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Developmental changes in child visual neurocognition and play interactions

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Project Statement.

This thesis forms part of a larger collaborative research project conducted within Project NeuroSync, involving multiple PhD students. As part of this overarching effort, certain datasets and methodological frameworks have been shared among contributors. While some data used in this thesis overlaps with that of other PhD students, all analyses, interpretations, and conclusions presented here are the result of independent work. The research was conducted autonomously under the guidance of the supervisory team and represents an original contribution to the field. The data from this project was from an externally funded grant awarded to Dr Wijeakumar by the Leverhulme Trust (Grant no. RPG-2019-286).

Abstract.

Visual cognition emerges in infancy and plays a fundamental role in cognitive, academic, and lifelong outcomes. Despite its significance, the early environmental and brain mechanisms that shape visual cognition development remain poorly understood. This thesis investigates the influence of caregivers and stimulus characteristics on early visual cognition through a series of experimental studies examining behaviour and brain function in infants and toddlers.

The first study examined whether caregivers' ability to regulate inhibitory control was linked to infants' visual working memory processing. Caregivers completed a Go-NoGo task to assess inhibitory control efficiency, while their infants engaged in a preferential looking task with simultaneous functional near infrared spectroscopy (fNIRS) recording. Although no direct relationship was found between caregiver inhibitory control and infant visual working memory behaviour, an indirect link emerged: infants with less efficient caregivers showed greater modulation of parietal activity with increasing task difficulty, whereas those with more efficient caregivers exhibited more stable responses. These findings highlight how caregiver cognitive traits may influence infant brain function during early memory processing.

The second study explored how caregiver-infant behaviours during dyadic play interactions related to infant visual working memory. Infants aged between 6 and 10 months and their caregivers participated in two types of play interactions, single object (SO) and multi-component object (MO) play. Both play interactions were coded for caregiver scaffolding, caregiver intrusiveness, infant object engagement, and infant distractibility. Infant visual working memory was assessed via a preferential looking task. Results revealed that scaffolding and object engagement were higher in MO play, and that specific caregiver-infant interaction patterns during MO play were associated with visual working memory performance. Moreover, caregiver behaviours were directly associated with infant prefrontal activation, suggesting that real-time interaction qualities impact emerging visual memory systems.

The third study followed the same dyads longitudinally to assess changes in caregiver-child interaction from infancy (6–10 months) to toddlerhood (18–22 months). Across both SO and MO play, scaffolding, intrusiveness, object engagement, and distractibility behaviours were coded. While toddlers showed

higher engagement and lower distractibility during MO play, caregiver behaviours remained consistent across contexts. Longitudinal analyses revealed that early caregiver scaffolding in SO play predicted greater toddler engagement and reduced distractibility one year later. These findings point to the enduring role of early play interactions in shaping attentional and regulatory development.

Finally, the fourth study investigated the influence of stimulus complexity on toddler visual cognition and its association with dyadic interactions. Toddlers completed two versions of the preferential looking task, one with simple coloured shapes and one with complex real-world images, while behavioural metrics and fNIRS were recorded. Although behavioural performance varied by stimulus complexity, brain activation patterns remained stable, with consistent engagement of fronto-parietal regions. Cross-task comparisons revealed shared behavioural and brain engagement patterns, suggesting a common underlying mechanism. Additionally, caregiver scaffolding and toddler object engagement during concurrent MO play was associated with toddler visual working memory performance in the complex task, highlighting the role of real-world interactions in supporting cognition, especially when experimental tasks mirror naturalistic contexts.

Together, these studies provide novel insights into the factors that shape early visual cognition development. They underscore the critical role of caregivers in fostering cognitive growth through inhibitory control, play interactions, and scaffolding, while also highlighting the importance of ecologically valid stimuli in understanding visual cognition. These findings contribute to the broader field of early neurocognitive development and have implications for designing interventions to support optimal cognitive outcomes and understanding individual differences in young children.

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List of Abbreviations.

Abbreviation	Meaning
ANCOVA	Analysis of Covariance
CP	Change Preference
EEG	Electroencephalography
fMRI	Functional Magnetic Resonance Imaging
fNIRS	Functional Near-Infrared Spectroscopy
HbO	Oxygenated Haemoglobin
HbR	Deoxygenated Haemoglobin
MLD	Mean Look Duration
MO	Multi-component Object
MRI	Magnetic Resonance Imaging
ROI	Region of Interest
RT	Reaction Time
SO	Single Object
SR	Switch Rate
TLD	Total Look Duration
Y1	Year 1
Y2	Year 2

Abbreviation	Brain Region
AG	Angular Gyrus
DLPFC	Dorsolateral Prefrontal Cortex
IFG	Inferior Frontal Gyrus
IPL	Inferior Parietal Lobule
MFG	Middle Frontal Gyrus
MTG	Middle Temporal Gyrus
PG	Precentral Gyrus
SFG	Superior Frontal Gyrus
SPL	Superior Parietal Lobule
STG	Superior Temporal Gyrus

Prefix	Meaning
l	Left
r	Right

Chapter 1:

Developmental changes in child visual cognition – a review of the literature.

1.1. Introduction.

Visual cognition, the ability to process and interpret visual information, undergoes profound developmental changes during early childhood, laying the foundation for complex cognitive and perceptual skills. This chapter reviews the literature on developmental changes in child visual cognition, with a focus on its early emergence and evolution. It begins by examining visual cognition in infancy and toddlerhood, identifying key milestones and developmental trajectories. Theories of visual cognition and their relevance to early development are highlighted. Following this, experimental paradigms used to assess visual cognition are explored. The discussion then shifts to the brain networks underpinning infant visual cognition, detailing the mechanisms and pathways involved, as well as their longitudinal development. The chapter then delves into the interplay between child visual cognition and naturalistic play interactions, offering insights into how these real-world contexts shape this cognitive process. Together, these sections provide a comprehensive overview of the developmental changes in visual cognition and their broader implications.

1.2. Visual cognition in infancy – insights from developmental changes.

Visual development is a key part of infant and child development as it is critical for exploring, understanding, and interacting with the world. It also supports key developmental milestones such as motor coordination (Fang et al., 2017), navigation (Franchak & Adolph, 2010), and language development (Hellendoorn et al., 2015). During infancy, visual abilities progress rapidly, supporting the child's growing understanding of both physical and social environments (Atkinson & Braddick, 2020). At birth, infants' visual capabilities are relatively limited. For

example, visual acuity (i.e., the ability to detect spatial detail) in one-month-olds is approximately 8 to 25 times poorer than an adult's acuity. However, it shows rapid development in the first 6 months and continues to improve over the following 6 years (Maurer et al., 2005). Infants also show contrast sensitivity as they struggle with fine details and prefer high contrast patterns, such as black and white stripes (Fantz, 1961). This preference for contrast extends to face-like stimuli, with newborns showing a strong interest in human faces, a phenomenon thought to support early social bonding and communication (Johnson et al., 1991).

While newborns possess basic colour vision, they primarily respond to shades of black, white, and grey, with the ability to distinguish between red and green emerging by 2-months and full colour vision developing by 3- to 4-months (Bornstein, 1985). Visual tracking, the ability to follow moving objects, undergoes significant improvement during the first few months of life. Initially, newborns exhibit jerky, reflexive saccades when attempting to follow a moving stimulus. However, by 6 to 8 weeks, smoother pursuit movements emerge, enabling more effective tracking of objects (Johnson et al., 1991). This development coincides with improvements in visual attention. While newborns are drawn to high-contrast and novel stimuli, their ability to sustain attention and selectively focus improves markedly only after 4 months of age (Colombo, 2001). These advances in tracking and attention are crucial for engaging with dynamic environments and for learning from caregiver interactions.

As infants gain motor control, their visual and motor systems begin to integrate, allowing for more purposeful interactions with their surroundings. By 4 to 6 months, infants start to reach for objects within their visual field, relying on depth perception and visual guidance to refine their grasp. This integration continues to improve, enabling complex tasks such as visually guided locomotion by the end of the first year (Smith et al., 1999). These milestones in visual processing are foundational for a wide range of developmental domains. Visual acuity and tracking skills support object recognition, while attention and visual-motor integration are critical for exploratory behaviour, problem-solving, and early social interactions. Delays in achieving these milestones may signal underlying developmental issues, emphasising the importance of early detection and intervention.

The following few years of life represent a critical period for the development of attention. By the end of the first year, noticeable changes occur, signalling the emergence of more intentional attention processes. One significant change is the increase in time that infants can visually focus on stimuli and events. Early in life, attention is primarily reflexive, characterised by an obligatory focus on prominent stimuli and movement, and is often marked by "sticky fixation" (Johnson et al., 1991). “Sticky fixation” refers to young infants’ difficulty in disengaging their attention from a visual stimulus once it has captured their gaze. In early infancy, attention is largely reflexive, driven automatically by salient features in the environment, such as brightness, colour, or motion. As a result, when infants look at a prominent or interesting stimulus, they tend to remain fixated on it for longer than older infants or adults would, even if another stimulus appears elsewhere that might also be of interest. Between 3 and 6 months, infants become better at disengaging and shifting their attention, enabling faster and more efficient environmental processing (Moyano et al., 2023). Then, in the latter half of the first year, infants show improved ability to sustain attention on complex stimuli (Courage et al., 2006).

Previous research has used visual habituation paradigms to track attentional changes from 3 months to 2 years of age (e.g., Colombo & Mitchell, 1990; Courage et al., 2006). In these studies, children were shown simple images (e.g., computer-generated black-and-white patterns) and a brief clip from a children’s show (e.g., Sesame Street). From this, the researchers calculated the average peak look duration for each stimulus type and found that mean look duration decreased significantly between 3 and 6 months for all stimuli. This decline was attributed to faster processing speed and the maturation of posterior brain regions responsible for disengaging and shifting attention (Posner & Raichle, 1994). However, for complex stimuli like the Sesame Street clip, look durations began to increase only between 8 months and 2 years. This shift marked a transition from primarily exogenous (stimulus-driven) attention in early infancy to more endogenous (internally driven) control. As children developed the ability to sustain attention beyond the initial processing of stimuli, they became better able to engage with complex, meaningful content, reflecting growing cognitive control and goal-directed focus (Courage et al., 2006). Other studies have also found that look durations continue to increase beyond

the first year (Ruff & Capozzoli, 2003; Ruff & Rothbart, 1996) and that sustained attention improves significantly during the toddler and preschool years (Breckenridge et al., 2013; Ruff & Lawson, 1990). Collectively, these findings highlight a shift in attention by the end of the first year, as infants develop greater voluntary control over their visual focus.

Building on emerging voluntary control, the second year of life is marked by substantial gains in infants' ability to regulate their visual attention in a more flexible and goal-directed manner (Clohessy et al., 2001; Sheese et al., 2008). These developments allow infants not only to sustain attention on relevant objects or people, but also to disengage and shift their focus more efficiently. As a result, they are better equipped to explore their environments and engage in joint attention and other forms of social interaction, experiences that are foundational for language learning and social-cognitive growth (Yogman et al., 2018). These early advances in attentional control form the basis for the gradual emergence of more complex self-regulatory skills across early childhood. As attentional systems mature and integrate with broader executive processes, children begin to demonstrate increasing flexibility in switching between task demands (Zelazo & Reznick, 1991) and in inhibiting impulsive responses in contextually appropriate ways (Carlson, 2005). The developmental trajectory and supporting empirical evidence indicate that systems governing attentional control become integrated with those responsible for behavioural regulation (Papageorgiou et al., 2014). Thus, the improvements in visual attention observed during infancy represent an important stepping stone in the development of more sophisticated cognitive control.

The emergence of visual attention control in infancy forms a foundation for later cognitive, executive, and academic abilities, particularly in populations at risk for developmental difficulties such as preterm children. Understanding the early origins of these abilities is critical for identifying pathways to resilience or vulnerability. For instance, Rose and colleagues (2012) examined the relationship between early cognitive abilities and executive functions in preadolescence. This study investigated whether cognitive abilities such as processing speed, attention, and memory, observed in infancy and toddlerhood, could predict executive functions at age 11. To achieve this, the researchers conducted a longitudinal study involving

203 children, both preterm and full-term, who were assessed at multiple time points: infancy (7 and 12 months), toddlerhood (24 and 36 months), and preadolescence (11 years). Infant and toddler cognitive abilities were measured using tasks targeting attention, memory, and processing speed. At age 11, a comprehensive battery of tasks assessed the three core components of executive functions. Their findings revealed significant predictive relationships between early cognitive abilities and later executive functions. Specifically, both infant and toddler processing speed and memory were strong predictors of working memory at age 11. Together, these early cognitive abilities accounted for 9-19% of the variance in executive functions (Rose et al., 2012). These results highlight the critical role of early cognitive abilities in the development of higher-level executive functions. Among these early abilities, processing speed emerged as particularly influential, supporting theories that faster cognitive processing underpins the development of complex functions like working memory (Salthouse, 1996, 2011). Memory also played a significant role, suggesting that early retrieval and recognition abilities contribute to the development of advanced cognitive skills. The study underscores the continuity between infancy and later cognitive development and the findings also emphasised the potential for early interventions, such as training attentional control in infancy, to improve cognitive outcomes later in life (Wass et al., 2011). Overall, the research demonstrates that basic visual cognitive processes emerging in infancy, particularly processing speed, and memory, have long-term implications for executive functions in preadolescence. The predictive links between early processing speed and memory and later executive functions underscore the importance of fostering early cognitive abilities to support more optimal developmental outcomes.

The early development of systems that support the flexible maintenance and manipulation of information become increasingly critical as attentional control and higher-order cognition continue to mature. Key systems underpinning this developmental continuity are short-term and working memory, which support the temporary retention and manipulation of information. Additionally, visual working memory is the subset of working memory dedicated to visual and spatial content. While short-term memory typically involves passive maintenance over brief intervals, working memory entails active control and processing in the service of cognitive goals (Baddeley, 2012; Luck & Vogel, 2013). The distinction between

short-term memory and working memory is often operationalised through task demands, simple span tasks are considered measures of short-term memory, whereas complex span or manipulation tasks are used to index working memory (Cowan, 2008). Visual working memory is critically constrained by capacity limits, generally estimated to be around 3–4 items in adults (Luck & Vogel, 1997), and even more limited in young children (Simmering, 2012). These constraints necessitate attentional selection mechanisms to determine which visual inputs are encoded and retained. Attentional control thus acts as a gatekeeper for visual working memory, modulating which representations are prioritised and which are suppressed (Gazzaley & Nobre, 2012). Importantly, this relationship is bidirectional as visual working memory can guide attention toward matching items in the environment (Olivers et al., 2011), while attention determines what information enters and remains in visual working memory (Cowan, 2011). The interface between perception and visual working memory is particularly salient in tasks that require ongoing maintenance of visual representations, such as visual search or change detection. Visual working memory is not isolated from perceptual systems but is embedded within a dynamic loop that allows perceptual input to update memory representations, and vice versa (Awh et al., 2006). This interplay enables flexible cognition in rapidly changing environments and is already evident early in development, as infants exhibit visual working memory-driven attentional biases in preferential looking paradigms (Káldy & Leslie, 2003).

