While caregiver looking behaviours did not directly impact activation in this region in infants, there was an indirect alignment in its functional role in both caregivers and young infants. Here, it was proposed that later in development, caregivers might more directly impact infant brain function, leading to more evident behavioural outcomes.

To summarise, the over-arching objective was to investigate whether caregiver looking behaviours were associated with infant looking behaviours. In the first finding, both caregivers and infants showed load-dependent modulation of looking behaviours. Importantly, better ability to detect change in caregivers was associated with better ability to detect change in infants at the low load. In the second finding, better caregiver ability to detect change was directly associated with increasing left parietal activation in young infants. In the third finding, there was a spatial overlap in regions in the right parietal cortex linked to looking behaviours in caregivers and infants. These results provide evidence of a visual neurocognitive association between caregivers and their children in the first year of life.

7.2.2 Modality-based differences during object engagement in caregiver-infant interactions

The previous chapter found associations between looking behaviours and brain function in caregivers and infants. Previous research has also found that infants are influenced by caregiver attention during dyadic play interactions. Importantly, there is evidence that 'multimodal engagement', describing the combination of gaze, manual handling, and verbalisations surrounding objects, leads to play bouts lasting significantly longer in comparison to those without (Schatz et al., 2022). Despite this, neuroimaging research focussed on brain activation in both caregivers and infants during dyadic interactions is limited (Michel et al., 2024; Wass, Noreika, et al., 2018) and neural mechanisms underlying modality differences during these interactions remain unclear.

This chapter inquired whether infant and caregiver behaviours and brain function differed across types of object engagement during dyadic interactions. Further, this chapter also examined whether these caregiver-infant behaviour-brain associations predicted infant VWM. To do this, caregivers and their infants (aged 6- to 10-months) were recorded for 5- to 7-minutes as they naturalistically played with toys. Brain function was also recorded from both partners using fNIRS. Video recordings were split into 5-second epochs and coded for unimodal (look only), bimodal (look and touch), and multimodal (look, touch, and vocalisation/verbalisation) engagement. This chapter had four research objectives. The first objective was to examine whether there was a difference in the duration of unimodal, bimodal, and multimodal engagement in infants and caregivers. The second objective was to identify key brain regions engaged in caregivers and infants during each modality. The third objective was to examine whether there were any behaviour-brain associations in caregivers and infants. The final research objective was to examine whether afore-mentioned caregiver-infant behaviours and brain function was associated with infant VWM during the preferential looking task.

This chapter had several key findings. Regarding first research objective, both caregivers and infants showed greater duration of bimodal compared to unimodal and multimodal engagement. This result was in line with previous work in similar settings (Yu & Smith, 2013, 2017). Whilst caregivers showed comparable right-lateralised recruitment across engagement categories, only infants showed modality-specific changes in the right-lateralized fronto-parietal cortex suggesting a role in actively shifting between attentional demands (Gottlieb, 2007; Japee et al., 2015; Singh-Curry & Husain, 2009). Further, infants demonstrated a 'source-sink' effect, in which greater rMFG activation was accompanied by a trend for greater rAG suppression. Similar findings have been reported in research on sensory decline in adults (Ansado et al., 2012; Davis et al., 2008; Grady et al., 1994; Wijeakumar, Magnotta, et al., 2017; Zhang et al., 2017). Here, inverse posterior-anterior associations were thought to represent context-dependent connectivity between the frontal and parietal cortices. In addition, greater rAG activation in caregivers was linked to reduced rAG activation/greater rAG suppression in infants, across engagement categories. Here, this finding was proposed to be associated with caregivers' abilities to respond more effectively to infants' cues, thus leading to greater overall suppression in the rAG throughout the interaction.

Furthermore, greater rMFG activation in caregivers was associated with greater rMFG activation in infants during unimodal engagement only, suggesting that early alignment in frontal regions may not yet extend to more complex contexts.

Concerning the final research objective, there were no links between caregiver-infant behaviours and infant VWM. This finding was unexpected, given that existing literature reports associations between caregiver engagement and infant cognition (Bernier et al., 2010; Brandes-Aitken et al., 2020; Lawson & Ruff, 2004; Lugo-Gil & Tamis-LeMonda, 2008; Ruff et al., 1990). Notably, in this chapter, engagement categories were independently coded for each partner, thus collapsing both joint and solo periods. Critically, it was proposed that significant associations might emerge from examining caregiver-infant behaviours during joint attention periods

To summarise, the over-arching objective was to investigate whether infant and caregiver behaviours and brain function differ across types of object engagement during dyadic interactions, and whether these behaviours and brain function were associated with infant VWM. In the first finding, both caregivers and infants showed greater proportion of bimodal compared to unimodal and multimodal engagement. Further, caregivers showed right-lateralised recruitment across engagement categories, but infants showed modality-specific right-lateralised fronto-parietal engagement, as well as a 'source-sink' effect, with greater right frontal activation and a trend towards greater right parietal suppression across all engagement categories. Further, greater right parietal activation in caregivers was linked to reduced right parietal activation in infants across engagement categories. Contrary to predictions, no associations were found between behaviour and brain function and infant VWM during the preferential looking task. These findings provide novel contributions to the understanding of the cortical mechanisms underlying different types of object engagement.

7.2.3 Brain-behaviour associations underlying joint and continued attention during caregiver-infant interactions

The ability to sustain attention progressively improves over the first few years of life (Ruff & Capozzoli, 2003). Furthermore, previous research has highlighted the importance of caregiver-infant joint attention on subsequent infant attention (Deák et al., 2014; Schatz et al., 2022; Schroer & Yu, 2022; Yu & Smith, 2013, 2016).

Neuroimaging research in adults suggests that joint attention occurs as an outcome of integrated activity between the anterior and posterior attention systems (Morales et al., 2000; Mundy & Newell, 2007; Posner & Rothbart, 2007). To some extent, research in infancy supports this characterisation (Grossmann et al., 2013; Mundy et al., 2000; Naoi et al., 2022), however, studies that focus upon cortical activation underlying attention processes in both caregivers and infants during dyadic interactions is limited (Michel et al., 2024; Wass, Noreika, et al., 2018). Furthermore, associations with infant visual cognition remain unclear.

This chapter examined the duration of caregiver-infant joint attention and infant continued attention, and underlying brain function during dyadic interactions. Further, this chapter also examined whether these caregiver-infant behaviour-brain associations were associated with infant VWM. To do this, modality analyses from Chapter 4 were further collapsed into caregiver-infant joint attention and infant continued attention periods. To code caregiver-infant joint attention periods, epochs in which caregivers showed multimodal engagement while interacting with the same object as their infant were identified. To code infant continued attention periods, epochs in which the infant continued to interact with that same object after caregiver multimodal engagement ended were identified. This chapter had five research objectives. The first objective was to examine whether overall duration of joint attention was associated with overall duration of continued attention in infants. The second objective was to identify key brain regions engaged in caregivers and infants during periods of joint and continued attention. The third objective was to examine whether there was an association between brain function in caregivers and brain function in infants during joint attention and, how these brain function measures were linked to duration of joint attention. The fourth objective was to examine whether the duration of continued attention in infants, was associated with brain function in infants during continued attention, brain function in infants during joint attention, and brain function in caregivers during joint attention. The final research objective was to examine whether afore-mentioned caregiver-infant behaviours and brain function during dyadic interactions would predict infant VWM during the preferential looking task.

Concerning the first research objective, the duration of joint attention between caregivers and infants was linked to duration of continued attention in infants. This

result was in line with existing joint and sustained attention research (Yu & Smith, 2016). Regarding the second research objective, infants showed activation in the bilateral STG and suppression in the lSPL during joint attention. The STG has been implicated in several aspects of social cognition and perception (Deen et al., 2015). With respect to the third and fourth research objectives, reduced lSTG activation in caregivers during joint attention was associated with reduced lSTG activation in infants during joint activation, longer duration of joint attention and longer duration of continued attention. It was proposed that reduced activation or suppression of the temporal cortex is necessary for critical cognitive functions involved in working memory/distractor suppression, which subsequently impacts joint and continued attention durations.

Regarding the final research objective, reduced lSTG activation in caregivers during joint attention was associated with better VWM in infants. Greater caregiver lSTG suppression in during joint attention might provide more frequent and/or better opportunities for continued attention infants and improve their visual cognition. This interpretation partially aligns with findings in both children and adults showing that suppression in the right temporal cortex is linked to better attention and working memory processing (Todd et al., 2005; Wijeakumar et al., 2023). Further, this interpretation may also lend support to studies implicating left temporal engagement in completion of working memory tasks (Brahmbhatt et al., 2008; Delgado Reyes et al., 2020). Further research is required to better compare contextual variation in brain function across dyadic interactions and experimental tasks.

To summarise, the over-arching objective was to investigate whether behaviours and brain function differ across caregiver joint attention, infant joint attention, and infant continued attention during dyadic interactions, and whether these behaviours and brain function were associated with infant VWM. Caregiver-infant joint attention duration was linked to infant continued attention duration. Further, infants showed bilateral activation of the temporal cortex and left-lateralised suppression of the parietal cortex during joint attention. Critically, reduced left temporal activation in caregivers during joint attention was associated with reduced left temporal activation in infants during joint activation, longer duration of joint and continued attention, and better VWM in infants. These findings enhance the

understanding of cortical mechanisms involved in attention periods in caregiver-infant interactions, and importantly, their potential link to visual cognition in infants.

7.2.4 Longitudinal changes in visual neurocognition from infancy to toddlerhood

Novelty preference procedures have highlighted improvements in visual cognition across the first year of life, including increases in VWM capacity limits and abilities to process more complex stimuli (Mitsven et al., 2018; Oakes et al., 2013, 2017; Ross-Sheehy et al., 2003). Moreover, research has found similar increases in visual cognitive abilities in toddlerhood (Cheng et al., 2019a, 2019b, 2020; Delgado Reyes et al., 2020; Kaldy et al., 2016). In early life, neuroimaging studies have implicated both the frontal and posterior parietal cortex in visual cognition development (Baird et al., 2002; Bell & Wolfe, 2007; Cuevas, Bell, et al., 2012; Delgado Reyes et al., 2020; Ellis et al., 2021; McKay et al., 2021; Perlman et al., 2016; Perry et al., 2016; Todd & Marois, 2004, 2005; Wilcox & Biondi, 2016). However, there is a gap in the research in our understanding of caregiver influences on longitudinal changes in behaviour and brain function from infancy to toddlerhood. Thus far, studies have implicated factors such as caregiving styles, resources, SES, caregiver income, and stress, on visual cognition development (Bernier et al., 2010; Brandes-Aitken et al., 2020; Lugo-Gil & Tamis-LeMonda, 2008; McKay et al., 2021; Ribner et al., 2022; Wijeakumar et al., 2019, 2023). Nonetheless, more longitudinal research is essential to better understand how caregiving behaviours during social interactions might contribute to the development of visual neurocognition.

To bridge this gap, this chapter examined longitudinal changes in looking behaviours and brain function from infancy to toddlerhood. Further, this chapter also examined how caregiver looking behaviours and brain function and caregiver-infant dyadic behaviours impact these longitudinal changes. To do this, children were presented with variants of the preferential looking task (Ross-Sheehy et al., 2003) at two timepoints. The first timepoint (T1) was when children were 6- to 10-months old (findings reported in Chapter 3) and the second timepoint (T2) was when children were aged 18- to 22-months old. Across both timepoints, load was manipulated (T1: one, two, and three items; T2: two, four, and six items). To examine behavioural associations, looking dynamics were extracted from video recordings, and to examine brain associations, brain function was recorded using fNIRS whilst the children engaged with the task. This chapter had three research objectives. The first objective

was to investigate if there were longitudinal changes in behavioural performance from T1 to T2. The second research objective was to examine whether there were longitudinal changes in brain activation from T1 to T2. The final research objective was to examine caregiver influences on longitudinal changes in behaviour and brain function.

This chapter had several behavioural findings. First, this chapter reported that children both showed load-dependent modulation of CP scores across both timepoints. In line with findings in Chapter 3, as load increased, CP scores decreased, with the highest CP scores at the low load. Regarding the first research objective, children also explored the displays for longer and switched less at T2 in comparison to T1. This result was proposed to reflect children's improving visual cognitive abilities, as they become better able to sustain attention to the task, and less distracted by the changing side (Kannass & Oakes, 2008; Richards & Casey, 1992; Ruff & Capozzoli, 2003).

This chapter also had several brain findings. Regarding the second research objective, three key regions showed developmental effects. Children showed greater activation in the rSPL at T2 compared to T1, suggested to reflect a developmental shift to more specialised visuo-spatial attention processes (Berryhill & Olson, 2008; Buss et al., 2014; Corbetta & Shulman, 2002; Delgado Reyes et al., 2020; Pisella, 2017; Ren et al., 2019). Further, children showed greater activation in the lMFG at T1 compared to T2, a positive association between activation at T1 and activation at T2, and positive association with CP scores only at T1. Notably, the frontal cortex has been associated with early attention-related behaviours (Cuevas, Swingler, et al., 2012; Ellis et al., 2021; Perry et al., 2016). Here, the reduction in activation from T1 to T2 was proposed to reflect better neural efficiency over time (Rueda et al., 2012; Tsujimoto et al., 2013). Finally, in the left temporal cortex, children showed a trend towards increased activation at T1, and an inverse association between activation at T1 and activation at T2. Notably, this region has previously been linked to visual perception (Allison et al., 2000; Bonda et al., 1996; Corbetta & Shulman, 2002; Deen et al., 2015) and the processing of socially relevant motion cues (Carter & Pelphrey, 2006; Grossman et al., 2004; Grossman & Blake, 2002; Grossmann et al., 2008; Lloyd-Fox et al., 2009; Mosconi et al., 2005; Pelphrey et al., 2003).

Importantly, regarding the final research objective, caregiver influences on longitudinal changes were observed in two regions. First, the lMFG cluster that showed developmental effects spatially overlapped with the lMFG cluster that was inversely associated with CP scores in caregivers (Chapter 3). The shift in functionality observed in this region was proposed to reflect a heritability-related link (Blokland et al., 2008, 2011; Park et al., 2024). Second, there was a moderating effect of caregiver-infant joint attention during dyadic interactions on the lMTG cluster that showed developmental effects. Specifically, infants who experienced greater durations of joint attention at T1 showed a weaker association between left temporal activation at T1 and T2. Building on left temporal associations found in Chapter 5, it was suggested that exposures to episodes of joint attention with caregivers can significantly shape developmental changes in brain regions that are involved in both social cognition (Carter & Pelphrey, 2006; Grossmann et al., 2008; Lloyd-Fox et al., 2009; Mosconi et al., 2005) and EF (Brahmbhatt et al., 2008; Delgado Reyes et al., 2020) contexts.

To summarise, the over-arching objective was to investigate longitudinal changes in looking behaviours and brain function from infancy to toddlerhood, and how caregiver looking behaviours and brain function and caregiver-infant dyadic behaviours impact these longitudinal changes. In the first finding, infants and toddlers showed load-dependent modulation of looking behaviours, as well as increased looking durations and decreased shifting, from infancy to toddlerhood. Brain findings also reported that infants showed greater activation in frontal regions, thought to underly early visual behaviours, and toddlers showed greater activation in posterior parietal regions, thought to underly visuospatial attention, VWM and sustained attention processes. Further, there was a positive association between activation in the frontal cortex, and a negative association between activation in the temporal cortex, between infancy and toddlerhood. Critically, findings in the frontal cortex provided support for a heritability-related link, while findings in the temporal cortex suggested caregiving-related effects. Importantly, this chapter offered novel insight and highlighted the importance of studying caregiver-infant interactions to understand visual cognition development.