Working memory is widely recognised as a central component of executive function, alongside inhibitory control and cognitive flexibility (Diamond, 2013). Visual working memory underpins many everyday cognitive tasks that require sustained attention, spatial reasoning, and the regulation of actions in visually dynamic environments. Executive functions, conceptualised as a set of top-down control processes, rely heavily on working memory to maintain task goals, rules, and contextual cues over time. For instance, task switching, a common measure of cognitive flexibility, requires not only the suppression of prior task sets (inhibitory control) but also the active maintenance of the current task parameters in working memory. In this way, working memory plays a foundational and integrative role within the executive function system (Zelazo et al., 2003). Developmentally, the maturation of working memory systems reflects and enables the broader emergence

of executive function capacities in early childhood. Neuroimaging evidence reveals that frontoparietal networks involved in visual working memory are also consistently activated during tasks measuring executive function, suggesting a shared neural infrastructure (Curtis & D'Esposito, 2003; Kane & Engle, 2002). Furthermore, increases in working memory capacity and efficiency over the preschool years are strongly associated with gains in executive function performance and higher-order cognitive outcomes, including self-regulation, flexible problem solving, and academic achievement (Best & Miller, 2010; Diamond, 2013). As such, visual working memory is not only embedded within executive functioning but also serves as a sensitive indicator of its developmental trajectory. In sum, short-term and visual working memory are integral components of the cognitive system, underpinned by attentional mechanisms and supporting the development and operation of executive functions. The dynamic interplay between visual working memory, perception, and attentional control enables flexible, goal-directed behavior and serves as a critical scaffold for higher-order cognition across development.

1.3. Theories of visual cognition – relevance to early development.

Visual working memory, a key aspect of visual cognition, goes through a substantial development in the first few years of life; this period is recognised as being crucial for establishing cognitive behaviours and abilities that persist throughout life (Gilmore et al., 2018). For example, research has demonstrated that visual working memory is associated with academic achievement (Blair & Razza, 2007; Davidson, Shing, et al., 2023; Gathercole et al., 2004). There are several theoretical accounts of working memory. While broad theories of visual cognition provide important insights, more targeted frameworks have been developed to specifically explain the mechanisms and development of visual working memory. These focused accounts are particularly relevant when considering early development, and they provide a more precise lens for understanding how visual information is processed, stored, and used in young children. The most widely accepted theoretical account is Baddeley's model of working memory (Baddeley & Hitch, 1974). The model conceptualises working memory as a multi-component system, with each component being responsible for managing specific types of information. First, the central executive is the "control centre" of the working memory system. It is responsible for directing attention, selecting strategies, and

managing the flow of information between different subsystems (Baddeley, 2000). Second, the phonological loop component is responsible for managing verbal and auditory information. It includes a phonological store, which holds sounds for a brief period, and an articulatory rehearsal process that keeps information active. Work has demonstrated how the phonological loop operates by showing that memory span is longer for short words than for longer ones (Baddeley et al., 1975). Third, the visuo-spatial sketchpad component manages visual and spatial information (Logie, 1995). Finally, the episodic buffer integrates information across modalities (e.g., visual and verbal) and links working memory to long-term memory (Baddeley, 2000). This model can help explain how children's working memory develops, as each component appears to mature at different rates throughout childhood. For instance, improvements in the central executive are particularly evident in older children and adults, who show more advanced attentional control and greater use of memory strategies (Gathercole et al., 2004). Increased verbal memory span observed in older children is likely attributable to the maturation of the phonological loop component of working memory, a development that may be linked to greater efficiency in rehearsal processes (Hulme & Mackenzie, 1992). According to Baddeley's model, the phonological loop supports the temporary storage and maintenance of verbal information through rehearsal mechanisms, which helps explain this developmental improvement. Additionally, children demonstrate progressive improvements on tasks that require mental manipulation of visual-spatial information, indicating developmental refinement of the visuospatial sketchpad (Casey et al., 2005). This component, responsible for holding and manipulating visual imagery and spatial layouts, appears to become more robust and flexible with age, further supporting the model's view of working memory as a system composed of functionally distinct but interacting subsystems that develop at different rates. Overall, Baddeley's model of working memory provides a framework for understanding the structure of working memory, its developmental trajectory, and its role in various cognitive tasks across the lifespan. Alloway and colleagues (2004) sought to determine whether working memory in young children aged 4 to 6 years followed the multicomponent model proposed by Baddeley (2000), or if a simpler structure better explained cognitive performance. To investigate this, they conducted a study examining the functional organisation of working memory in this age group. Children's working memory was tested using measures of verbal short-term memory, complex memory span, and

sentence repetition. Data was analysed using exploratory and confirmatory factor analysis to evaluate competing models of cognitive structure. Results revealed that Baddeley's multicomponent working memory model provided the best fit. Notably, the episodic buffer emerged as a distinct component, supporting the integration of information from different cognitive systems. Phonological awareness was also found to be separate from phonological memory, reinforcing its independent role in literacy development. Further, the findings suggested that cognitive structures supporting learning were well established by school entry, reinforcing the importance of early working memory assessments in predicting later academic performance (Alloway et al., 2004).

Nelson Cowan's theory of working memory development posits that increases in storage capacity are a fundamental driver of cognitive development in childhood, rather than improvements in processing speed, knowledge, or filtering abilities. According to Cowan (1999), working memory capacity steadily increases with age: first-grade children can recall about 2.5 items, fourth-graders about 3, and adults around 3.5. This gradual increase reflects a basic cognitive constraint shaped by maturation and experience (Cowan, 2019). Beyond storage capacity, Cowan emphasises the central role of attention in working memory: capacity is defined not just by the number of items that can be stored, but by how many can be held in the focus of attention at once. This attentional focus is thought to expand with age, enabling children to maintain and manipulate more information simultaneously. Cowan's model also highlights the interaction between working memory and long-term memory. While familiarity with material can enhance recall, as shown in Cowan et al. (2015), the developmental trajectory remains stable across familiar (English letters) and unfamiliar (foreign characters) stimuli, indicating that capacity growth is not solely a function of prior knowledge. Furthermore, Cowan et al. (2006) tested whether processing speed accounts for age differences by having children accelerate their rehearsal rate. Even with faster rehearsal, younger children's capacity did not increase, suggesting that storage limits, not speed, are the core constraint. Together, these studies support Cowan's view that working memory development reflects genuine growth in capacity and attentional control, not just better strategies or greater experience.

Another theoretical framework that has been used to understand and instantiate visual cognition in early development is Dynamic field theory (DFT). DFT is a computational framework that is used to model cognitive and perceptual processes over time (e.g., Buss & Spencer, 2014; Johnson et al., 2008; Schutte et al., 2003; Wijeakumar et al., 2017; Wijeakumar & Spencer, 2021). It describes cognition as patterns of activation within continuous neural fields, where stable peaks of activity can represent different states (e.g., attentional states). These fields evolve dynamically in response to external stimuli and/or internal constraints, exhibiting properties such as stability and self-organisation. DFT makes a meaningful contribution to working memory because it can provide a real-time, dynamic account of how information is encoded, maintained, and updated in the brain. Unlike traditional verbal theories and models that think of memory as a static store, DFT emphasises a dynamic, continuous nature of neural activity in relevance to memory 'peak' formation and decline and how they evolve over time.

Building on this framework, Perone and colleagues (2011) applied DFT to investigate how developmental changes in neural dynamics support increases in visual working memory capacity during infancy. They used a dynamic neural field (DNF) model to simulate and explain behavioural data from a visual working memory task. In this task, infants viewed two displays: one in which an item changed colour after a brief delay (change display) and one where all items remained the same (no-change display) (Ross-Sheehy et al., 2003). If infants successfully maintained visual information, they were expected to look preferentially at the changing display. Behavioural results showed that 6-month-olds exhibited a change preference only for one-item arrays, whereas 10-month-olds demonstrated change preference across one- to four-item arrays, suggesting a developmental increase in memory capacity. Crucially, the DNF model provided a mechanistic account of these developmental changes. It incorporated a perceptual field that encodes sensory input, a working memory field that maintains active representations, and Hebbian learning mechanisms that strengthen neural connections with repeated activation. Simulations showed that increases in the strength of excitatory and inhibitory interactions within neural fields supported more robust memory maintenance, reduced interference, and enhanced sensitivity to change. Younger models (representing 6-month-olds) struggled to sustain multiple representations, whereas older models (10-month-olds) could maintain more items and respond more effectively to novel changes (Perone et

al., 2011). Theoretically, these findings advance our understanding of early working memory development by demonstrating that increases in capacity are not solely the result of acquiring new cognitive structures or strategies, but also reflect gradual, experience-driven changes in the dynamics of neural processing. By explicitly modelling how continuous neural activity patterns evolve over time, the DNF approach moves beyond static conceptions of memory storage to emphasise memory as an emergent, self-organising process grounded in basic neural mechanisms. In doing so, it highlights how even small changes in neural connectivity across infancy can have profound consequences for the development of higher-level cognitive functions.

While theories of visual working memory offer crucial insights into the short-term retention and manipulation of visual information, reconnecting with broader theories of visual cognition allows for a more integrated understanding of how attention, perception, and memory interact in early development. This broader perspective is essential for interpreting developmental changes in visual working memory within the context of the dynamic and interconnected nature of visual processing in infancy and childhood. One such theory that offers a valuable integrative perspective is Treisman's Feature Integration Theory (FIT) (Treisman & Gelade, 1980). FIT posits that basic visual features such as colour, shape, and orientation are processed automatically and in parallel across the visual field. However, the integration of these features into coherent perceptual objects requires focused attention, which operates in a serial manner across spatial locations. This attentional binding acts as a kind of 'glue', allowing separate features to be correctly combined and associated with their spatial positions. Without focused attention, features remain unbound and may give rise to 'illusory conjunctions' (i.e., erroneous combinations of features from multiple objects) (Treisman & Gelade, 1980). This distinction between feature registration and feature integration is especially pertinent to early development, as it underscores the role of attentional control in constructing stable visual representations from a complex sensory environment. By highlighting the dynamic interplay between attention and perception, FIT broadens the scope of visual cognition theories and offers a conceptual bridge between low-level sensory input and higher-order processes like visual working memory. Contemporary research has continued to investigate and refine the mechanisms proposed by FIT.

For instance, Toh and colleagues (2020) investigated how object features and spatial information are bound in visual working memory. In a series of experiments using real-world object photographs as stimuli, participants performed a location change detection task. They were instructed to treat objects as placeholders and to report whether any objects had moved between encoding and test arrays. Critically, across conditions, the identities of the objects either remained the same, changed within the same category (e.g., one book for another), changed to a new category, or were swapped in position. The findings showed that location memory was significantly disrupted when object identity changed, even though identity was task-irrelevant. Disruption was greatest when changes altered the spatial configuration of the array, such as in the object-swap condition (Toh et al., 2020). These results suggest that features such as shape and orientation are automatically bound to spatial locations, even when only location is relevant to the task. This aligns with Treisman's proposal that attended objects are integrated with their spatial context in memory. The results also extend FIT by showing that such binding persists into visual working memory, supporting the idea that attentional integration during perception lays the foundation for what is encoded and maintained in memory (Treisman, 1996, 1999).

Overall, these theoretical accounts highlight key aspects of visual cognitive development, including the structure and capacity of the system, the mechanisms supporting maintenance and updating, and the neural processes that underpin these functions. To build a comprehensive understanding of visual cognition, it is essential to consider how these mechanisms emerge and interact early in development. Infancy offers a unique opportunity to examine the foundational processes that support visual attention, feature binding, and memory under conditions of rapid neural and behavioural change. Studying visual cognition in early life not only sheds light on the origins of these complex systems but also allows for a critical evaluation of how theoretical models map onto developmental trajectories. The following section explores experimental paradigms used to assess visual cognition in young children and infants, highlighting how these methods capture the dynamic interplay between attention and memory processes from early developmental stages.

1.4. Using experimental paradigms to assess visual cognition in early childhood.

Several established tasks are used to measure visual cognition in young children and infants, each designed to assess different aspects such as visual attention, object recognition, and working memory. The visual paired comparison task is one of the most used preferential looking paradigms which measures recognition memory and attention by assessing a child's preference for novel versus familiar stimuli (Reynolds & Richards, 2019). In this task, children are presented with a pair of visual stimuli, one familiar stimulus that the child has had prior exposure to and one novel stimulus that the child has not seen before. If children spend longer looking towards the novel stimulus, exhibiting a novelty preference, this indicates memory recognition ability (Kingo et al., 2022). The visual paired comparison task has been used extensively to measure visual cognition abilities in infancy (Burbacher & Grant, 2012; Fisher-Thompson & Peterson, 2004; Oakes & Ribar, 2005; Pascalis et al., 1998; Richards, 1997; Snyder, 2010). Fisher-Thompson and Peterson (2004) used this task to examine infant looking behaviours, including side bias and familiarity-novelty preference. In this study, 3.5- to 6-month-old infants engaged with a visual paired comparison task and viewed trials where a familiar face was presented with novel faces on alternating sides. Results showed that infants showed an overall novelty preference, but many exhibited significant side biases by repeatedly looking towards one direction rather than shifting between stimuli. Additionally, the transition from familiarity to novelty preferences varied widely among individuals, suggesting variability in attentional strategies (Fisher-Thompson & Peterson, 2004). Another study by Oakes and Ribar (2005) investigated how the format of the visual paired comparison paradigm affected category formation in 4- to 6-month-old infants. They compared paired familiarisation (presenting two stimuli side by side) with successive familiarisation (presenting one at a time) across three experiments. In the paired condition, 4-month-olds showed a preference for novel, out-of-category stimuli, suggesting they formed narrow, adult-like categories (e.g., cats vs. dogs). In contrast, the successive condition led to broader category representations, especially in younger infants. A third experiment ruled out familiarisation time as a factor, indicating that the structure of the task, rather than exposure duration, shaped whether infants formed narrow or broad categories.