7.3 Implication of experimental studies

7.3.1 Assessing caregiver abilities using the adult preferential looking task

In Chapter 3 of the thesis, a variation of the preferential looking task was employed in the caregivers. Thus far, conventional VWM tasks have reported adult capacity limits of around three to five items (Cowan, 2001; Luck & Vogel, 1997). Further, studies report complexity in adult visual cognition, with capacity not simply defined by the number of items, but influenced by other factors within representations, such as object properties (Brady & Alvarez, 2011), object similarity and complexity (Awh et al., 2007), and object features (Fougnie et al., 2010; Wilken & Ma, 2004; Zhang & Luck, 2008). Typically, tasks employ conventional methods, which require participants to follow explicit instructions and prepare for effort required to meet challenging goals with increasing load. Further, outcome estimates are typically derived from either the response being correct or incorrect. For example, the change-detection task requires adults to respond to indicate whether two displays were the same or different.

Thus far, there is evidence for both familiarity and novelty as factors influencing preference in adults. One study presented adults with a preference task, in which two stimuli were presented side-by-side (Park et al., 2010). These stimuli were grouped into different object categories: faces, natural scenes, and geometric figures. Results found that whilst faces elicited a preference for familiarity, natural scenes elicited a novelty preference. These effects persisted, regardless of image presentation (such as inversion or line drawings). Further research has suggested that task context further influences how familiarity and novelty preferences manifest (Liao et al., 2011). Novelty preferences have also been examined with adults and children, finding that these preferences can be influenced by individual's goals (Sehl et al., 2022). For example, in the context of choosing items they would rather have, adults and children show a preference for familiar items, but in the context of learning, adults and children show a preference for novel items. Another study employed a visual paired comparison task to study novelty preferences in adults (Richmond et al., 2004). Here, consistent with infant studies, findings reported that as familiarisation time increased and retention periods decreased, adult novelty preferences increased. Whilst these studies employ novelty preference procedures in adults, primarily these use complex scenes/faces, and do not have a load manipulation.

To the best of current knowledge, this is the first time a variation of the child preferential looking task has been employed in adults. This paradigm differs from conventional adult VWM tasks for several reasons. Firstly, adults were not provided with any explicit instruction, and simply asked to explore the display, removing the need to prepare to meet challenging goals. Secondly, outcome measures were derived from looking measures, as opposed to correct/incorrect responses. Finally, in contrast to existing novelty preference procedures in adults, this task included a load manipulation. To achieve a novelty preference, adults must therefore re-orient between the displays, making comparisons and confirmatory looks. Given the importance of caregiver gaze during interactions with their infants (Hoehl et al., 2012; Yu & Smith, 2016), it seems critical to examine gaze dynamics during preferential looking tasks, and how these change with increased load demand, measures which are not typically extracted during conventional VWM tasks.

Findings from Chapter 3 therefore confirm that adults show a novelty preference during a variation of the preferential looking task with multiple stimuli. Importantly, this preference is impacted by increasing VWM demand. These findings have broad implications for visual cognition literature. Critically, this demonstrates the potential for use of this task in the examination of visual cognition. Importantly, looking scores extracted from this task allow for closer comparisons to real-world visual cognition. Specifically, adults must navigate their visual environment, shifting their attention, making comparisons between multiple objects, and detecting change, all behaviours which are employed during interactions with their children. Further, this task can also be used to make more direct comparisons to children's performance on the preferential looking task. This alignment may help to establish how specific looking measures manifest during dyadic interactions. Further, these looking measures can be analysed in association with brain activation to further understand how cognitive processes manifest in gaze behaviours.

7.3.2 Early associations between caregiver and infant brain function

In Chapter 3 of the thesis, findings reported that greater CP scores in infants were associated with greater lSPL activation in infants during the task. This association between caregiver visual cognition and left parietal activation was observed in young, but not older infants. Further, in Chapter 5, reduced lSTG activation in caregivers during joint attention was associated with reduced lSTG

activation in infants during joint activation, longer duration of joint and continued attention, and increased performance on the preferential looking task. Finally, in Chapter 6, there was an inverse association between activation in the temporal cortex in infancy and toddlerhood, which was moderated by caregiver-infant joint attention during play interactions.

Firstly, it is important to highlight that the association in Chapter 3 between caregiver visual cognition and left parietal activation was observed in young infants only. This result provides support for research indicating the heritability of general visual cognition mechanisms (Chen et al., 2018; Constantino et al., 2017; Quinn et al., 2022). Here, it was speculated that this association may become more shaped by social and environmental factors as the infant becomes more mobile. This finding also provides support for research that suggests cognitive functions have both genetic and social/environmental influences. For example, in caregiver-infant play interactions, one study found that after accounting for partner influences, developmental changes in play still remained, suggesting that changes and individual differences in behaviours, are partly influenced by independent processes, as well as interactions between caregiver-child dyads (Tamis-LeMonda & Bornstein, 1991). Understanding contributions of baseline cognitive associations, and contributions of each partners own cognitive capabilities, may better inform future research and tailored interventions for families.

Further, findings in Chapters 5 and 6 have highlighted the importance of temporal cortex activation in association with visual cognition. Specifically, left temporal associations were seen between caregiver and infant engagement during dyadic interactions, as well as longitudinally in the child across the first few years of life. Previously, research has suggested that integrated activity between the anterior and posterior systems are purported to support joint attention (Mundy, 2003; Mundy et al., 2000; Mundy & Newell, 2007; Williams et al., 2005). Findings here support existing research that suggests that joint and sustained attention processes are not solely reliant on the frontal and parietal cortex, but also involve contributions from the temporal cortex (Deen et al., 2015). Findings further implicate caregiver involvement during play on temporal cortex engagement across development. These associations not only point to the caregiver's role in development of visual cognition, but also in the development of social cognition. Concretely, findings in the temporal cortex

support that caregivers must use critical cognitive processes, such as attentional control, inhibitory control and working memory, to effectively join in and scaffold interactions with infants, but also step back and allow infants to sustain attention where needed.

7.3.3 Longitudinal changes in visual attention behaviours

Importantly, in Chapter 6, key findings shed light on current understanding of changes in visual cognition in early development. Notably, in this chapter, several behavioural findings shed light on changes in visual cognition in early life. Here, findings reported that both infants and toddlers demonstrate load-dependent modulation of CP scores in completion of age-appropriate variations of the preferential looking task. Infants were greater able to detect changes at a load of one item, in comparison loads of two and three items. Toddlers were also able to greater detect the change at a load of two items in comparison to six items. This result was in line with current findings indicating an increase in capacity limits in early childhood (Delgado Reyes et al., 2020; Mitsven et al., 2018; Oakes et al., 2013, 2017; Ross-Sheehy et al., 2003). Further, in toddlerhood, children showed increased looking durations and reduced switching, which was also in line with findings that report decreases in distractibility and casual attention, and increases in sustained attention across childhood (Kannass & Oakes, 2008; Richards & Casey, 1992; Ruff & Capozzoli, 2003). Changes in looking durations and switching provides novel insight into the varying behaviours that children employ to detect change in early life. In infancy, children may rely more heavily on exogenous-driven attention behaviours in completion of the task, whereas in toddlerhood, children may be better able to sustain attention, allowing them to suppress distraction towards the changing side.

Importantly, this perspective is also supported by brain findings in this chapter. These findings reported that infants showed greater activation in the frontal cortex, in comparison to toddlers who greater recruited the posterior parietal cortex. It is possible that in infancy, children greater recruit more immature frontal regions, in association with early visual behaviours, however in toddlerhood, refinement of posterior parietal regions, enables improvements in more sophisticated attention processes such as visuospatial attention, VWM and sustained attention. Collectively, these findings highlight the variability in visual attention behaviours used in early life, which should be taken into consideration in future research. Specifically, there remains a gap in our

understanding of how this variability influences important outcomes in later childhood.

7.3.4 Informing interventions

Finally, it is important to consider how these findings might be important for intervention strategies. There were two important findings across Chapter 5 and 6 that contribute to current accounts of joint and continued attention in early life. Firstly, in Chapter 5, duration of joint attention between caregivers and infants was linked to duration of continued attention in infants. Importantly, reduced left temporal activation in caregivers during joint attention was linked to reduced left temporal activation in infants during joint activation, longer duration of joint and continued attention, and better VWM in infants. Further, in Chapter 6, there was a moderating effect of joint attention on longitudinal left temporal engagement. Collectively, these findings highlight that joint attention may play a critical role in temporal cortex stability in relation to visual cognition.