Despite the value of the visual paired comparison task, one drawback is its inability to assess memory load effectively. As only one familiar and one novel stimulus are presented in each trial, it does not require infants to manage or recall multiple items in working memory. Using a task where working memory load can be manipulated is beneficial as it allows researchers to explore the limits and flexibility of an infant's working memory capacity. Understanding these thresholds is important for gauging developmental progress and recognising typical versus atypical cognitive development (Cowan, 2014). Additionally, tasks with variable working memory loads can reveal how working memory evolves over time. Younger infants may struggle with tasks involving multiple items but improve as they age (e.g., Ross-Sheehy et al., 2003). This kind of gradual assessment helps chart developmental trajectories and can be critical for identifying early indicators of cognitive strengths or weaknesses (Buss et al., 2018).

One effective way to assess the development of visual working memory capacity in infancy is through tasks that isolate short-term memory processes, such as the preferential looking paradigm developed by Ross-Sheehy et al. (2003). Specifically, the paradigm was designed to isolate short-term memory processes and minimise contributions from long-term memory. During the preferential looking task, infants are presented with two simultaneous displays of coloured squares that repeatedly flash on and off. On one side, the colours of the squares remain constant between flashes. Whereas on the other side, one random colour changes after every flash. Several aspects of the task emphasise the use of short-term memory systems. Firstly, each display was presented for only 500 ms, maximising the need for rapid memory formation, especially for arrays containing multiple items. Additionally, the retention period between each array display was only 250 ms, which is long enough to minimise contributions from iconic memory, a type of memory that allows people to briefly retain visual information after it has disappeared (Quilty-Dunn, 2020). Finally, all stimuli were simple coloured squares, further minimising long-term memory contributions. Multiple looking measures can be extracted from this task: total look duration (total amount of time a participant spent looking at both displays), mean look duration (average length of time a participant spent looking towards one display), switch rate (how often a participant switched from one display to the other), and change preference (whether a participant showed preference for the changing

display). Taken together, these looking measures assess visual cognition by providing insights into various aspects of how a participant processes and engages with visual stimuli. Total look duration indicates attention and engagement with the task. Mean look duration provides information on the depth of cognitive processing or focus on specific details. Switch rate highlights cognitive flexibility and the ability to manage multiple visual stimuli, revealing how participants allocate their attention. Change preference reflects the ability to process novelty and dynamic stimuli. Specifically, the change preference measure is most reflective of visual working memory. If infants prefer the changing side, then this would suggest that they have the capacity to encode and process items in working memory.

A central challenge in using looking behaviour as a proxy for cognitive processes lies in the interpretation of what longer looking truly reflects. While many studies assume that infants prefer novelty, there is evidence that this preference can reverse depending on various factors. For instance, infants may exhibit a familiarity preference when stimuli are complex, when exposure is brief, or when they are very young. The Hunter and Ames (1988) model offers a theoretical framework to explain this, proposing that infants initially show a familiarly preference and gradually shift to novelty preferences as they process the stimuli more fully. This shift is influenced by factors such as age, task difficulty, and familiarisation time. However, empirical support for this model has been inconsistent. The ManyBabies 5 project (Kosie et al., 2024) represents the most comprehensive attempt to systematically test this model at scale, across multiple countries and populations. By manipulating stimulus complexity, familiarisation time, and infant age, the study aims to clarify when and why infants display familiarity or novelty preferences. While the project is still in the early stages, the outcomes of this work will be crucial for interpreting measures like change preference in preferential looking paradigms. Specifically, it will aid researchers in distinguishing whether longer looking indicates novelty detection, familiarity recognition, or something else entirely.

Despite this ongoing debate about how to interpret looking measures, the preferential looking paradigm remains a highly effective and widely used method for assessing visual cognition that has consistently yielded valuable insights into early development. For instance, using this paradigm, Ross-Sheehy et al. (2003) found

significant developmental changes in memory capacity over the first year of life. They reported that 4- and 6.5-month-old infants were able to maintain only one item in working memory. However, by 10-months, infant's capacity increased to four items (Ross-Sheehy et al., 2003). Additional work utilising this task has revealed that performance does not improve even when every square changes on the changing side after every flash, suggesting that 6-month-old infants struggle to encode and compare multiple objects in visual short-term memory (Oakes et al., 2006). Notably, this difficulty extends beyond individual feature retention to the ability to bind features together. 6-month-olds can represent colour and location separately but fail to retain their conjunctions, whereas by 7.5 months, infants show significant improvement in colour-location binding (Oakes et al., 2006, 2009). Further, a study by Kwon et al. (2014) demonstrated that this developmental pattern extends to more complex objects. While 6-month-old infants could detect changes in simple, isolated objects, they struggled to do so when presented with multi-part objects, whereas 8-month-old infants successfully retained and compared such representations. The difference in performance indicates that, beyond increases in memory capacity, there is a developmental shift in how infants encode and organise information in visual working memory. The ability to selectively attend to and track distinct object features appears to emerge alongside the capacity to handle greater memory loads. Taken together, these findings highlight that while visual cognition is limited in infancy, it undergoes substantial developmental changes during the first year of life. These changes not only reflect an increase in storage capacity but also improvements in the ability to bind multiple features and encode complex objects, providing a more cohesive and integrated representation of the visual world. Such advancements play a critical role in supporting broader cognitive abilities, including problem-solving, learning, and social interaction. Moreover, the ability to accurately measure and assess visual working memory in infancy provides researchers with valuable tools to identify typical developmental trajectories and potential early markers of cognitive deficits. To understand how these early capacities evolve, it is essential to examine longitudinal changes in visual cognition across early development. This approach provides insights into the continuity and transformation of visual and cognitive abilities from infancy through childhood, shedding light on the factors that influence developmental progress and variability.

1.5. Brain function underlying visual cognition in early childhood.

Most research on early development has relied on behavioural measures, such as eye-tracking and video-recorded observations, to examine infants' visual cognition. However, neuroimaging measures offer insights into early brain organisation and processing that behavioural assessments alone cannot capture. Understanding brain function helps establish developmental continuity across the lifespan, particularly during periods, like infancy, where traditional tasks may be unsuitable or ineffective and observable behaviour may be limited or ambiguous. This continuity is critical for identifying how early neural patterns relate to later cognitive outcomes and supports the identification of early markers for atypical development, enabling earlier and more targeted interventions. Overall, studying brain function bridges gaps in our understanding of development by linking neural activity to observable behaviour across different ages.

In infancy, neuroimaging data has been collected using techniques such as magnetic resonance imaging (MRI), functional MRI (fMRI), electroencephalography (EEG), and functional near infrared spectroscopy (fNIRS). For instance, several studies have investigated the relationship between infant visual cognition and brain structure and connectivity using MRI techniques. Early white matter organisation, particularly in pathways like the corpus callosum, has been linked to individual differences in visual attention (Dowe et al., 2020). In addition, grey matter volume reaches about 80% of its total volume within the first year of life (Groeschel et al., 2010). Research has shown that the growth of grey matter in the caudate and globus pallidus was linked to improved visual-motor integration (Young et al., 2015). Moreover, studies examining structural connectivity using diffusion MRI have shown that the maturation of long-range association tracts, such as the inferior longitudinal fasciculus and superior longitudinal fasciculus, are related to emerging cognitive and perceptual abilities during the first year of life (Deoni et al., 2016; Dubois et al., 2015). Structural differences in regions associated with visual processing, such as the occipital cortex, have also been associated with variations in visual functioning (Shah et al., 2006). Complementing this structural evidence, fMRI studies have shown that resting-state networks, including the visual and sensorimotor systems, are already present in newborns, though less developed, and continue to

mature rapidly during the first year (Fransson et al., 2011). Furthermore, longitudinal fMRI work indicates that the infant brain undergoes dynamic reorganisation, with increasing long-range functional connectivity and integration that underpins developing perceptual and cognitive functions (Gao et al., 2017).

While connectivity work provides valuable insights into brain structures supporting visual cognition, it does not inform brain function. Instead, functional neuroimaging methods which measure brain activity in response to stimuli can reveal much more about processes and mechanisms. Ellis and Turk-Browne (2018) first argued that investigating infant neural activity with fMRI can provide insights into cognitive neuroscience as the technique offers whole-brain imaging, including subcortical structures, enabling a richer understanding of cognitive processes. In their seminal study, these researchers later investigated whether the frontal cortex, a key region for attentional control in adults, was active in infants during an attentional task (Ellis et al., 2021). To this end, the study recruited 20 infants between 3 and 12 months of age, conducting a total of 24 fMRI sessions while the infants were awake. The infants participated in a modified version of the Posner cueing task, which involved showing them a cue (either on the left, right, or both sides of a screen) before a target (a spinning pinwheel) appeared. The researchers used eye-tracking to measure how quickly the infants generated saccades toward the target. Results showed that infants responded significantly faster on valid trials, where the cue correctly predicted the target location, and slower on invalid trials, where the cue was misleading. This pattern closely resembled attentional cueing effects observed in adults, suggesting that even very young infants could use predictive cues to direct their attention. fMRI data revealed that brain regions typically associated with attention in adults, including the middle frontal gyrus, showed increased activation during invalid trials. The heightened activity in these regions indicated that parts of the attentional control network were already functioning in infancy (Ellis et al., 2021).

While the afore-mentioned evidence highlights fMRI as a valuable neuroimaging tool for studying infant attention, it also has several limitations. A key limitation is that fMRI is highly sensitive to movement, and even minor head movements can significantly distort the data. Such sensitivity poses a particular

challenge when working with infants, who are naturally prone to fidgeting and may struggle to remain still for extended periods. In addition, scanning protocols typically require infants to be either asleep or very still while awake, which can be difficult to achieve consistently. Participant attrition is also a significant concern. Many infants may not meet the inclusion criteria due to fussiness, falling asleep at the wrong time, or failing to complete enough trials for reliable analysis. As a result, final sample sizes are often smaller, and there is a risk of bias if only particularly calm or compliant infants are retained in the study. Moreover, the scanning environment itself can be intimidating for infants and their caregivers as the loud noises, confined space, and unfamiliar setting may contribute to distress, further increasing the likelihood of dropout or poor-quality data. The technical and logistical demands of fMRI studies, including the need for specialised equipment, trained personnel, and rigorous safety protocols, also make it a resource-intensive method that may not be feasible for all developmental research settings (Ellis & Turk-Browne, 2018). Additionally, its lack of portability restricts studies to controlled lab settings, limiting ecological validity. Given these constraints, alternative methods like EEG or fNIRS, which offer greater flexibility, reduced sensitivity to movement, and higher retention rates, can provide complementary insights into infant cognition.

EEG is a brain imaging technique used to measure the electrical activity of neurons in the cerebral cortex. This technique involves placing electrodes onto the scalp that detect signals created when large groups of cortical neurons are activating simultaneously (Pizzagalli, 2007). EEG power represents the amount of neural activity within specific frequency bands, such as delta, theta, alpha, and beta, which are associated with different cognitive and physiological states. Higher power in each frequency band is indicative of increased engagement of underlying neural processes. EEG coherence, on the other hand, measures the synchronisation of neural oscillations between electrode sites, reflecting the functional connectivity between different brain regions. Higher coherence suggests stronger network integration, while lower coherence may indicate more independent processing or weaker connections (Xiao et al., 2018). EEG has good temporal resolution as it can capture changes in milliseconds, allowing for the isolation of brain activity occurring at any given moment. Many studies have used EEG in infancy to examine attentional and cognitive processes. For example, Cuevas et al. (2012) aimed to investigate the

psychophysiological correlates of working memory in infancy, specifically at 5 and 10 months of age, using EEG power and coherence measures. The researchers sought to determine whether these measures were differentially activated during working memory processing at these two developmental stages and whether they were associated with individual differences in performance. To achieve this, they recorded EEG from infants at both timepoints during both baseline and performance on a looking version of the A-not-B task (Bell & Adams, 1999). Findings revealed that infants exhibited working memory-related increases in EEG power across all electrodes at both ages. However, at 10 months, power changes were more localised to frontal regions, aligning with prior research on increasing cortical specialisation with age (Bell & Wolfe, 2007). Additionally, at 5 months, working memory-related increases in coherence were observed in frontal pole-medial frontal, medial frontal-temporal, and medial frontal-occipital electrode pairs. However, by 10 months, working memory-related coherence increases were limited to medial frontal-occipital pairs, suggesting increasing specificity in frontal-posterior functional connectivity with age (Cuevas et al., 2012). Similarly, Xie et al. (2018) found that sustained attention in infants was associated with increased theta power and decreased alpha power, with these effects becoming more pronounced and regionally specific from 6 to 12 months, highlighting the developmental refinement of attentional networks. In a complementary line of research, Reynolds et al. (2011) investigated individual differences in visual attention and recognition memory in 6- and 7.5-month-old infants. Infants were classified as short or long lookers based on their peak look durations during a familiarisation phase, then shown familiar and novel stimuli while EEG was recorded. Short lookers showed enhanced neural markers of attention and recognition memory in response to novel stimuli, suggesting more efficient encoding and processing. Individual differences in infant looking behaviour were mirrored in distinct neural processing patterns, highlighting the value of EEG in capturing both developmental and individual variability in early cognitive functioning.