In the current thesis, it was suggested that caregivers who were greater able to suppress activity in the temporal cortex during play interactions, may be better able to pick up their children's cues, thus scaffolding their infants own attentional behaviours. This perspective aligns with previous work emphasising the importance of temporal contingency and semantic relevancy in caregiver responsiveness and scaffolding (Schroer & Yu, 2022). Specifically, that caregivers must be able to promptly respond to their infants, but that this response must be appropriate to the infant's activity or focus. Training programmes could therefore focus on enhancing caregiver attunement to infant cues, with particular emphasis on both the timing (i.e. responding promptly to infants shifts in attention) and relevance (i.e. object-specific verbalisations) of input during periods of joint attention. Existing studies lend support to similar intervention approaches that more generally target increasing joint attention. For example, studies have demonstrated that children are receptive to targeted joint attention training with positive outcomes (Hwang & Hughes, 2000; Kasari et al., 2006, 2008; Whalen & Schreibman, 2003). Additionally, caregiver-led interventions that promote increased infant engagement have been associated with improved social and cognitive outcomes in autistic children (Drew et al., 2002; Ingersoll & Wainer, 2013; Kasari et al., 2010, 2015; Perera et al., 2016).

Importantly, novel findings in the temporal cortex highlight the potential to incorporate assessments of neural activation into these intervention techniques as a measure of efficacy. For example, assessing temporal cortex activation before and after interventions could provide additional insight into the extent to which training enhances caregivers' capacity to respond in a timely and contextually appropriate manner. Such neural assessments may not only serve as an index of intervention effectiveness, but also inform the refinement of training techniques, allowing for more targeted support that aligns with individual caregiver-infant dynamics.

7.4 Strengths and limitations

7.4.1 Strengths of the thesis

This thesis has several notable strengths. Firstly, behavioural and brain data was collected from a considerable sample size. As detailed in Chapter 3, power calculations revealed that a sample size of 85 infants was required to detect an effect of load on behavioural performance in the preferential looking task (one-factor ANOVA with load on looking measures from Delgado Reyes et al., 2020; effect size = 0.15, alpha = 0.05 and power = 0.80). Extensive recruitment efforts resulted in 90 families who visited the lab at T1, reaching the required sample size from the power calculations. This sample size ensures that the thesis had strong statistical validity and adequate power to detect expected effects. This sample size also provides further support for additional sub-group follow-up analyses. For example, in Chapter 3, Section 4.2.2. *Brain regions associated with infant visual cognition*, the association between caregiver CP score and infant lSPL activation also showed an effect of age. To analyse this further, infants were therefore divided into two groups: young and old infants, with findings reporting that higher CP scores were associated with increasing HbO concentration in the lSPL in young infants only. This follow-up allowed further inferences to be made, as early in infancy, infants who showed greater activation of the lSPL had caregivers with greater ability to detect the change, but later in infancy this effect was no longer present. Importantly, this allowed for further discussion regarding the contributions of heritability and social/environmental factors to visual cognition development. It is important to note that at T2, following attrition/further recruitment, the number of families that visited the lab dropped to a total of 77. While this is close to the target of 85, this is slightly lower, potentially impacting the validity of the results. Given the importance of visual cognition in predicting later cognitive

and academic outcomes (Conway et al., 2003; Gathercole et al., 2004; Leather & Henry, 1994; McQuade et al., 2013), and its receptibility to intervention techniques (Lakes & Hoyt, 2004; Lillard & Else-Quest, 2006; Raver et al., 2008, 2011), it is necessary to acknowledge this in the interpretation of longitudinal findings. While it is important to consider, it is worth noting the findings in Chapter 6 still aligned with existing research using the preferential looking task in toddlerhood (Delgado Reyes et al., 2020), as well as other measures of visual cognition across development (Cheng et al., 2019a, 2019b; Riggs et al., 2006; Simmering, 2012, 2016a, 2016b), providing support for the validity of the effects seen.

In addition, this thesis employed a preferential looking task that has previously been used in infancy and toddlerhood, replicating similar results. Notably, the preferential looking task was first developed by Ross-Sheehy et al. (2003) to measure visual cognition between the ages of 4 and 13 months. Here, the authors reported that infants aged 6 months could only detect changes in displays of one item, but by 10 months this had increased to up to four items. More recent findings from Delgado Reyes et al. (2020) reported further increases into toddlerhood with the addition of brain findings. This task has also been administered in low-resource settings, to examine the impact of adversity on visual cognition development (Wijeakumar et al., 2019, 2023). Findings from the current thesis reproduce many behavioural and brain findings from these studies. For example, in Chapter 3 and Chapter 6, infants and toddlers showed decreasing CP scores with increasing load, and in Chapter 6, children showed increased TLD scores with age, consistent with previous findings (Delgado Reyes et al., 2020; Ross-Sheehy et al., 2003). These findings not only highlight the reliability and validity of using this task in early childhood, but also demonstrate its potential for future applications, for example, in diagnostic or intervention settings.

Furthermore, this thesis integrated the preferential looking task, an independent measure of visual cognition, alongside behavioural and brain analyses of dyadic play interactions. This combination not only provides a more comprehensive view of visual cognition in the context of cognitive and social development, but also contributes novel findings to current literature, as combinations of these types of measures is rare. Notably, current findings from dyadic interaction research also tend to focus upon language outcomes (Brooks & Meltzoff, 2008; Charman et al., 2000; Kannass & Oakes, 2008; Yu et al., 2019) and social abilities (Brooks & Meltzoff, 2015;

Carpenter et al., 1998; Charman et al., 2000), supporting the influence of joint attention on word learning and social communication skills. Crucially, this integration provides insight into the relationship between brain maturation and behaviour, and how this supports visual cognitive development.

The methodology and analyses approach used in Chapters 4 and 5 also contributes novel findings to current dyadic interaction literature. While there is an abundance of research investigating behaviour during dyadic interactions between children and caregivers (Deák et al., 2008, 2014; Monroy et al., 2021; Schatz et al., 2022; Suarez-Rivera et al., 2019, 2022; Yu et al., 2019; Yu & Smith, 2013, 2016), less is known about underlying brain function. Existing research on childhood often involves structured tasks and/or pairs the child with either a virtual partner/experimenter (Grossmann et al., 2013; Mundy et al., 2000; Naoi et al., 2022), or extracts inter-brain synchrony measures (Leong et al., 2017; Marriott Haresign et al., 2023; Nguyen et al., 2020, 2021; Papoutselou et al., 2024). Ultimately, literature that examines cortical underpinnings of attention in both caregivers and infants is limited (Michel et al., 2024; Wass, Noreika, et al., 2018). Adding to this, many dyadic interaction studies have focused on later infancy and toddlerhood (Herzberg et al., 2022; Rachwani et al., 2020; Schatz et al., 2022; Schroer & Yu, 2022; Suarez-Rivera et al., 2022; Tamis-LeMonda & Bornstein, 1991; Yu & Smith, 2013, 2016). Notably, there is less research focusing on the second half of the first year (Michel et al., 2024; Monroy et al., 2021), despite gaze following and joint attention abilities emerging around this time (Scaife & Bruner, 1975; Striano, Chen, et al., 2006; Striano & Stahl, 2005). More generally, a key strength of this thesis, is its contributions to areas with very limited research.

7.4.2 Limitations of the thesis

There are also several limitations of the thesis which are important to consider when interpreting the results. Firstly, the diversity of the current sample is limited. Details of overall SES data across all tasks and timepoints is provided in the socioeconomic and demographics table in Appendix C: *Appendix Table C.3*. This data highlighted that almost three-quarters of families who took part in data collection contributing to this thesis were White British. This lack of ethnic diversity necessitates caution when generalising the findings beyond the studied population. Notably, previous research has highlighted that caregiving practices, such as physical care,

cognitive engagement, warmth, acceptance, guidance and discipline, can vary across cultures (Bornstein et al., 2011; Lansford, 2022). Importantly, in the current thesis, these variations have the potential to impact how caregivers engage with their infants during the dyadic interactions. This implication underscores the need for greater sample diversity, to contextualise findings across different ethnic backgrounds.

It should also be noted that the investigations in this thesis focus on the primary caregiver. While focusing on a single caregiver reduces variability when accounting for multiple roles, this approach may overlook the influence of other caregivers, such as the secondary caregiver or other family members, thus providing a limited perspective. For example, Ribner et al. (2022) examined differences in caregiver EF and parenting behaviours on child EF development. In this study, the authors found that *both* parents contributed to child EF. Findings reported that father EF similarly predicted child EF development to that of mother EF, and when both caregivers were considered together, the combination of both collectively contributed to child EF. The perspective of focusing solely on the primary caregiver in this thesis, may also disregard diverse family structures and may not apply to families where caregiving responsibilities are more equally shared.

It is important to highlight limitations of using fNIRS for brain function studies. Firstly, it is not possible to probe deeper sub-cortical structures using fNIRS, as infrared light generally penetrates only 1.5 – 2 cm through the skull, reaching the outer 5 – 10 mm of brain tissue (Fukui et al., 2003; Huppert et al., 2009; Okada & Delpy, 2003a, 2003b). While a significant proportion of the VWM network is located near the cortical surface (Buss et al., 2014; Cutini et al., 2011), sub-cortical structures have been associated with visual cognition and broader cognitive processes. For example, the superior colliculus has been associated with detecting and orienting events in the environment, visuo-spatial attention, and decision-making (Benarroch, 2023). The anterior cingulate cortex has also been associated with inhibitory control (Rubia et al., 2007). More recently, work has used gaze-coding in combination with fMRI to simultaneously study behavioural and brain measures of visual cognition (Ellis et al., 2021). Whilst this allows for the study of deeper structures, it is important to consider the feasibility of fMRI methods in investigation of naturalistic play in young children, designs which are ultimately intended to resemble day-to-day interactions. Secondly, scalp landmarks were not obtained from all infants and

caregivers. The current thesis therefore does not consider variations in head shape, head size, and probe placement. Research has reviewed literature on brain structure across development (Gilmore et al., 2018), finding that infant brain growth is very rapid, doubling from term size during the first year, and increasing a further 15% to around 80% of adult size during the second year. Cortical surface area also expands dramatically, increasing by around 76% during the first year, and around 22% during the second year. Following this, white matter volumes steadily increase into adulthood, peaking at around age 30. From around age 40, this then decreases at a rate of approximately 5% per decade. Individual digitisations/MRI from each participant would better address variations across development. As this was not feasible in the current thesis, participants were instead separated and grouped based upon age-related atlases that were available from the Neurodevelopmental MRI database (Richards et al., 2016). A greater number of atlases would however better account for the dramatic changes in brain development over the first few years of life (Gilmore et al., 2018).

Notably, there were some limitations that were specific to the collection of dyadic data. First, the interactions lasted only for a maximum of only 7 minutes. Future work should aim to collect interaction data for a longer duration to gather more events of each condition. Second, in the current thesis, it was necessary to collect play interaction data in laboratory conditions, to allow for collection of fNIRS data. Conducting this in a laboratory environment, as opposed to the infant's familiar home environment, reduces the ecological validity of the findings. Finally, due to the reduction in sources and detectors, which resulted in a limited number of channels, broader regions of the fronto-parietal network could not be examined. While this limits the examination of broader regions, it is important to consider comfort when collecting fNIRS data from young children.

7.5 Future Directions

7.5.1 Refining research approaches

Whilst the current thesis provides valuable insights to the development of visual cognition in early childhood, there are several alterations that could be made to methodological approaches and analyses to improve interpretations. Firstly, concerning the preferential looking task, previous research has also analysed change-preference scores with time (Delgado Reyes et al., 2020). Specifically, researchers

analysed latency to change-preference across the trial. Notably, to ensure for optimal statistical modelling, the time-series data had to be trimmed at 2300 ms, after the subjects had viewed three flashes, and at 9000 ms, as data in the final second was typically noisy due to a decline in engagement, potentially resulting in data loss. Further, the sample size was considerably lower (4-month-olds: n = 16, 1-year-olds: n = 19, 2-year-olds: n = 22). Nonetheless, it is important to consider that extracting latency to change preference, might allow for a more detailed approach when analysing the factors influencing individual differences in visual cognition.

Along a similar line, more recent research has additionally distinguished between the side in which children started on when completing the preferential looking task (Spencer et al., 2023). When engaging with the task, if infants look towards the non-changing display first, infants are not yet able to distinguish between the changing and non-changing side. Further, when infants look towards the changing display first, they are more likely to detect novelty and sustain attention towards the display, leading to above chance responding. The authors therefore state that the side in which children start upon might place different demands on visual cognition. Resultingly, trials in which children look towards the non-changing side first might be more sensitive to individual differences in visual cognition, and might further uncover differences in looking dynamics, enabling deeper insights into the attentional behaviours employed across childhood. Future work should therefore aim to analyse the time course of change preference abilities and differentiate trials depending on which side the child looked to first.

Furthermore, adaptations to dyadic procedures and analyses may also shed further light onto differences in attentional behaviours and brain function during play. Notably, in Chapter 5, it was not possible to identify brain correlates across all joint attention periods, regardless of modality. Future studies should design paradigms in which caregivers are explicitly asked to complete attention periods with specific modality types, enabling comparison across these. Further, the interactions had a maximum duration of 7 minutes. Across this, caregivers and infants contributed an average of 3 events each for both joint attention and continued attention. Future work should aim to collect interaction data for a longer duration to gather more events of each condition. Finally, dyadic interaction data was collected in lab-based settings. Future work could apply portable fNIRS methods, to collect data from the caregiver

and infant's familiar home environment. This environment might improve infants' ease and cooperation, allowing them to exhibit play behaviours that more closely resemble their day-to-day interactions with caregivers, thus increasing the ecological validity of the findings.

7.5.2 Functional connectivity

Functional connectivity is typically measured by analysing similarities between brain activity between distinct regions (Mohanty et al., 2020; Power et al., 2011). If two regions show a strong correlation, it may indicate that regions are functionally connected in the brain (Damoiseaux et al., 2006; Greicius et al., 2003; Mohanty et al., 2020; Salvador et al., 2005; Shirer et al., 2012). This method has been applied to research on joint and sustained attention during infancy. One study used functional connectivity MRI and behavioural assessments to investigate initiating joint attention in infants and toddlers (Eggebrecht et al., 2017). In this study, the authors found different networks associated with initiation of joint attention at 12 and 24 months. In the older children, there was an increase in correlated ROI pairs, which were more distributed throughout the brain. These findings were thought be influenced by changes in social experience-dependent learning and increases in verbal communication abilities, which may strengthen/increase connections over the second year. Further, another study used fNIRS to examine functional connectivity in 7- to 12-month-old infants during initiation and response to joint attention bids with an experimenter (Naoi et al., 2022). In this study, infants showed stronger functional connectivity in the right ventral prefrontal region during responding to joint attention bids, in comparison to initiating joint attention bids. Here, it was suggested that this increase in the right ventral frontal area during responding to joint attention represented a shift towards the joint attention stimulus. In comparison, during initiation of joint attention, infants must inhibit attention to the external environment, thought to result in lower functional connectivity during these bids. Collectively, studying functional connectivity, allows researchers to make informed conclusions as to how different regions interact during social and visual cognition.

In Chapter 4, modality-analyses revealed that infants demonstrated a 'source-sink' effect, in which greater rMFG activation was accompanied by a trend for greater rAG suppression during multimodal engagement. This finding was similar to a mechanism associated with cognitive decline in studies with older adults, specifically,

a posterior to anterior shift in activation (Ansado et al., 2012; Wijeakumar, Magnotta, et al., 2017; Zhang et al., 2017). In this chapter, it was suggested that inverse posterior-anterior associations might represent weak connectivity in the frontal cortex, which is still structurally and functionally immature (Casey et al., 2005; Collin & Den Heuvel, 2013; Huttenlocher & Dabholkar, 1997; Matsuzawa et al., 2001). Future research should therefore aim to include functional connectivity between anterior and posterior regions showing task-based activation to examine 'source-sink' effects. This approach may increase understanding of interactions between regions in the developing brain, and how the brain compensates for functionally immature regions in early life.