While EEG is a valuable tool for studying infant development, it has poor spatial resolution, meaning the precise source of electrical activity cannot be determined. Additionally, EEG is highly susceptible to motion artefacts, which can be particularly challenging in infant studies where movement is often unavoidable. A worthy alternative is fNIRS. fNIRS is a non-invasive neuroimaging technique that

relies on the principle of shining near-infrared light to measure changes in oxygenated and deoxygenated haemoglobin, providing insight into localised cortical activity. Unlike EEG, which captures rapid neural oscillations offering excellent temporal resolution but poor spatial resolution, fNIRS offers improved spatial resolution with decent temporal resolution in seconds, while remaining tolerant to movement, making it particularly well-suited for studying cognitive development in infants (Cutini & Brigadoi, 2014; Emberson et al., 2017). This technique has allowed researchers to explore how visual cognition-related neural networks emerge and change over time in early development. One limitation of fNIRS is that it is restricted to surface regions, as near-infrared light cannot reach subcortical areas (Wilcox & Biondi, 2015). Nevertheless, it can assess hemodynamic activation in fronto-parieto-temporal areas, which are typically engaged in visual cognition. For these reasons, this technique was employed in two chapters of the current thesis.

fNIRS systems consist of light sources, which emit near-infrared light, and detectors, which capture the transmitted and scattered light after it has travelled through the underlying tissue (Figure 1.1a). These sources and detectors are arranged on a head cap in specific configurations, creating channels (Figure 1.1b). Light is differentially absorbed by oxygenated (HbO) and deoxygenated (HbR) haemoglobin concentrations, and these differential absorption spectra are used to examine activation in a specific brain region. The depth and path of the detected signal, known as the banana-shaped photon propagation path (Figure 1.1a) (Mansouri et al., 2010), depend on the source-detector separation, with typical measurements capturing cortical activity within 1–3 cm beneath the scalp. When a brain area becomes active, there is typically an increase in HbO and a decrease in HbR, relative to a resting baseline (Lloyd-Fox et al., 2010). It is important to report both HbO and HbR concentrations separately as researchers can gain a more detailed understanding of the hemodynamic response to neural activity (Strangman et al., 2002). Reporting both HbO and HbR enhances accuracy as it allows researchers to better interpret the data and avoid false positives or misinterpretations. For instance, changes in HbO without corresponding changes in HbR can suggest the presence of artifacts or systemic changes like blood pressure fluctuations rather than actual brain activity (Huppert et al., 2009). Therefore, analysing both signals provides a more robust indicator of localised brain function (Gagnon et al., 2014). Overall, fNIRS allows for

localised, non-invasive monitoring of brain activation in response to experimental stimuli, making it particularly useful for studying cognitive development in infants and young children, who may not tolerate other neuroimaging methods requiring strict stillness.

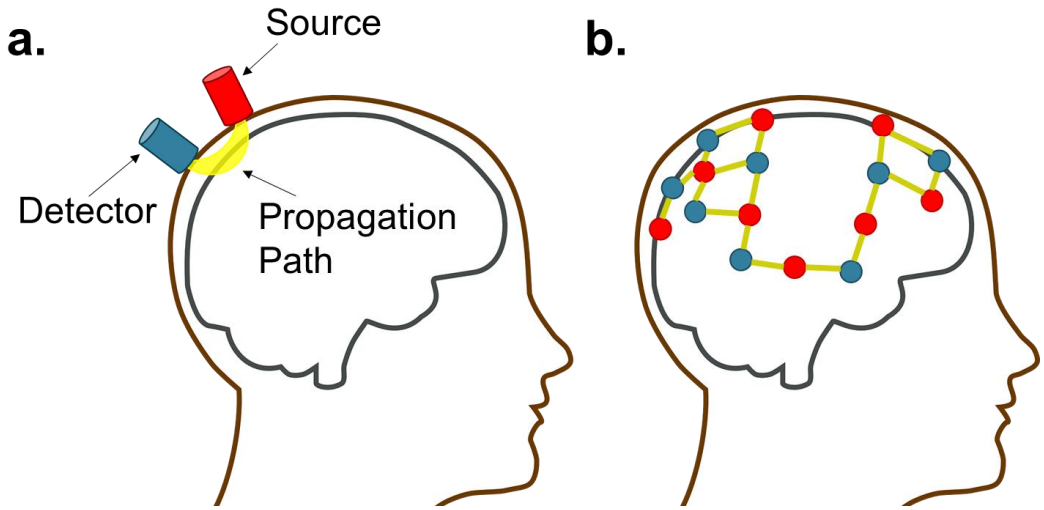


Figure 1.1. (a) Schematic showing a source, which emits near-infrared light, and a detector, which captures the transmitted light. The yellow represents the banana-shaped photon propagation path. (b) An example arrangement of sources (red circles) and detectors (blue circles). The yellow lines between each source and detector represent the channels.

1.6. Developmental changes in brain function involved in visual cognition.

Developmental changes in brain function are central to the emergence and refinement of visual cognitive abilities. Across infancy and early childhood, visual cognition becomes increasingly supported by coordinated activity across distributed networks, particularly in the prefrontal and parietal cortices. These changes reflect both structural maturation and functional reorganisation, enabling more efficient processing of visual information. Neuroimaging studies, especially those using fNIRS, have provided valuable insights into how these systems evolve over time to support attention and memory processes.

As highlighted, visual working memory is a key aspect of visual cognition. In a review exploring the development and neural substrates of different elements of executive functions, Fiske and Holmboe (2019) highlighted key visual working memory studies using fNIRS technology with infants. These studies showcase the role that areas of the prefrontal cortex (e.g., dorsolateral prefrontal cortex (DLPFC) – Baird et al., 2002) and beyond (e.g., posterior temporal cortex – Wilcox & Biondi,

2016) play during these processes. For example, Baird and colleagues (2002) employed fNIRS to examine frontal lobe activation during object permanence in infants. Object permanence is a cognitive process that requires the ability to pay attention and maintain an object in working memory (Ryu et al., 2017). The researchers tested infants monthly from 5 months to 12 months old. Infants recruited the DLPFC when holding objects in their visual working memory. Further, Wilcox and Biondi (2016) found that regions beyond the DLPFC also play an important role in working memory processing. The researchers reported that, during a working memory maintenance task, infants showed decreasing task-related activation in the posterior temporal cortex from 3 to 12 months. This decrease in activation was suggested to reflect the functional specialisation of visual working memory across the second half of the first year of life. More specifically, infants between 3 to 6 months initially showed robust activation in the posterior temporal cortex and then showed little to no activation once they reached 10 to 12 months. Another finding showed that the occipital cortex consistently exhibited robust activation across 3 to 12 months. Overall, the contribution of the posterior cortex to infants' processing of moving occluded objects changes considerably during the first year (Wilcox & Biondi, 2016).

During the first few years of life, children's brain networks experience both structural and functional changes that enable the development of more complex and refined cognitive abilities. In this context, Delgado Reyes and colleagues (2020) conducted a cross-sectional study to investigate the functional brain networks that underlie visual working memory in early development. Here they focused on four main hypotheses about the localisation of the visual working memory network in infancy: (1) the network is not localised in the fronto-parietal cortex; rather, it is mediated by the medial temporal lobe, (2) the network is mediated by the posterior cortex, (3) the network is lateralised, and (4) the network will show an adult-like cortical spatial organisation. They examined 4-month-olds, 1-year-olds, and 2-year-olds performance on a preferential looking task (Ross-Sheehy et al., 2003). With this paradigm, the researchers aimed to shed light on the neural mechanisms underlying performance on the preferential looking task, and what changes in the brain to support infants' improving ability to detect changes in a visual stream. In their findings, Delgado Reyes and colleagues (2020) reported localised task-specific

activation within the fronto-parietal network. Further, they found this localised activation in portions of the frontal cortex including the DLPFC – a hub for working memory as shown by previous work (Baird et al., 2002; Buss et al., 2014). They also found significant task-related activation in the right inferior frontal gyrus (IFG) and superior frontal gyrus (SFG). The SFG is a key area in the frontal attention network (Petersen & Posner, 2012), so its involvement may be related to the attentional demands of the preferential looking task. Wijeakumar et al. (2019) reported comparable findings when testing infants in rural India; showing robust cross-cultural engagement of the frontal visual working memory network. They found that activity in the right IFG and DLPFC decreased as preference to the changing side increased. They suggested that this suppression was necessary to prevent the non-changing side from capturing the infants' attention. Previous research has shown that the frontal cortex plays a key role in suppressing irrelevant or distracting information (Cosman et al., 2018). In summary, research on the neural basis of visual cognition in infancy highlights the dynamic development of brain networks involved in visual working memory. Key regions include components of the fronto-parietal network, with evidence pointing to increasing functional specialisation over the first year of life.

Previous work also demonstrates that the prefrontal cortex continues to play a critical role in visual working memory beyond infancy. For example, Buss and colleagues (2014) used fNIRS to examine the visual working memory capacity of 3- to 4-year-old children using a change-detection task. Their findings revealed that during working memory maintenance, both the frontal and parietal cortex showed increased activation. Notably, the activation in the parietal cortex was greater in 4-year-olds compared to 3-year-olds, indicating the region's sensitivity to visual working memory load (Buss et al., 2014). Another fNIRS study by Perlman et al. (2016) investigated 3- to 7-year-olds and observed increased lateral prefrontal cortex activation during a working memory task compared to rest. The study found that, as anticipated, accuracy and response speed in the working memory task improved with age. At the neural level, this improvement corresponded to increased DLPFC activation in older children. Additionally, longer response delays led to heightened activation in the lateral prefrontal cortex. These findings indicate that working memory develops gradually during early childhood, with the lateral prefrontal cortex

playing a consistent role, exhibiting activation sensitive to working memory load (Perlman et al., 2016). This evidence suggests that both the frontal and parietal cortices continue to stay engaged beyond infancy. Overall, the longitudinal development of brain networks involved in visual cognition exemplifies the intricate interplay between structural maturation, functional connectivity, and experience-driven plasticity, which collectively shape early cognitive abilities. fNIRS has proven particularly useful in elucidating these processes, offering localised insights into cortical activity while maintaining feasibility for infant research. These findings provide a foundation for understanding the neural architecture supporting visual cognition and its developmental trajectory.

The development of visual cognition can also be profoundly influenced by environmental contexts, particularly formal schooling and exposure to life stress. The transition from kindergarten to primary education marks a critical period during which schooling exerts a unique and measurable impact on brain function, above and beyond chronological age. Davidson et al. (2023) demonstrated that one year of formal schooling significantly improved children's visual working memory performance, vocabulary, and numeracy skills, independent of age-related maturation. These cognitive gains were supported by increased engagement of a left-lateralised fronto-parietal network during a colour-change detection task, suggesting that structured educational environments catalyse the refinement of brain systems responsible for maintaining and manipulating visual information. The exposure to formal schooling appeared to support more efficient recruitment of frontal and parietal regions implicated in executive and attentional control, thereby enhancing the cognitive flexibility needed for complex academic tasks (Davidson, Shing et al., 2023). Simultaneously, adverse environmental factors, such as life stress, can also play a critical role in modulating visual cognitive functions. McKay et al. (2021) found that preschool children experiencing higher levels of life stress exhibited distinct patterns of brain activation during a colour-change detection task. Specifically, greater parent-reported stress was associated with heightened activation in the left parietal cortex as task demands increased, suggesting that stressed children might need to recruit additional neural resources to achieve comparable performance levels. This increased parietal activation partially mediated the relationship between life stress and visual working memory performance, revealing a compensatory

mechanism where cognitive processing becomes less efficient under stress (McKay et al., 2021). These findings highlight that life stress can alter the typical developmental trajectory of brain systems supporting visual cognition, potentially leading to long-term differences in cognitive capacity and academic achievement. Taken together, these studies illustrate that the maturation of visual cognitive processes in older children is not solely the result of intrinsic neural development but is deeply embedded within social and environmental contexts.

1.7. Child visual cognition during naturalistic play interactions.

Understanding child visual cognition requires a balance between experimental approaches and ecological validity. While experimental tasks have been instrumental in isolating key mechanisms of visual processing, they often fall short of capturing the dynamic and context-rich environments wherein visual cognition emerges. Naturalistic play interactions, in contrast, provide an insight into how visual attention and processing operate in real-world settings. These interactions reflect the multifaceted stimuli and spontaneous behaviours that characterise everyday life, making them crucial for a comprehensive understanding of visual cognition. This section will discuss child behaviours during naturalistic interactions. Although the studies and interactions highlighted involve a social partner, the emphasis will remain on the child to allow for an in-depth exploration of child-specific visual processes in these rich contexts. The role and contributions of the social partner will be discussed in the following chapter. Ultimately, by transitioning from controlled experimental tasks to naturalistic settings, this section aims to illuminate how early visual cognition manifests and adapts within the complexities of real-world environments.

Play is a key context for the development of visual cognition in young children as it offers opportunities to explore and learn through interaction with their environment and peers (Whitebread et al., 2017). Naturalistic play settings provide a unique lens for understanding how children deploy their visual attention and process dynamic stimuli or objects (McQuillan et al., 2020). Object manipulation is a central component, where infants and young children use their hands and eyes together to investigate the properties of objects such as size, shape, texture, and weight. Studies have shown that infants who frequently handle objects develop stronger visual-motor

integration skills, which are essential for tasks like reaching, grasping, and problem-solving (Needham et al., 2002; van den Berg & Gredebäck, 2021). Constructive play, such as building with blocks or assembling puzzles, promotes visual-spatial reasoning. These activities require children to mentally manipulate objects and consider spatial relationships, which are linked to later academic success (Verdine et al., 2014). For example, stacking blocks teaches concepts of balance and stability, while fitting pieces into a puzzle enhances the ability to visualise spatial configurations. Dynamic and fast-paced social play, such as chasing games or shared toy exploration, requires children to rapidly shift their visual attention between objects and social cues. This fosters the ability to track multiple moving stimuli and anticipate the actions of others, skills that are vital for both social and cognitive development (Soto-Icaza et al., 2015). Cognitive developmental theories also highlight the importance of children's active engagement in their learning, as they can acquire new knowledge and skills through discussions and play with their peers (Piaget, 1962). Similarly, sociocultural accounts highlight a progression from sensory and perceptual experiences to conceptual and language-based understanding, with a focus on the role of social interactions. Social approaches stress that infants' attention to social agents aids in acquiring concepts and key information (Vygotsky, 1967).