7.5.3 Extending longitudinal investigations

Across four experimental chapters, different approaches have revealed important findings informing visual cognition in early life. Critically, in Chapter 5, caregiver brain function was linked to infant brain function, joint and continued attention during dyadic interactions, and visual cognition during the preferential looking task. Further, in Chapter 6, longitudinal investigations suggested a shift in visual attention behaviours, and the brain networks that underly these across infancy and toddlerhood. Further, joint attention in infancy moderated associations between brain function in infancy and brain function in toddlerhood. This result allowed hypotheses to be drawn related to effective caregiving strategies that might foster infant's attention and visual cognition development. However, it remains unclear how these longitudinal patterns extend into childhood.

Previous findings have implicated early caregiving behaviours, with developmental changes later in toddlerhood and childhood. For instance, joint attention measures have been shown to mediate the relationship between caregiving at 15 months, and child EF at 48 months (Brandes-Aitken et al., 2020). Further, findings report that mother and child EF are moderately correlated at 24 months, and robustly correlated by 36 months of age (Cuevas, Deater-Deckard, Kim-Spoon, Watson, et al., 2014). Attention in infancy also has implications later for social (Brooks & Meltzoff, 2015; Charman et al., 2000) and language outcomes (Brooks & Meltzoff, 2008; Yu et al., 2019). Future research should therefore aim to longitudinally investigate the impact of early caregiving behaviours and infant visual cognition, on measures of EF, language, and social abilities later in life. This approach would allow for a deeper understanding of what mechanisms drive later childhood associations and

greater inform intervention strategies for children with atypical developmental pathways.

7.6 Conclusions

Visual cognition develops early in infancy, as children begin to demonstrate foundational attentional and visual cognitive abilities. This system is critical to study due to its implications for many real-world outcomes. During this time, infants also begin to share attention with mature caregivers, to learn about objects and their environments. Similarly, these moments of shared attention are also predictive of later cognitive, social and language outcomes. This thesis aimed therefore aimed to investigate longitudinal associations between infant and toddler visual neurocognition, with insights from caregiver visual neurocognition and dyadic interactions. To assess visual cognition, age-appropriate variations of the preferential looking task were presented to caregivers and infants in the first year of life. Further, in the second year, toddlers were re-assessed with the same task. In addition, dyadic interactions between caregivers and infants were analysed, to investigate multimodal, joint and continued engagement with objects. During the preferential looking tasks and dyadic interactions, fNIRS was used to collect brain activation data.

Novel findings in this thesis contribute to current understanding on the development of visual cognition and underlying brain function. Findings in Chapter 3, reported early associations between caregiver and infant behaviours and brain function during an experimental task. In Chapter 4, novel caregiver-infant findings on modality-related brain function were observed. Further, in Chapter 5, early associations were observed between caregiver and infant brain function, object engagement and visual cognition. Finally, Chapter 6 revealed a moderating effect of joint attention during play interactions on associations between infant and toddler temporal cortex engagement. Collectively, findings highlighted the variability in attention strategies used in visual cognition and underlying brain function across infancy and toddlerhood, which should be taken into consideration in future research. Further, results here offer insight into the influences of caregiving behaviours on infant behaviour and brain function. More generally, these findings align with research that highlights the importance of temporal contingency and semantic relevancy of caregiver input during interactions. Further, findings provide support for the self-regulatory framework, which indicates that critical cognitive processes, such as

attentional control, inhibitory control, and working memory, must be regulated in the caregiver as well as between the caregiver and infant during interactions. Ultimately, these processes allow the caregiver to effectively join in and scaffold their infant's attention appropriately, but also to allow infants the opportunity to sustain attention when required. Ultimately, these findings may contribute to informing parenting practices, early intervention methods, and future longitudinal research.

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Appendices

Appendix A: Recruitment Documents





Faculty of Science
School of Psychology
University of Nottingham
University Park
Nottingham
NG7 2RD

Dear Manager,

We are a group of developmental researchers in School of Psychology at the University of Nottingham. We are about to start a new research project investigating how babies learn to interact with, respond to and eventually 'fall into sync' with their mothers/birth-givers. Specifically, we want to understand how the nature of these interactions in the first few years of life will build and develop critical cognitive functions and brain networks in babies.

We would like to invite families whose babies are or about to be 6 to 9 months of age to participate in our study via your centre with your permission. The study will be carried out at the Infant and Toddler Lab in the University Park campus at the University of Nottingham. The study will involve about 2-4 visits each year across three years. This will help us build a comprehensive picture of how mother/birth-giver baby interactions develop across the first critical three years of the baby's life. During each visit, we will take video recordings and put caps with sensors on the mother/birth-giver and the baby's heads to measure brain activity in a safe manner. While wearing the cap, they will be shown objects on a TV – for instance, colored shapes and we will monitor how and where they examine the TV. We will also measure brain activity while the baby plays with toys with their mother/birth-giver. Finally, we want to understand the mother's/birth-giver's own perspective of their baby's cognitive development so we will send them some questionnaires to fill in based on their own observations of their baby.

Parents will be paid £10 per visit as a 'thank you' for their participation. All members of the research team have completed recent DBS certification that we are happy to present for your inspection. All members have received both Covid-19 and booster vaccinations. We attach the safety and hygiene practices we follow in our lab. This study has already received full ethical approval from the University of Nottingham Ethics Committee.

We have attached our poster advertisement and a letter for the families. We would really appreciate your help in sharing these documents with the families. We can also provide more information to help the parents make an informed decision as to whether they would like to participate in our study. We really hope that this study is of interest to your centre and that you would be willing to support our recruitment efforts to understand how mothers/birth-givers and babies interact with one another.

Our research team will be also more than happy to get in touch with your centre and answer any queries. If you are interested to share the information of our study and/or would like more information, please do get in touch with us and a member of the research team will contact you and share more information. Please contact us either via email at project-neurosync@nottingham.ac.uk or via phone on 0115 951 5312.

Thank you for your time and consideration.

Best,
The Project NeuroSync Team

Email: project-neurosync@nottingham.ac.uk
Phone: 0115 951 5312
Twitter: @NeurosyncP
Instagram: @neurosyncp
Facebook: @NeurosyncP
Website: www.projectneurosync.co.uk
University Webpage: https://www.nottingham.ac.uk/psychology/research/project-neurosync.aspx

Appendix Figure A.1 Letter to organisations (page 1 of 1).

University of Nottingham
UK | CHINA | MALAYSIA

NeurSync

Faculty of Science
School of Psychology
University of Nottingham
University Park
Nottingham
NG7 2RD

Dear Parent,

We are a group of developmental researchers in School of Psychology at the University of Nottingham. We are about to start a new research project investigating how babies learn to interact, respond to and eventually 'fall into sync' with their mothers/birth-givers. Specifically, we want to understand how the nature of these interactions in the first few years of life will build and develop the critical cognitive functions and brain networks in babies.

We would like to invite parents whose babies are or about to be 6 to 9 months of age to participate in our exciting project. The study will be carried out in the Infant and Toddler Lab in the University Park campus of the University of Nottingham. The study will involve about 2-4 visits each year for three years. This will help us build a comprehensive picture of how interactions between you and your baby develop across the first three critical years of their life. During each visit, we will take video recordings and put caps with sensors on your and your baby's heads to measure brain activity in a safe manner. While wearing the cap, you both will be shown objects on a TV – for instance, colored squares, and we will monitor how and where you examine the TV. We will also measure brain activity while you and your baby play with each other. Finally, we want to understand your own perspective of your baby's cognitive development so we will send you some questionnaires to fill in based on your own observations.

You will be paid £10 per visit as a 'thank you' for your participation. All members of the research team have completed a recent DBS certificate that we are happy to present for your inspection. All members have received both Covid-19 and booster vaccinations. We attach the safety and hygiene practices we follow in our lab. This study has already received full ethical approval from the University of Nottingham Ethics Committee.

Our research team will be more than happy to get in touch with you over the phone or via email and answer any queries and provide more information. We really hope that this study is of interest to you and that you would be willing to help us understand how mothers/birth-givers and babies connect with one another. If you are interested to participate in our study, please contact us either via phone on 0115 951 5312 or email us at project-neurosync@nottingham.ac.uk.