Play also serves as a platform for refining attentional skills. Kannass and Oakes (2008) examined how attention changes from infancy to toddlerhood and its relationship to language development. Concretely, the study explored longitudinal development of attention from 9 to 31 months in two distinct free-play tasks: a single-object task and a multiple-object task. For both tasks and at both timepoints, attention was coded for the duration of looking, the number of inattention episodes, and the average length of looks. Vocabulary was assessed at 31 months using a picture vocabulary test. Significant developmental changes in attention were observed between 9 and 31 months of age. Infants at 9 months spent a similar proportion of time looking during both tasks, while toddlers at 31 months demonstrated more sustained attention in the single-object task. In the multiple-object task, toddlers showed longer average looks, fewer episodes of inattention, and fewer shifts between objects compared to infants. The study also revealed distinct relationships between attention and vocabulary. Shorter looking durations in the

single-object task at 9 months were associated with larger vocabularies at 31 months, consistent with previous findings that link shorter looking to greater processing efficiency (Bornstein & Sigman, 1986). On the other hand, longer looking durations in the multiple-object task at 9 months positively correlated with vocabulary, reflecting the role of goal-directed attentional control (Colombo & Cheatham, 2007). Along a similar vein, Schneider and Scher (2011) examined the role of exploratory play in infant development, focusing on changes in attention and task persistence between 10 and 14 months. The study had three primary aims: to assess changes in attention and persistence over time, to investigate the relationship between the quality of play and attention/persistence, and to determine whether play behaviours at 12 months could predict later developmental trajectories. To achieve this, they used the Infants' Play Behaviours with Objects during Semi-Structured Tasks (POST) procedure to observe play behaviours during home visits at 10, 12, and 14 months. Specifically, the POST allows for the observation of infants' levels of object play, as well as their capacity to focus, sustain attention, and persist in tasks that require purposeful exploration. Infants were presented with a series of play scenarios involving single and multiple objects, and their attention, persistence, and level of play were assessed. Results revealed that attention, persistence, and level of play behaviour significantly increased with age. Additionally, higher levels of attention and persistence were strongly associated with more sophisticated object play. Overall, their findings suggested that 12 months of age was a focal point for observing changes in an infant's ability to sustain attention and persist in exploratory play (Schneider & Scher, 2011). Both studies underscore the importance of examining multiple, diverse task types to understand child attention during play. However, as child attention can be influenced by the presence and behaviours of a partner, such as a caregiver, it is crucial to also investigate interactive play scenarios that involve these dynamics.

There are several studies that investigate joint attention and engagement between caregivers and children (e.g., Chiang et al., 2016; Markus et al., 2000; Pusiol et al., 2014; Vaughan et al., 2003). During joint play with caregivers, children learn to sustain their attention on shared tasks while managing competing visual stimuli. These experiences are crucial for developing selective attention, allowing children to filter out distractions and focus on relevant aspects of their environment

(Ruff & Capozzoli, 2003). For example, Quinn and Kidd (2019) aimed to determine whether symbolic play fostered more frequent and sustained joint attention and greater gesture use compared to functional play in 18-month-old children. Symbolic play is characterised by the non-literal use of objects and actions and is associated with socio-cognitive and language development. Whereas functional play refers to the use of objects in a manner consistent with their intended purpose. Both interactions were analysed for joint attention and gesture use, with gestures categorised as deictic (e.g., pointing) or iconic (e.g., miming actions). Their results showed that symbolic play promoted significantly more frequent and longer episodes of joint attention compared to functional play. Symbolic play also elicited greater use of gestures, particularly iconic in-hand gestures, which supported the negotiation of meaning within the play context. In contrast, functional play saw limited gesture use, primarily involving deictic gestures. The findings suggested that symbolic play fosters a cooperative environment that enhances children's understanding of others as intentional agents. Such outcomes are consistent with socio-cultural theories that emphasise the role of collective intentionality in symbolic play (Rakoczy, 2008). The authors argued that the representational and collaborative nature of symbolic play provides a fertile ground for developing foundational communicative skills, including gesture use and joint attention, which are critical for later language development (Quinn & Kidd, 2019).

1.8. Summary.

This chapter has explored visual cognition's developmental trajectory, from infancy through early childhood, with an emphasis on the interplay between cognitive processes, brain mechanisms, and environmental interactions. Visual cognition evolves rapidly during infancy. Early visual abilities, such as low visual acuity and rudimentary colour perception, undergo marked improvement in the first year, alongside motor integration, enabling behaviours like object tracking and depth perception. By six months, visual acuity increases, smoother tracking emerges, and attentional focus shifts from reflexive to sustained. These milestones underpin early learning and social interactions, but delays may indicate developmental issues.

Visual cognition continues to mature into toddlerhood and preschool years, with notable shifts in attention control. Infants' reflexive attention transitions to

intentional focus, enabling exploration and problem-solving. Longitudinal studies reveal significant growth in attentional capabilities, with sustained attention and cognitive flexibility emerging by age four. This progression correlates with the integration of attentional systems and behavioural regulation, forming the foundation for executive functioning. Visual working memory, critical to visual cognition, also develops significantly. Tasks such as the visual paired comparison task offer insight into infants' working memory but face limitations, particularly in assessing memory load capacity. Tasks enabling manipulation of working memory load, such as the preferential looking paradigm, remain underexplored but could provide valuable insights into cognitive development.

Theoretical accounts provide different explanations for how working memory functions and develops. Baddeley's multicomponent model describes working memory as a system comprising the central executive, phonological loop, visuo-spatial sketchpad, and episodic buffer. Research shows that these components become more efficient with age, with improvements in attentional control, memory span, and visuospatial processing. Cowan's capacity-based model suggests that developmental increases in working memory stem from an expanding storage limit rather than faster processing or improved filtering. Findings show that younger children recall fewer items than older children and adults and that memory constraints persist even when knowledge or rehearsal speed increases. Next, DFT provides a neural explanation of working memory development by modelling cognition as patterns of neural activation. Finally, FIT offers an account of how attention is required to bind basic visual features, such as colour and shape, into coherent object representations. Together, these theories highlight different aspects of visual working memory development and emphasise the importance of early processes in shaping later cognitive abilities.

Advancements in neuroimaging, including EEG and fNIRS, have facilitated exploration of the neural bases of visual cognition in infancy. EEG studies demonstrate developmental changes in power and coherence, highlighting the role of fronto-posterior connectivity in supporting working memory. However, EEG's poor spatial resolution limits alignment with findings from adult studies. fNIRS offers better spatial localisation and feasibility for infant research, enabling exploration of

cortical contributions to visual cognition. For example, studies using fNIRS show developmental shifts in activation across the DLPFC and posterior temporal cortex, reflecting functional specialisation during the first year. Emerging findings reveal the fronto-parietal network's centrality in visual working memory, with evidence of increasing functional specialisation and connectivity during infancy and early childhood. However, more work is required to fully understand the functional organisation of visual cognition in the brain.

Naturalistic play offers a rich context for studying visual cognition. Play involves dynamic interactions with objects, peers, and caregivers, fostering attention control, object recognition, and social-cognitive growth. Research emphasises the benefits of constructive play, which promotes spatial reasoning, and joint play with caregivers, which enhances selective attention. Studies have explored play's role in refining attentional skills, showing that goal-directed attention emerges during the toddler years and is associated with language development. However, there is limited understanding of how specific play activities shape visual cognitive trajectories. Investigating varied play scenarios could deepen insights into their contributions to cognitive growth.

Overall, this chapter provides a comprehensive overview of child visual cognition's developmental milestones, neural underpinnings, and environmental influences, emphasising their implications for broader cognitive and social outcomes. While significant advances have been made, further research is essential to address gaps in understanding. A balanced integration of experimental control and ecological validity, coupled with longitudinal approaches, will be key to advancing the field. Brief overviews of the relevant background and literature are provided in upcoming experimental chapters to contextualise the specific topics discussed in each. These mini-introductions are intended to ensure clarity and coherence for the reader as each chapter addresses distinct aspects of the overall research. The next chapter will focus on the role that caregivers play in this period of early child development.

Chapter 2:

Caregiver involvement in dyadic play interactions – a review of the literature.

2.1. Introduction.

Dyadic play interactions between caregivers and children play a pivotal role in shaping early developmental trajectories, encompassing social, emotional, and cognitive domains. This chapter provides a comprehensive review of the literature on caregiver involvement in these interactions. First, it explores coding schemes used to analyse caregiver-child interactions, emphasising the tools and frameworks that capture the nuanced dynamics of these exchanges. Second, it highlights key caregiving behaviours that are particularly salient during dyadic play, and their impact on developmental outcomes. Next, it considers longitudinal changes in caregiving practices, tracing how these interactions evolve over time and across developmental stages. Following this, caregiver executive functions and their influence on caregiving behaviours are highlighted. By synthesising these perspectives, the chapter aims to shed insight on the role that caregiver involvement plays for child development.

2.2. Coding schemes for caregiver-child dyadic interactions.

Caregiver-child dyadic interactions are marked by dynamic exchanges between the caregiver and the child, encompassing complex behaviours, emotions, movements, and shared activities. Coding schemes are standardised frameworks used to analyse these interactions, providing systematic methods for observing, categorising, and analysing behaviours and dynamics within dyads. Such schemes allow researchers to quantify complex processes and make comparisons across studies, contexts, and populations, offering insights into the nature of caregiving and its impact on children's socio-emotional and cognitive development. Standardisation helps mitigate observer bias, allowing for more objective and reproducible results. Ultimately, the use of standardised coding schemes enhances the validity of

conclusions drawn about the mechanisms underlying child development within caregiving contexts. This section explores coding frameworks, the dimensions they capture, issues of reliability and validity, illustrative studies using these methods, and the challenges inherent in applying them. The subsequent section will explore the specific behaviours identified through these coding schemes, examining their manifestation in caregiver-child interactions and their relevance to early development.

Coding and measurement approaches generally fall into three broad categories: global coding schemes, micro-coding schemes, and automated approaches (see Table 2.1 for an overview of featural differences). Global coding involves assigning holistic ratings to interactions, usually on a numerical scale (e.g., Likert-type scales from 1 to 5) or using descriptive categories. Observers make evaluative judgements about overall qualities of the interaction based on either live observation or recorded sessions (Carlson & Grotevant, 1987). This approach is relatively efficient and provides a broad picture of relational dynamics, which is particularly valuable in large-scale studies or clinical assessments. However, global coding is inherently subjective: coders must interpret complex behaviours into single summary ratings, which increases the potential for observer bias and reduces transparency in how those ratings were derived. It also relies on the coder's memory of the interaction, which may be influenced by interfering events or distractions during coding. The lack of temporal precision also limits its ability to capture fine-grained behavioural patterns.

Micro-coding, by contrast, breaks interactions into discrete, defined behavioural units, which are then coded either in real-time or from video recordings. This approach includes both event-based coding (e.g., counting specific behaviours) and time-based coding (e.g., measuring the duration of behaviours in intervals such as 10 or 30 seconds). Micro-coding can provide highly detailed data on the timing, frequency, and sequence of behaviours, offering insights into moment-to-moment interaction dynamics (Schneider et al., 2023). Despite its structured nature, micro-coding still requires subjective judgement in interpreting behaviour categories, and inter-rater reliability must be carefully established. It is also resource-intensive and may miss broader contextual or relational aspects by focusing narrowly on discrete behaviours.

Automated approaches represent a third category, enabled by advances in technology. These approaches include the use of head-mounted cameras, eye-tracking, wearable sensors, and machine learning algorithms to passively capture and analyse interaction data. For example, head-mounted cameras worn by infants and caregivers can provide first-person perspectives on visual attention and social referencing in naturalistic environments (Smith et al., 2015). Eye-tracking systems have been used to measure gaze coordination and joint attention without the need for manual annotation (Franchak et al., 2011). Machine learning tools can further automate the identification of behavioural patterns from large video datasets (Bhatt et al., 2023). A variety of work has utilised these tools for assessing the quality of parent-child interactions (e.g., Nikbakhtbideh et al., 2023; Saraswat et al., 2023; Wang et al., 2024). These methods have also recently been used to uncover biological mechanisms in parent-child interactions (Mora-Jensen et al., 2025). Additionally, machine learning models can help predict long-term outcomes, such as externalising problems or developmental disorders, by examining dynamic interaction patterns, which enables timely and personalised interventions (Chen et al., 2024; Li et al., 2025). These methods offer objective and continuous data capture and reduce reliance on human coders, potentially mitigating observer bias. However, they introduce other challenges, including data processing complexity, calibration and hardware constraints, and the interpretability of algorithm-generated measures. Moreover, decisions about what counts as meaningful behaviour, whether made by coders or algorithms, are still shaped by underlying assumptions and conceptual frameworks.

Each approach comes with trade-offs. While global and micro-coding methods provide structured frameworks grounded in behavioural theory, they both involve subjective decisions at various levels (e.g., in defining behavioural categories or applying rating scales). Automated approaches offer objectivity and scalability but are not free from interpretation, especially during data labelling, training phases, and post-hoc analysis. As such, all approaches involve assumptions that must be explicitly acknowledged. Ultimately, integrating multiple methods can offer a more comprehensive understanding of caregiver-child interactions. Combining global assessments with micro-coded sequences, or supplementing human-coded data with sensor-derived measures, enables researchers to balance depth, efficiency, and objectivity across levels of analysis. To enhance the precision

and relevance of the research, the examination of coding schemes will continue, as they are central to capturing the nuanced dynamics of caregiver-child interactions. In an upcoming experimental chapter, a tailored coding scheme will be developed to better align with the specific needs of the study, with a review of the main coding schemes outlined below informing this process.

Table 2.1. Featural differences between coding approaches.

	Global Coding	**Micro-Coding**	**Automated Approaches**
Level of Detail	Low (broad ratings)	High (specific behaviours)	Very high (continuous, real-time data)
Efficiency	Fast & subjective	Slow & objective	Variable (automated but requires setup & processing)
Data Type	Qualitative/Numeric Scales	Quantitative (behavioural counts)	Quantitative
Bias Risk	Higher (subjective interpretation)	Moderate (objective behaviour tracking)	Lower (less human involvement, but algorithm design matters)
Best for	Relationship quality, overall patterns	Specific behaviours, micro-level interactions	Gaze patterns, attention, coordination, large-scale behaviour tracking

There are various coding schemes available for analysing caregiver-child interactions (see Table 2.2 for an extensive list). For the current section, a selection of frameworks has been chosen due to their specific applicability to infant populations. These commonly used frameworks include the Emotional Availability Scales (EAS) (Biringen, 2000), the Mutually Responsive Orientation (MRO) framework (Kochanska, 2002), the Early Mother-Child Interaction Coding System

(CITMI-R) (Cerezo et al., 2021), and Coding Interactive Behaviour (CIB) (Feldman, 1998). Each of these frameworks offer valuable insights into early caregiver-child dynamics and each offer unique strengths and limitations.

The EAS provides a global assessment of the quality of emotional interactions between caregivers and children. It assesses six dimensions: parental sensitivity, parental structuring, parental non-intrusiveness, parental non-hostility, child responsiveness, and child involvement (Biringen, 2000). This scheme is applicable across different age groups (infancy to adolescence) and is useful for both clinical and research settings. However, it requires coders to be trained to ensure accurate scoring. Little and Carter (2005) used the EAS to evaluate how maternal–infant emotional availability during play related to 12-month-olds' ability to regulate distress. They found that lower emotional availability, particularly higher maternal hostility, was linked to poorer emotion regulation in infants. These findings indicate that infants exposed to maternal hostility may struggle to develop effective emotion regulation, highlighting the importance of emotionally supportive caregiver–infant relationships in early development. Another study by Easterbrooks and colleagues (2005) assessed mother–infant interactions, showing that emotional availability varied significantly across dyads and was associated with maternal depression, social support, and past relationships with caregivers. Underscoring the importance of viewing emotional availability as a relational construct shaped by both individual and contextual factors.

Frameworks such as the MRO emphasise the emotional connection and shared cooperation within dyads. Developed by Kochanska (2002), the MRO framework focuses on the quality of the parent-child relationship, particularly how mutual cooperation and positive emotional engagement shape early socialisation and moral development. This scheme highlights the bidirectional nature of caregiver-child interactions and emphasises positive, prosocial aspects of development. However, it may not be as applicable to highly directive or authoritarian parenting styles and is more focused on long-term relationship quality rather than momentary behaviours. For instance, the MRO framework has been employed in longitudinal studies to explore the long-term impact of cooperative, emotionally connected interactions. Kochanska et al. (2008) examined the mechanisms through which MRO

observed at 7, 15, and 25 months in parent-child dyads influenced children's internalisation and self-regulation at 52 months. Here, they found that early MRO predicted secure attachment, moral internalisation, and self-regulation in children. Overall, the MRO framework provides a valuable lens for understanding how early, emotionally positive dyadic interactions contribute to children's social and moral development over time.

The CITMI-R is a structured observational tool designed to assess early mother-child interactions, particularly in relation to risk factors for maltreatment, neglect, or disrupted attachment relationships. It was developed to capture the timing and flow of caregiver-infant interactions within naturalistic settings, highlighting both their theoretical significance and practical relevance for identifying interactional risk (Cerezo et al., 2021). The scheme assesses a variety of behaviours, including parental sensitivity, parental stimulation, parental control strategies, parental negativity, child social engagement, and child distress and regulation. It is useful for assessing high-risk families and potential child maltreatment and provides a structured framework that can be applied in clinical and intervention contexts. Nevertheless, it requires trained coders and is primarily designed for early interactions, limiting its applicability to older children. Perea-Velasco et al. (2023) used the CITMI-R to examine longitudinal changes in maternal sensitivity and response latency during dyadic free play across the first 18 months of life. They found that sensitive responses increased while intrusive behaviours decreased over time, suggesting that mothers adapted their behaviour to support children's growing autonomy and developmental needs. Thus, the CITMI-R offers a valuable approach for identifying and tracking early relational risks and developmental changes within caregiver-infant interactions.

Finally, the CIB is an observational coding system designed to assess parent-child interactions in naturalistic and structured settings, widely used in developmental psychology and clinical research. It includes multiple parent and child variables, grouped into several domains: parenting behaviours (e.g., sensitivity, warmth, intrusiveness), child behaviours (e.g., social engagement, negative affect), and dyadic measures (e.g., synchrony, mutual responsiveness) (Feldman, 1998). This scheme is beneficial as it captures various aspects of interactions and can be applied

across different contexts (e.g., free play, feeding). However, the use of this coding system requires extensive training. Ferber et al. (2008) investigated the developmental trajectories of maternal touch and mother-infant reciprocal communication across the first year of life. They used the CIB to assess maternal sensitivity and dyadic reciprocity during play. Results revealed that while affectionate and stimulating touch decreased across the first year, dyadic reciprocity increased, with affectionate touch predicting reciprocity, highlighting the evolving role of touch in mother-infant communication. Overall, the CIB provides a comprehensive and flexible framework for capturing the dynamic and evolving nature of parent-child interactions across early development.

While these coding schemes have been widely validated and have advanced the study of caregiver-child interactions, they each have limitations. The MRO framework provides a rich understanding of emotional connection and cooperation but is less applicable to directive or authoritarian parenting styles and focuses more on long-term relationship quality than on capturing moment-to-moment behaviours. The CITMI-R, while valuable for identifying relational risk in early development, is primarily limited to infant populations and requires substantial coder training, which may restrict its broader use. The CIB captures diverse aspects of dyadic interaction across contexts but demands extensive and costly training, presenting significant accessibility barriers. Similarly, the EAS offers a flexible tool for assessing emotional availability across a wide age range and in clinical and research contexts, but also requires specialised training for reliable use, and tends to focus on broad emotional constructs rather than fine-grained moment-to-moment processes. More broadly, these frameworks share several common challenges: the potential for observer bias (Jung & Heinrichs, 2023), high resource and time demands for training and coding (Chorney et al., 2015), constraints on sample size and generalisability, and issues with accessibility due to costly and limited training opportunities. Taken together, while these coding schemes have provided systematic and valuable insights into key dimensions of caregiver-child interaction, their limitations highlight the need for more accessible, scalable, and adaptable approaches. Addressing these challenges is crucial for developing new observational tools that better meet the demands of contemporary developmental research.

Table 2.2. Examples of coding schemes used to assess various behaviours.

Coding Scheme	**Coding Scheme (Incl. Author and Publication)**	**Age Ranges**	**Coding Type**
DPICS	Dyadic Parent-Child Interaction Coding System (Eyberg et al., 2001)	3 to 12 years	Micro
EAS	Emotional Availability Scales (Biringen, 2000)	Birth to 14 years	Global
MRO	Mutually Responsive Orientation Framework (Kochanska, 2002)	7 to 25 months	Global
CITMI-R	Early Mother-Child Interaction Coding System (Cerezo et al., 2021)	6 to 18 months	Micro
CARE	Child-Adult Relationship Experimental Index (Crittenden, as cited by (Bind et al., 2021))	Birth to 36 months	Global
CIB	Coding Interactive Behaviour (Feldman, 1998)	Infancy to adolescence	Global
GRS	Global Rating Scale (Murray et al., 1996)	Infancy	Global
IRS	Interaction Rating Scale (Field, 1980)	Infancy to 8 years	Global
MM	Mind-Mindedness (Meins & Fernyhough, 2015)	Infancy	Global
MSS	Maternal Sensitivity Scale (Ainsworth, 1969)	Infancy	Global
BMIS	Bethlem Mother-Infant Interaction Scale (Kumar & Hipwell, 1996)	Birth to 24 months	Global
ICEP	Infant and Caregiver Engagement Manual (Weinberg and Tronick, as cited by (Kaitz et al., 2010))	Infancy	Micro
MPM	Monadic Phases Manual (Tronick et al., 1980)	Infancy	Micro

PCERA	Parent-Child Early-Relational Assessment (Clark, as cited by (Anke et al., 2020))	Infancy to early childhood	Global
AFFEX	Automatic Affect Expression System (Izard and Dougherty, as cited by (Weinberg et al., 2006))	Infancy	Micro
NICHD	Scales from the NICHD study (Owen, 1992)	Infancy to early childhood	Global
GLOS	Greenspan Lieberman Observations System (Greenspan & Lieberman, 1989)	Infancy to early childhood	Global
HOME	Home Observation for Measurement of the Environment (Caldwell & Bradley, 2003)	Birth to 15 years	Global
IFIRS	Iowa Family Interaction Rating Scales (Melby et al., as cited by (Jaser et al., 2008))	2 to 17 years	Global
POSER	Play Observation Scheme and Emotion Rating (Wolke, as cited by (Hipwell et al., 2000))	Infancy to early childhood	Global

2.3. Caregiving behaviours during dyadic interactions.

Caregiving encompasses a range of behaviours that can have both positive and negative effects on a child's development. Responsive, warm, and sensitive caregiving fosters emotional security, strengthens attachment, and supports healthy growth (Hawk et al., 2018; Taber, 2018). Conversely, inconsistent, unresponsive, or harsh caregiving can contribute to stress, insecurity, and developmental challenges (Mortensen & Barnett, 2019). These interactions shape the caregiver-child bond and influence social, emotional, and cognitive outcomes. This section explores both perspectives of caregiving within dyadic interactions, highlighting their impact on the child's well-being and overall development.

Sensitive and responsive caregiving is a key aspect of high-quality dyadic interactions. Sensitive caregiving refers to a caregiver's ability to accurately perceive and interpret the child's signals and respond appropriately to their needs and interests (Ainsworth, 1979). Bowlby's (1969) theory of attachment emphasises the importance of shifts between positive and negative emotions as the primary method of communication for infants. Specifically, transitions from positive to negative emotions signal distress and a need for comfort from the caregiver. For a secure attachment relationship to develop, the caregiver must recognise and respond to these emotional changes. Therefore, sensitive caregiving reflects the coordination of caregiving behaviours with the infant's attachment system (Ainsworth, 1979; Bowlby, 1969). Through repeated experiences of responsive caregiving, children develop a sense of efficacy and agency, enabling them to express their emotions in a well-regulated way (Tronick, 1989). This responsiveness, particularly in the context of play, has been associated with numerous positive developmental outcomes. For example, Tamis-LeMonda et al. (2001) investigated the role of maternal responsiveness in predicting the timing of early language milestones in children. Using a prospective longitudinal design, the researchers observed 40 mother-child dyads through videotaped free-play sessions at 9 and 13 months, coding maternal responsiveness (e.g., descriptions, play prompts, imitations) and children's activities (e.g., vocalisations, play). Additionally, maternal interviews from 9 to 21 months provided detailed reports on children's language development, tracking five milestones: first imitations, first words, 50-word vocabulary, combinatorial speech, and the use of language to talk about the past. Their findings demonstrated that mothers who followed their child's lead during play had children who exhibited enhanced cognitive and linguistic development. These mothers mirrored their child's actions, expanded on their child's verbalisations, and encouraged their exploration (Tamis-LeMonda et al., 2001). Further, responsive caregivers are attuned to their child's cues, both verbal and non-verbal, adapting their behaviours to maintain engagement without overwhelming the child and causing them to withdraw from the interaction (Shire et al., 2016). Such contingent responses support the child's sense of agency and foster secure attachment, which is critical for emotional regulation and resilience (Hong & Park, 2012).

Caregivers who use positive reinforcement and encouragement create a supportive environment that fosters motivation and persistence. Positive reinforcement involves acknowledging and rewarding desirable behaviours, which strengthens the likelihood of their recurrence (Cameron & Pierce, 1994). In the context of dyadic play, positive reinforcement can take the form of praising a child's effort, expressing enthusiasm, or celebrating small achievements. Gunderson et al. (2013) explored how the type of praise parents gave to young children influenced their later motivational frameworks. Observing parent-child interactions at home with children aged 14 to 38 months, the researchers found that process praise (e.g., "You worked hard"), emphasising effort and actions, was positively associated with an incremental mindset in children at ages 7 and 8. This incremental mindset is characterised by the belief that traits can be developed, a willingness to embrace challenges, and the use of strategies to support improvement. In contrast, person praise, which attributes success to fixed traits (e.g., "You're so smart"), did not predict children's motivational orientations. Interestingly, boys received more process praise than girls, potentially contributing to gender differences in motivational beliefs. These findings suggest that early use of process-oriented praise fosters adaptive beliefs about learning and effort, with implications for parenting and educational practices (Gunderson et al., 2013).

An important behaviour that underpins sensitive and effective caregiving is mind-mindedness, defined as a caregiver's tendency to view and treat their child as an individual with their own thoughts, feelings, and intentions (McMahon & Bernier, 2017). This quality is especially important during dyadic interactions, where attuned caregiving behaviours are foundational for fostering secure attachment and emotional development. Caregivers who demonstrate high mind-mindedness are more likely to interpret and respond appropriately to their child's cues, engaging in sensitive and contingent interactions (Planalp et al., 2019). Such responsiveness not only supports the child's emerging sense of self but also promotes cognitive and social competencies by encouraging the child to see themselves as an intentional agent within a reciprocal relationship. Empirical evidence supports these links. In a longitudinal study, Meins et al. (2002) found that mothers who used appropriate mental state language during free-play interactions with their 6-month-old infants, specifically comments that accurately reflected their infant's internal experiences,

predicted children's later success on theory of mind tasks at ages 45 and 48 months. Importantly, this effect was independent of attachment security and general maternal sensitivity, highlighting that the specificity of mind-minded interactions, rather than general warmth or responsiveness, plays a distinct role in fostering children's early mentalising abilities. Building on this, Nikolić et al. (2022) examined both mothers' and fathers' mind-mindedness at 12 and 30 months and its impact on children's self-regulation at age 4.5 years. They found that fathers' appropriate mind-related comments were positively associated with children's effortful control and behavioural self-regulation, while non-attuned comments from either parent, those that misrepresented the child's mental state, were linked to poorer physiological and temperamental regulation. These findings suggest that mind-mindedness, especially when accurate and contingent, contributes meaningfully to a child's developing capacity to regulate emotions and behaviour in the preschool years.

Caregiver scaffolding also plays a crucial role in a child's development (Vygotsky, 1986), but if not carefully balanced, it risks either fostering dependency or hindering independent problem-solving. Scaffolding refers to the support a caregiver provides to help a child achieve a task that would otherwise be beyond their independent capabilities (Mermelshtine, 2017). This support is gradually withdrawn as the child gains competence, promoting autonomy and mastery (Mermelshtine, 2017). In the context of play, scaffolding often involves modelling appropriate behaviours, offering hints or prompts, and breaking down tasks into manageable steps. Wood et al. (1976) first conceptualised scaffolding in problem-solving contexts, but its relevance extends to play interactions. For example, a caregiver might guide a child in building a block tower by demonstrating how to stabilise the base and then encourage the child to take over. Hammond et al. (2012) explored the effects of parental scaffolding of children's problem solving on the development of executive functions. The researchers assessed children's executive functioning abilities using a variety of tasks at ages 2, 3, and 4. Additionally, at ages 2 and 3, children engaged with a problem-solving puzzle during which parents offered structured assistance. Results revealed that scaffolding at age 3 had a direct effect on executive functioning at age 4. Overall, they found that scaffolding during play not only enhances cognitive outcomes but also strengthens executive functioning, including attention, working memory, and self-regulation.