Thank you for your time and consideration.

Best,
The Project NeuroSync Team

Email: project-neurosync@nottingham.ac.uk
Phone: 0115 951 5312
Twitter: @NeurosyncP
Instagram: @neurosyncp
Facebook: @NeurosyncP
Website: www.projectneurosync.co.uk
University Webpage: https://www.nottingham.ac.uk/psychology/research/project-neurosync.aspx

Appendix Figure A.2 T1 letter to families (page 1 of 1).



University of Nottingham
UK | CHINA | MALAYSIA



Faculty of Science
School of Psychology
University of Nottingham
University Park
Nottingham
NG7 2RD

Dear Parent,

We hope you and your family are well.

As you know, over the last two years, we embarked on a project investigating how children learn to interact with, respond to and eventually 'fall into sync' with their caregivers. Specifically, we wanted to understand how the nature of these interactions in the first few years of life will build and develop critical cognitive functions and brain networks in children. We are happy to report that 90 families participated in our study!

Now that your little one will soon be between 30 and 38 months of age, we are excited for the next phase. We would like to welcome you and your child to our lab. During each lab visit, we will take video recordings and put caps with sensors on you and your child's heads to measure brain activity in a safe manner. We will measure brain function as you interact with your child. We will also request you to complete some questionnaires about yourselves and your child.

You will be compensated as a 'thank you' for your participation. Members of the research team who will be directly interacting with your family have completed a recent DBS certificate that we are happy to present for your inspection. This study has already received full ethical approval from the University of Nottingham Ethics Committee.

Our research team will be in touch with you over the phone or via email to provide more details, answer any queries and book you and your little one in for the visits.

Thank you for your time and consideration.

Best,
The Project NeuroSync Team

Email: project-neurosync@nottingham.ac.uk
Phone: 0115 951 5312
Twitter: @NeurosyncP
Instagram: @neurosyncp
Facebook: @NeurosyncP
Website: www.projectneurosync.co.uk
University Webpage: https://www.nottingham.ac.uk/psychology/research/project-neurosync.aspx

Appendix Figure A.3 T2 letter to families (page 1 of 1).

University of Nottingham
UK | CHINA | MALAYSIA

Information Sheet for Parents

Project NeuroSync

What is the purpose of this study?

We are interested in understanding how children learn to interact with, respond to and eventually, 'fall into sync' with their caregivers. To this end, we will study how the nature of these interactions in the first few years of life will build and develop critical cognitive systems and brain networks in children.

Who is the research team?

Our research team is composed of academics with expertise in Psychology, Neuroscience, Computational modelling, Engineering and Computer Vision at the University of Nottingham, University of Stirling and University of East Anglia. Data will also be collected, analysed, written, and presented by PhD students, postdoctoral researchers, postgraduate students, undergraduate students, and students on summer bursaries, internships, placements and visiting scholarships.

Why has my family been invited?

We are inviting families and their children who are between 30 and 38 months of age to participate in our study.

Do we need to take part in the study?

It is up to you whether you would like to take part in the study. If you are interested to take part and contact us, a member of our team will contact you to explain the study and answer any questions that you may have and schedule a convenient time for you to visit our lab. If you do decide to take part, you will be asked to sign a consent form. You and your child's participation in this study is totally voluntary and you are under no obligation to take part. Your family is free to withdraw at any point before or during the study.

What does participation in the study involve?

We want to build a comprehensive picture of how your child interacts with you and simultaneously develops their cognitive abilities across these critical years of their lives. To do this, we must track cognitive development in each child and their caregivers. We will invite you and your child to attend 1-2 visits to our lab this year. You will be compensated as a 'thank you' from us for taking part in our study.

What happens during each lab visit?

You will visit the Infant and Toddler Lab in the School of Psychology at the University of Nottingham. Each visit will last up to 2.5 hours. We will take video recordings of you and your child using cameras and head-mounted cameras while you play with each other. Please ask us if you would like to see the video recordings – we will be happy to show them to you after the session. We will also use a brain imaging technique to measure brain activity from you and your child during this period. The equipment we will use to measure brain activity is called functional near-infrared spectroscopy. This is a completely safe technique and will not hurt you or your child. It involves researchers placing a cap with sensors on the head. This technique has been used in neurotypical and neurodivergent populations of babies, children, young and older adults without any issues or concerns. We will also ask you to complete some experimental tasks and questionnaire about yourselves and your child.

Appendix Figure A.4 Information sheet for families (page 1 of 3).

How will you handle our video recordings?
We will use your video recordings only for data analyses purposes. The video recordings of you and your child playing with each other will be used to understand how you both interact with the toys and with each other using socio-emotional behaviours and face expressions. All data collected will be kept strictly confidential and used for research purposes only. Data will be stored in compliance with the Data Protection Act. We will store all data in secure Teams and One Drive folders with access provided only to members of the research team (see section 'Who is the research team' section above). We will not share the video recordings with anyone else. Video recordings will be kept securely for 10 years after which they will be securely disposed. We routinely present our research findings at research conferences, publish journal articles, deliver public engagement events and on our official project website and social media pages (please see below for information). To demonstrate the methodology used, researchers use photos and short videos of the parent and child doing the tasks. We also encourage families to take photos of their child during visits on their phones if they want to. We will email you a photo/video consent form to request if you are willing to grant consent for us to use photos, and videos of you or your child engaging in the tasks for the purposes mentioned above. You are free to indicate no to specific items or no to all items.

How will all the other data (for eg. brain imaging data) be handled?
We will follow ethical and legal practice and all information about you and your child will be handled in confidence by the members of the research team. All data collected will be kept strictly confidential and used for research purposes only. Data will be stored in compliance with the Data Protection Act. We will store data in secure Teams, One Drive folders, and password-protected University server drives with access provided only to members of the research team. All research data will be kept securely for 10 years after which they will be securely disposed.

What will happen if we want to withdraw from the study?
You and your child's participation are voluntary, and you are all free to withdraw at any time without giving any reasons. This would not affect any medical care or legal rights of your child. We will ask you to indicate in the consent form if you decide to withdraw whether you will permit us to use the data that we would have collected until the point of withdrawal. If you indicate yes, then we will use your data collected until the point of withdrawal in our study and not contact you any further. If you indicate no, then ALL data regarding you and your child will be deleted, including the video recordings.

What are the possible disadvantages and risks?
It is possible that children (particularly those who are not accustomed to wearing caps) might feel some mild discomfort when the cap is placed on their head. Our researchers are very calm, gentle, and trained to handle this procedure, so you do not need to worry. All members interacting with you and your child have also passed the necessary DBS clearance checks. We are obliged to make you aware that there could be a potential risk of intrusion by outside agents, for example through hacking, and therefore the possibility of being identified.

What are the possible benefits for taking part?
We cannot promise there will be direct benefits for taking part in our study, but we are hopeful that our findings will reveal information about how children start to build, develop, and synchronize their behaviours with their caregivers. We are also passionate about sharing our research goals with the local community. We will aim to publish our research in journal and at conferences. We will also share our findings through the project media pages, and yearly newsletter.

What if there is a problem?
If you have a concern about any aspect of this study, our researchers will be more than happy to speak with you and do their best to answer questions. Alternatively, you can also email the

Appendix Figure A.5 Information sheet for families (page 2 of 3).

research lead, Dr. Sobana Wijeakumar (sobanawartiny.wijeakumar@nottingham.ac.uk). If you remain unhappy and wish to raise a formal complaint, you can do this by contacting Professor Stephen Jackson (Stephen.jackson@nottingham.ac.uk), the Chair of the Ethics Committee.

What will happen to the results of the research study?
The results of the study will be written up into doctoral theses, journal articles, conference presentations and shared through the project's social media sites and wider public engagement events.

Who has reviewed the study?
All research at the university is approved by the Research Ethics Committee at the School of Psychology Ethics Committee.

Appendix Figure A.6 Information sheet for families (page 3 of 3).