Scaffolding plays a critical role in supporting language development, as it provides the structure and guidance necessary for children to expand their communicative abilities. By adapting their input to the child's current capabilities, caregivers can facilitate learning and encourage more complex language use. Tomasello and Farrar (1986) highlighted how caregivers' expansions of children's utterances during symbolic play, such as transforming "car" into "The car is driving fast!", facilitated vocabulary growth and syntactic development. This practice enriches the child's language environment while reinforcing the connection between words and concepts. In another study, Dieterich and colleagues (2006) examined the impact of maternal verbal scaffolding on the development of decoding and reading comprehension skills in children. The authors reported that maternal scaffolding indirectly influenced both decoding at 8 years old and comprehension at 10 years old, through its support of children's language abilities at 3 and 4 years old. Beyond language development, Dilworth-Bart et al. (2010) investigated how maternal scaffolding impacted visual-spatial processing and working memory in toddlers. They found that higher maternal attention scaffolding, i.e. guiding and maintaining the child's focus, during play at 16 months was positively correlated with verbal working memory at 24 months. Whereas, lower maternal emotion scaffolding, i.e. minimal efforts to help maintain positive emotions or soothe negative emotions, was also associated with better verbal working memory. The association between lower maternal emotion scaffolding and better verbal working memory may indicate that minimising emotional intrusions enables toddlers to focus more effectively on cognitive tasks (Dilworth-Bart et al., 2010).

Scaffolding plays a critical role not only in typical development but also in supporting atypical development, where its effectiveness may be shaped by unique developmental trajectories. For example, Lowe and colleagues (2013) compared the relationship between maternal verbal scaffolding and cognitive outcomes in toddlers born preterm and full term. They reported that mothers of full-term toddlers used more complex scaffolding (e.g., explaining object functions or making associations) compared to mothers of preterm toddlers. The authors suggested that this difference may have reflected a process in which mothers adjust their scaffolding based on their perception of their child's level of development. They also found that verbal scaffolding was associated with cognitive outcomes for the full-term toddlers and the

preterm toddlers who were healthier during the neonatal period (Lowe et al., 2013). Similarly, Altman et al. (2024) found that while caregivers of toddlers with autism spectrum disorder (ASD) produced fewer pretend play utterances related to their child's actions compared to caregivers of neurotypical toddlers, they still demonstrated a high level of attunement to their children's play skills. These findings highlight the importance of scaffolding, even when opportunities for complex pretend play are less frequent in children with atypical development. Pierucci (2016) also highlighted the importance of scaffolding for toddlers with ASD, showing that mothers' scaffolding techniques during a social-communication intervention increased over time, with all toddlers exhibiting pretend play by the end of the study. These results support the idea that scaffolding can help foster developmental progress, even in children with ASD. Taken together, these findings suggest that maternal scaffolding is a critical factor in supporting the development of children and promoting complex and tailored scaffolding practices could potentially mitigate developmental delays, particularly in children facing neonatal risks or developmental challenges such as ASD.

Negative caregiver behaviours can have detrimental effects on a child's development. These behaviours undermine the child's sense of agency and emotional security, impacting their ability to form healthy attachments and develop essential cognitive and emotional skills. One such negative behaviour is intrusiveness. Intrusive caregiving behaviours are characterised by excessive control, interruptions, or a disregard for the child's autonomy and preferences (Biringen & Robinson, 1991; Carlson & Harwood, 2003). These behaviours often manifest as frequent corrections, unsolicited instructions, or insistence on the caregiver's agenda during play. Research has consistently linked intrusive caregiving to negative developmental outcomes (e.g., Egeland et al., 1993; Swingler et al., 2017). In one study, Broomell and colleagues (2018) explored the context and timing of maternal intrusiveness during infancy and its relation to executive functions at age 4. Results revealed that intrusiveness during structured play at 5 months predicted better executive function outcomes, while intrusiveness during structured play at 10 months was negatively associated with executive function outcomes. These findings suggested that maternal intrusiveness may have different implications depending on the infant's age. At 5 months, intrusiveness may support cognitive development by acting as scaffolding,

but by 10 months, it may interfere with development as infants become more socially capable. The change in the effect of maternal intrusiveness over time likely reflects developmentally appropriate shifts in caregiver-infant interaction (Broomell et al., 2020).

There is also evidence from neuroimaging studies for the early impacts of intrusive behaviours on brain function in the first year of life. For example, Swingler et al. (2017) examined whether maternal intrusiveness predicted neural and attention processes in infants from the ages of 5 to 10 months. To assess attention, the researchers used a glove puppet adorned with facial features on the palm and small bells attached to each fingertip. A greater proportion of time spent attending to the puppet was indicative of greater attention. Intrusive behaviours were shown to have a disruptive effect on attention, resulting in suboptimal neural activation. Specifically, intrusiveness at 5 months was associated with greater activation in the left medial frontal region during the attention task at 10 months (Swingler et al., 2017). More recently, Huffmeijer and colleagues (2020) examined the effects of maternal intrusiveness on infants' neural responses to emotional prosody. Mothers and their 6- to 7-month-old infants were observed during free-play with objects. Additionally, infants were presented with a task featuring simple directive statements, spoken with either a happy or angry prosody, while their brain activity was recorded using EEG. Here, maternal intrusiveness was linked to changes in infants' event-related potential responses, such that, infants with less intrusive mothers showed larger differences in neural processing between happy and angry prosody. These studies have shown that parental intrusiveness often leads to less optimal developmental outcomes. Further, timing and the specific interactional contexts are also crucial in determining whether intrusiveness has supportive or harmful implications. Overall, intrusiveness affects both behavioural and neurocognitive domains, influencing social-cognitive and executive function development.

2.4. Longitudinal changes in caregiving practices.

Ensuring that children meet their developmental milestones as they age, necessitates shifts in caregiving behaviours. In infancy, caregivers focus primarily on physical and emotional care, such as feeding, soothing, and maintaining routines,

and responsive interactions, such as eye contact, infant-directed speech, and contingent responding, laying the foundation for attachment and early communication (Bowlby, 1969; Papousek & Papousek, 1991). By toddlerhood, the emphasis shifts to fostering autonomy, scaffolding learning, and encouraging social and emotional competencies. This transition reflects children's evolving cognitive, motor, and social abilities, requiring caregivers to adapt their interactions accordingly. As toddlers begin to explore their environment more independently, caregivers shift towards scaffolding learning through joint attention, labelling objects, and supporting problem-solving (Brezack et al., 2021; Rogoff, 1990). Emotion regulation also becomes a key focus, as caregivers help toddlers navigate frustration and social interactions by modelling appropriate responses and providing guidance (Kopp, 1989). By the preschool years, caregiving further evolves to promote self-regulation, peer relationships, and school readiness, with a growing emphasis on structured learning, perspective-taking, and rule-based play (Landry et al., 2006; Yogman et al., 2018). Here, caregivers progressively take on the role of facilitators, balancing guidance with autonomy to support children's emerging competencies (Cohn & Tronick, 1988; Kopp, 1982).

Research on longitudinal changes in caregiving has highlighted both stability and variation in parenting behaviours across early childhood. Verhoef et al. (2023) identified three maternal parenting profiles, Competent, Sufficient, and Maladaptive, and found that while most mothers maintained their style, those in the Maladaptive group showed more instability. Higher education and agreeableness promoted stability, whereas economic stress and lower education increased instability. Similarly, Gutman and Feinstein (2010) found that early affectionate interactions supported better child development, but parenting behaviours evolved toward more cognitive engagement over time. Lower socioeconomic status was linked to fewer interactive behaviours, though high maternal responsiveness helped buffer these effects. Other research has further demonstrated these patterns across different developmental periods. For example, Dallaire and Weinraub (2005) showed that sensitive and stimulating parenting behaviours were relatively stable across the first six years of life, while negative behaviours such as detachment and negative regard were less stable. In middle childhood and early adolescence, parental communication and strict control behaviours showed moderate relative stability, although strict

control and hostility declined as children aged (Carrasco et al., 2011). Similarly, Rimehaug et al. (2011) found that, even over a nine-month period, dimensions of parenting such as Warmth, Protectiveness, and Authoritarianism showed varying degrees of stability, with Warmth being the most stable and Authoritarianism the least. Overall, while many caregivers show consistency in their behaviours, external factors such as stress, socioeconomic conditions, and child developmental stage can contribute to changes in caregiving over time.

Longitudinal changes in caregiving are heavily influenced by contextual factors, including mental health, personality traits, and social support. For instance, Waylen and Stewart-Brown (2010) demonstrated that maternal depression, financial circumstances, housing tenure, and marital status impacted parenting behaviours from 8 to 33 months postpartum, with maternal mental health being the strongest predictor. Mothers with increasing depression showed declines in caregiving quality, such as reduced warmth and greater negativity. Interestingly, improving financial circumstances alone did not enhance parenting, highlighting the importance of integrated support that addresses both emotional and economic stressors. Similarly, research by Smith et al. (2007) identified maternal personality traits, specifically Agreeableness and Conscientiousness, as key predictors of sensitive parenting, while Neuroticism was associated with reduced sensitivity. Positive emotional expressiveness, such as smiling and laughter, was found to mediate the link between these traits and caregiving behaviours, underlining the importance of emotional expression in nurturing interactions. Work by Belsky and Fearon (2002) expands this perspective by showing how maternal psychological well-being, shaped by stress, financial strain, and depression, interacts with early attachment security to influence caregiving outcomes. Secure infants exposed to maternal insensitivity tended to have mothers facing higher stress and lower social support, while insecure infants who received sensitive care were often in more favourable emotional contexts. Together, these studies underscore the crucial role of both enduring caregiver characteristics and dynamic contextual factors in shaping caregiving trajectories and child development.

Longitudinal caregiving research also has significant implications for early interventions. Programs that provide continuous support and education, such as those

focusing on responsive caregiving and scaffolding strategies, can help caregivers adapt to their child's changing needs (e.g., Cologon et al., 2017; Magnuson & Schindler, 2019; Salomone et al., 2019). For example, the Caregiver Skills Training program aims to support both child and caregiver outcomes by targeting four main goals: enhancing the child's behaviour and communication; strengthening the caregiver–child relationship; promoting participation in daily activities; and improving caregiver confidence, skills, knowledge, and psychological well-being (Salomone et al., 2019). Additionally, addressing external stressors, such as financial or marital difficulties, may enhance caregiving quality and consistency. Altogether, longitudinal changes in caregiving practices reflect the dynamic interplay between child development, caregiver adaptation, and contextual influences (Belsky & Fearon, 2002; NICHD Early Child Care Research Network, 1999). These changes can involve shifts in caregivers' emotional responsiveness, discipline strategies, and capacity to scaffold autonomy as children mature. Empirical evidence highlights the importance of responsive and adaptive caregiving for supporting child development across various domains (Gee & Cohodes, 2021; World Health Organisation, 2004). By understanding these changes, researchers and practitioners can design interventions that provide ongoing support to caregivers, helping them navigate the complexities of parenting and fostering positive developmental outcomes for children.

2.5. Caregiver executive function and its links to caregiving practices.

Executive functioning skills in adulthood are foundational for success and general well-being in various domains of life (Diamond, 2013). These set of skills include working memory, cognitive flexibility, and inhibitory control. They contribute to efficient decision making, self-regulation, and adaptability, all of which are crucial for thriving in a fast-paced and often complex adult world (Baumeister & Vohs, 2004). These skills are particularly crucial in the context of caregiving, where they enable parents to respond sensitively and consistently to their child's needs, regulate emotional responses, and adapt to dynamic and often challenging situations. Strong executive functioning capacities have been repeatedly linked to more effective and sensitive caregiving behaviours. Deater-Deckard and colleagues (2012) found that maternal executive function moderated the association between harsh parenting and child conduct problems in children aged 3 to 7. Specifically, harsh

parenting was only predictive of conduct problems when maternal executive function was low, suggesting that well-developed executive skills may buffer against the adverse effects of harsh parenting. Mothers with stronger executive function capacities were more likely to be responsive to their children's cues and less likely to engage in inconsistent or punitive parenting practices. These findings point to the broader regulatory role of executive function in caregiving practices, providing a foundation for understanding how specific components individually contribute to caregiving. Each executive sub-function within the context of caregiving is discussed below.

Working memory plays a central role in helping caregivers manage emotional responses in the moment. It facilitates the ability to reappraise stressful or frustrating situations and avoid reactive behaviours (Ochsner & Gross, 2005, 2008). Deater-Deckard et al. (2010) examined how maternal working memory relates to reactive negativity, emotionally charged and often disproportionate responses to challenging child behaviours (Chang et al., 2003). Mothers with lower working memory were more likely to respond with reactive negativity when their children were oppositional or distractible. Conversely, mothers with better working memory exhibited greater emotional regulation and were less likely to react harshly. These findings underscore the value of working memory in supporting emotion regulation within caregiving and highlight a potential target for interventions aimed at improving parenting quality.

Cognitive flexibility, defined as the ability to shift thoughts and behaviours in response to changing demands or perspectives (Flujas-Contreras et al., 2023), is another subcomponent that supports adaptive caregiving. Effective parenting often requires adjusting expectations, strategies, or communication styles as a child develops or as the context changes. Martin and Rubin (1995) described cognitive flexibility as involving three core abilities: recognising multiple response options, adapting to change, and maintaining confidence in navigating new challenges. This flexibility is vital in parent-child interactions, where caregivers must be responsive and open to new perspectives. Previous work has shown that cognitively flexible parents tend to communicate more empathetically and assertively, while being less likely to engage in aggressive or rigid communication patterns (Curran & Andersen, 2017; Martin & Anderson, 1998). Empirical work has also demonstrated that greater

cognitive flexibility is associated with lower parenting stress, more cohesive family relationships, and fewer child behavioural problems (Daks & Rogge, 2020), while low flexibility is linked to increased use of harsh disciplinary strategies (Burke & Moore, 2015; Shea & Coyne, 2011).