University of Nottingham
UK | CHINA | MALAYSIA

School of Psychology

Consent Form

Title of Project: Project NeuroSync

Ethics Approval Number Archive Number: F1318

Researcher(s): Christina Davidson, Ghada Amaireh and Aimee Theyer

Research Lead: Dr. Sobana Wijeakumar (sobanawartiny-wijeakumar@nottingham.ac.uk)

The participant should answer these questions independently:

- **Have you read and understood the Information Sheet?** *YES/NO*
- **Have you had the opportunity to ask questions about the study?** *YES/NO*
- **Have all your questions been answered satisfactorily (if applicable)?** *YES/NO*
- **Do you understand that you are free to withdraw from the study (at any time and without giving a reason)?** *YES/NO*
- **I give permission for the collection and access of behavioral data, video recordings and brain activity data from me and my child by members of the research team.** *YES/NO*
- **If I decide to withdraw participation, I permit the use of all data that has been collected until the point of withdrawal.** Please note that if you indicate no, then ALL data regarding you and their child will be deleted, including the video recordings. YES/NO
- **I give permission for completely anonymized data to be shared with other researchers. This will allow with sharing our findings with the wider community.** *YES/NO*
- **Do you agree to take part in the current study?** *YES/NO*
- **I give permission to add mine and my child's details (full name, date of birth and contact details) to our Summer Scientist Week database? Through this, we might also contact you about new studies that you are eligible to participate in, in the future and invite you to our annual summer event.** *YES/NO*

Signature of the Participant: **Date**:

Name (in block capitals):

I have explained the study to the above participant, and they have agreed to take part.

Signature of researcher: **Date:**

Appendix Figure A.7 T1 consent form (page 1 of 1).

University of Nottingham
UK | CHINA | MALAYSIA

School of Psychology

Consent Form

Title of Project: Project NeuroSync

Ethics Approval Number Archive Number: F1407

The participant should answer these questions independently:

- **Have you read and understood the Information Sheet?** *YES/NO*
- **Have you had the opportunity to ask questions about the study?** *YES/NO*
- **Have all your questions been answered satisfactorily (if applicable)?** *YES/NO*
- **Do you understand that you are free to withdraw from the study (at any time and without giving a reason)?** *YES/NO*
- **I give permission for the collection and access of behavioral data, video recordings and brain activity data from me and my child by all members of the research team. As mentioned in the Information sheet, video recordings will be kept for 20 years and used for research purposes.** *YES/NO*
- **I give permission for the access and use of behavioural data, video recordings and brain activity data from me and my child during the first year of the project (in 2022) by all members of the research team for research purposes. As mentioned in the Information sheet, our research team is composed of academics with expertise in Psychology, Neuroscience, Computational modelling, Engineering and Computer Vision at the University of Nottingham, University of Stirling and University of East Anglia. Data will also be analysed, written up, and presented by PhD students, postdoctoral researchers, postgraduate students, undergraduate students, and students on summer bursaries, internships, placements and visiting scholarships. As mentioned in the Information sheet, video recordings will be kept for 20 years and used for research purposes.** *YES/NO*
- **If I decide to withdraw participation, I permit the use of all data that has been collected until the point of withdrawal.** Please note that if you indicate no, then ALL data regarding you and their child will be deleted, including the video recordings. YES/NO
- **I give permission for completely anonymized processed data to be shared with other researchers. This will allow with sharing our findings with the wider community.** *YES/NO*
- **Do you agree to take part in the current study?** *YES/NO*

Appendix Figure A.8 T2 consent form (page 1 of 2).

- **I give permission for mine and my child's details to be kept so that we can be contacted regarding scheduling future sessions on this project.** *YES/NO*

- **I give permission to add mine and my child's details (full name, date of birth and contact details) to our Summer Scientist Week database? We might also use these details to contact you about new studies that you are eligible to participate in, in the future.** *YES/NO*

Signature of the Participant: **Date**:

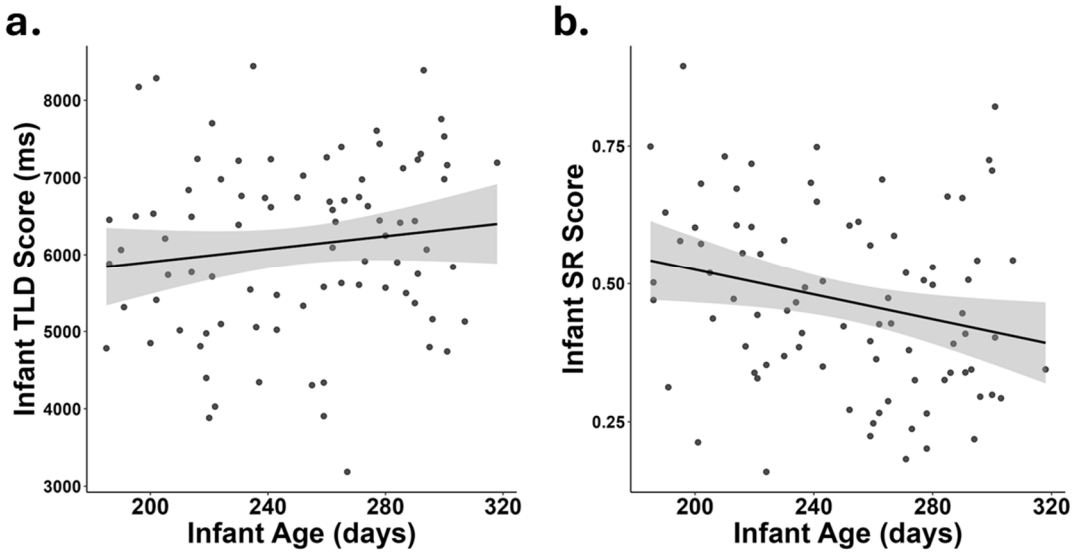
Name (in block capitals):

I have explained the study to the above participant, and they have agreed to take part.

Signature of researcher: **Date:**

Appendix Figure A.9 T2 consent form (page 2 of 2).

Appendix B: Figures



Appendix Figure B.1 Interaction between infant age and (a) infant TLD score and (b) infant SR score.

Appendix C: Data Tables

Appendix Table C.1 Summary of statistics and ANOVA results for infant looking measures across load. * p < .05 and *** p < .001

Measure	F Statistic	p Value	Sig.	Load	Mean	± SD	Summary of results
TLD	0.99	0.372	ns	Low Medium High	6069.95 6097.72 6185.52	1163.35 1152.35 1329.05	-
SR	4.93	0.011	*	Low Medium High	0.50 0.46 0.45	0.19 0.17 0.18	Low > High *
CP	12.11	< .001	***	Low Medium High	0.59 0.55 0.54	0.08 0.07 0.07	Low > High ***, Low > Medium ***

Appendix Table C.2 Summary of ANCOVA results and findings for looking measures across load and timepoint whilst controlling for T1 and T2 age difference. * p < .05, ** p < .01, and *** p < .001.

Measure	Effect	F Statistic	p Value	Sig.	Summary of results
TLT	Load x timepoint	0.44	0.648	ns	
	Load	1.03	0.359	ns	
	Timepoint	10.35	0.002	**	T1 < T2
	Age difference	0.97	0.328	ns	-
SR	Load x timepoint	1.03	0.361	ns	
	Load	1.10	0.338	ns	
	Timepoint	24.11	< .001	***	T1 > T2
	Age difference	0.74	0.393	ns	-
CP	Load x timepoint	0.71	0.494	ns	
	Load	12.99	< .001	***	High < Low ***, High < Medium *
	Timepoint	0.16	0.689	ns	
	Age difference	0.03	0.869	ns	-

Appendix Table C.3 Socioeconomic and demographic information was collected via questionnaire after the family visited the research facility. Values here are calculated based upon families who contributed any data to any aspect of the current thesis.

Family Member	Measure	N	Mean	± SD
Primary Caregiver	**Education (years)**	84	16.27	2.29
	Income	77	£27,249	£13,140
Secondary Caregiver	**Education (years)**	83	13.89	4.26
	Income	55	£31,278	£11,361
Primary Caregiver	**Ethnicity**	**N**	**%**	
	Arab	1	1%	
	Asian	5	5%	
	Mixed	4	4%	
	White British	72	74%	
	Other White	1	1%	
	Did not answer	14	14%	