Inhibitory control, the capacity to suppress automatic or impulsive responses, also plays a critical role in caregiving. Caregivers with high inhibitory control are better equipped to resist reacting harshly to challenging behaviour, instead applying structured and consistent discipline (Bridgett et al., 2013). Inhibitory control enables caregivers to resist distractions that could undermine the quality of interaction, such as mobile device use (Radesky et al., 2014). Gonzalez (2015) also found links between inhibitory control and sensitive caregiving behaviours, suggesting that caregivers with better inhibitory capacities are more emotionally regulated and responsive. These traits, in turn, are associated with stronger attachment relationships and improved child socioemotional outcomes. Taken together, these findings demonstrate that caregiver executive functioning supports high-quality parenting by enabling emotional regulation, responsiveness, adaptability, and consistency. Each subcomponent of executive function offers unique contributions to caregiving, but collectively, they underpin a caregiver's ability to manage the cognitive and emotional demands of raising a child.

While research has considered the role of executive function in caregiving behaviours, a growing body of work supports the idea that caregiver executive functioning plays a role in shaping the development of children's own executive functioning skills. Existing evidence suggests that caregiver executive function may be a meaningful predictor of child executive function across early development, with potential contributions from both genetic and environmental mechanisms. For example, Cuevas et al. (2014) conducted a longitudinal study assessing mother-child dyads at three timepoints across toddlerhood and early childhood (24, 36, and 48 months). Using age-appropriate executive function tasks, they found that maternal and child executive function were modestly associated by 24 months, with this relationship remaining stable through to 48 months. Importantly, the associations remained significant even after controlling for maternal education and verbal ability in both mother and child, suggesting that executive function links are not merely the result of general cognitive or socioeconomic factors. These findings support the idea

that bio-social mechanisms underpinning executive function may be established in infancy and continue to influence development throughout early childhood. More recent research by Ribner and colleagues (2022) has expanded on this work by investigating how maternal and paternal executive function contribute to emergent executive function in toddlers. Their findings showed that maternal executive function significantly predicted child working memory and cognitive shifting at 24 months, whereas paternal executive function only predicted child shifting. These results not only reinforce the significance of caregiver executive function in child cognitive development but also highlight potential differences in maternal and paternal contributions to specific executive function domains during early childhood.

The heritability of executive sub-functions has also been examined through genetically informed research designs. Wang et al. (2012) used a behavioural genetic twin study to assess working memory and attention in 7-year-old children, employing both task-based measures and parent-report questionnaires. The study found that the observed correlation between working memory and attention was entirely explained by overlapping genetic covariance, pointing to a common genetic mechanism underlying both domains. The finding of a shared genetic basis for working memory and attention strengthens the argument that similarities in executive function between parents and children may be largely driven by inherited factors, rather than solely by caregiving practices or shared environments. Further insight into the familial nature of executive function was provided by Jester et al. (2009), who investigated whether executive functioning is transmitted from parents to children independently of general intelligence. Results confirmed that both maternal and paternal executive function were associated with children's executive function even after controlling for IQ. These findings underscore that intergenerational links in executive function cannot be solely attributed to general cognitive ability, strengthening the case for executive function as a distinct and heritable construct with implications for child development. Taken together, these studies suggest that caregiver executive function is associated with child executive function from as early as toddlerhood and that these links are likely shaped by a combination of genetic and environmental factors. While maternal executive function appears particularly influential during the early years, both parents' executive function abilities may contribute to the development of executive

processes in children over time. Nevertheless, this area of research remains relatively under-explored, and more work is needed to disentangle the specific pathways through which caregiver executive function is transmitted. Much of the afore-mentioned work focuses on overall executive function ability, rather than specific sub-functions. Examining sub-functions might pin-point precise mechanisms and enable researchers to develop a more nuanced understanding of the caregiving process. Future research should aim to clarify how specific caregiver executive functions support or constrain children's emerging capacities.

2.6. Summary.

This chapter provides a comprehensive review of caregiver involvement in dyadic play interactions, emphasising their critical role in shaping children's socio-emotional and cognitive development. It examines key areas including coding schemes for analysing caregiver-child interactions, caregiving behaviours during play, longitudinal changes in caregiving behaviours, and the influence of caregiver executive functions. By synthesising these perspectives, the chapter offers valuable insights into the dynamic interplay between caregivers and children, highlighting factors that promote optimal developmental outcomes.

The section on coding schemes emphasises their importance as tools for systematically analysing the quality and dimensions of caregiver-child interactions. Frameworks such as the EAS, MRO, and CIB are frequently used to capture aspects like sensitivity, scaffolding, and joint attention, which are pivotal for understanding developmental outcomes such as language acquisition and secure attachment. However, identifying a coding scheme that encompasses all behaviours of interest can be challenging. Many frameworks are designed to focus on specific aspects of interaction making it difficult to capture the full complexity of dyadic play. As a result, researchers often need to use multiple coding schemes or adapt existing ones, which can introduce inconsistencies or gaps in analysis. Moreover, the application of many coding schemes requires attending specialised training courses to ensure reliability and validity in coding. These courses, which often come at a significant financial cost, include intensive workshops or certifications, posing a barrier for researchers with limited resources. Even with training, coding is a highly time-consuming process, requiring extensive observation and detailed analysis, which

limits the feasibility of applying these schemes to large samples or longitudinal studies. These challenges highlight the need for more accessible and inclusive coding frameworks that can effectively capture the richness and variability of caregiver-child interactions.

Caregiving behaviours in dyadic interactions and their impact on child development emerge as a central theme. Sensitive and responsive caregiving fosters secure attachment, emotional regulation, and cognitive development, with evidence linking maternal responsiveness to early language milestones and adaptive learning beliefs. Scaffolding, or guided support, plays a crucial role in cognitive and executive function development, particularly in problem-solving and language acquisition. In contrast, intrusive caregiving, characterised by excessive control and disregard for child autonomy, has been associated with poorer self-regulation, reduced cognitive skills, and altered neural responses to social stimuli. These findings highlight the importance of adaptive and responsive caregiving practices in promoting positive developmental outcomes. Despite the wealth of findings, research gaps remain, particularly in comparing the distinct benefits of various play types.

Longitudinal studies explored in the chapter reveal how caregiving practices evolve alongside a child's developmental milestones. As children grow, caregiving shifts from physical care in infancy to fostering autonomy and emotional competencies during toddlerhood and preschool years. Key factors influencing these changes include maternal well-being, socioeconomic status, and social support. Research shows that responsive caregiving in early childhood, particularly in areas like language development and emotional regulation, has lasting effects on child outcomes. Interventions focusing on maternal mental health and support systems are crucial for enhancing caregiving and fostering positive child development.

Caregiver executive functions play a crucial role in shaping both caregiving behaviours and children's emerging executive functioning skills. Strong caregiver executive function supports emotional regulation, adaptability, and consistency in caregiving, with individual components, such as working memory, inhibitory control, and cognitive flexibility, each contributing uniquely to high-quality

caregiving. Emerging research also shows that caregiver executive function is associated with children's executive function from as early as toddlerhood, with contributions from both maternal and paternal executive function. Evidence from longitudinal and genetically informed studies suggests that these links are shaped by a combination of environmental and genetic factors, independent of general cognitive ability. However, most research to date has focused on overall executive function rather than specific sub-functions. Future work should investigate how distinct executive function components are transmitted across generations and how they influence caregiving behaviours, to better understand the mechanisms underlying child executive function development.

In summary, this chapter underscores the intricate dynamics of caregiver-child interactions during play and their profound implications for child development. While significant progress has been made in understanding these relationships, addressing research gaps by focusing on specific caregiver executive functions and diverse play contexts is essential. These advancements will enhance the field's capacity to support caregivers in promoting positive developmental outcomes. Brief overviews of the relevant background and literature are provided in upcoming experimental chapters to contextualise the specific topics discussed in each. These mini-introductions are intended to ensure clarity and coherence for the reader as each chapter addresses distinct aspects of the overall research.

Gaps in the research.

Across the developmental literature, there is growing recognition of the critical role caregivers play in shaping early cognitive outcomes. However, several key gaps remain that limit our understanding of the nuanced mechanisms through which caregiver characteristics and interactions influence early cognition. This thesis seeks to address these gaps through four experimental chapters, each targeting a specific underexplored dimension within this broader framework.

First, while much research has examined the caregiver-child dynamics in preschool and school-aged populations, fewer studies have focused on the infancy period - a time marked by rapid cognitive development. This lack of emphasis on infancy represents a significant gap, as early caregiver influences may have foundational effects on the developmental trajectory of cognitive skills. Moreover, existing studies frequently rely on broad assessments of caregiver executive function, often overlooking the distinct contributions of subcomponents such as inhibitory control. As such, Chapter 3 investigates the association between caregiver inhibitory control and infant visual cognition. This study is motivated by the need to unpack how specific caregiver cognitive traits, rather than general executive function abilities, may shape early visual attention and processing in infants.

Second, caregiver-infant interactions have long been established as central to infant development. However, there is limited research focusing on multiple interaction types within the same timepoint. Additionally, there is a lack of research connecting these dynamic social exchanges to specific cognitive systems, such as visual working memory. Chapter 4 addresses this gap by examining how the quality and nature of caregiver-infant interactions, in two distinct play interactions, relate to infant visual working memory, a foundational cognitive skill with implications for later learning and attention. This approach shifts focus from isolated behavioural outcomes to more specific cognitive mechanisms influenced by social experience.

Third, much of the existing research on caregiver-child interactions is cross-sectional, limiting insights into how these relationships evolve over time. Further,

most longitudinal research again focuses on a singular interaction type. Chapter 5 responds to this limitation by exploring caregiver-child behaviours during two distinct dyadic interactions across time, capturing the dynamic nature of these relationships. By employing a longitudinal design, this study aimed to identify stable patterns and developmental shifts in dyadic behaviour that may relate to cognitive outcomes.

Finally, while the role of caregiver interactions in shaping infant cognition has been well documented in naturalistic contexts using real-world objects, much less is known about how these interactions relate to experimental settings, where cognitive functions are typically assessed using standardised and often unrealistic stimuli. Chapter 6 examines how different types of visual stimuli impact toddler visual cognition and how these effects are associated with behaviours during dyadic interactions. This study bridges the gap between task-based assessments and naturalistic settings by testing how stimulus type and caregiver-child behaviours jointly influence cognitive outcomes.

Together, these four experimental chapters aim to address critical gaps in our understanding of the caregiver-child dyad by focusing on key early developmental stages, specific cognitive processes, longitudinal trajectories, and the interaction between ecologically-valid stimuli and social experience. In doing so, this thesis seeks to move beyond general associations and toward a more mechanistic and grounded account of how caregivers contribute to early cognitive development.

Chapter 3:

Experiment 1: The association between caregiver inhibitory control and infant visual cognition.

The following chapter was published in Infant Behavior and Development on January 3rd, 2024 (https://doi.org/10.1016/j.infbeh.2023.101921). A modified version of this paper with additional content is included here.

3.1. Introduction.

The first few years of life are associated with rapid and dynamic changes to executive functions, a set of cognitive skills used in daily life to select and monitor behaviours that facilitate the attainment of chosen goals (Friedman & Miyake, 2017; Zelazo et al., 2004). Of the executive function sub-functions, working memory, responsible for the temporary storage and manipulation of information, is associated with academic abilities (Blair & Razza, 2007; Gathercole et al., 2004), reading and mathematics abilities (Gathercole et al., 2006), global fluid intelligence (Fukuda et al., 2010; Shipstead et al., 2016), and social skills (Caporaso et al., 2019). There are several working memory systems; visual working memory is of particular importance because it is pervasively involved in daily life. It is used approximately 10,000 times a day to detect changes in the environment and compare precepts that cannot be viewed simultaneously (Vogel et al., 2001). Critically, this function is related to academic outcomes (Davidson, Shing, et al., 2023), household enrichment (Davidson, Caes, et al., 2023), birth status (Wijeakumar et al., 2023), health status (Spencer et al., 2023), and socioeconomic status (Wijeakumar et al., 2019). Importantly, this system is measurable in pre-verbal infants as early as four months of age (Ross-Sheehy et al., 2003). Thus, it is important to understand how this system emerges and develops in the first critical years of life.

3.1.1. The development of visual working memory in infancy.

The development of visual working memory in infancy is a gradual process, as infants grow and their cognitive abilities develop, their capacity for storing visual information increases. This process plays a pivotal role in the way infants process, learn, and respond to their visual world (Buss et al., 2018). Previous research has used preferential-looking paradigms to study how infants hold items in visual working memory across the first year of life (Ross-Sheehy et al., 2003). These paradigms have shown that infants display an increase in the number of items they can retain in visual working memory across the first year of life, referred to as capacity. In these paradigms, infants are presented with two simultaneous flashing displays of coloured squares wherein, on one side, the colours of the squares remained constant between flashes and on the other side, one random square changed colour after every flash. Ross-Sheehy et al. (2003) examined whether infants preferred and stayed fixated on the changing side as visual working memory load increased from one to three items. The authors reported that 4- and 6.5-month-olds could only detect changes at a load of one item, whereas 10- and 13-month-old infants could detect changes up to a load of three items. Oakes et al. (2011) examined the development of visual working memory for location by presenting 6- to 12-month-olds with side-by-side flashing arrays of coloured circles. On the changing side, one or more circles changed location after each flash. Here, 6.5-month-old infants only showed evidence of visual working memory for a single location whereas 8- to 12.5-month-olds could store multiple locations, up to three items. Further, Kwon et al. (2014) demonstrated similar findings in 6- to 8-month-olds in response to complex objects. They reported that 6-month-olds showed a robust preference for one complex item, whereas 8-month-olds exhibited a preference for arrays featuring two complex items. These behavioural studies have provided evidence that infants' visual working memory for feature changes (e.g., colour and location changes) emerge by 6-months and that visual working memory capacity for these changes steadily increase across the first year of life.

Developmental changes in behavioural performance are accompanied by similar changes in brain function. Previous research has used fNIRS to study brain function in infancy and toddlerhood. Baird and colleagues (2002) employed fNIRS

to examine infants' frontal lobe activation during object permanence - a cognitive process that requires the ability to pay attention and maintain the object in working memory (Ryu et al., 2017). They tested infants monthly from 5 months to 12 months old. Infants recruited the DLPFC when holding objects in visual working memory. The DLPFC is involved in maintaining and manipulating information (Barbey et al., 2013), retrieval (Hayama & Rugg, 2009), and facilitating task switching (Cole et al., 2010). Overall, it serves as a crucial hub for the organisation and control of working memory functions (Baird et al., 2002; Buss et al., 2014). Recently, Delgado Reyes et al. (2020) conducted a cross-sectional study to investigate the functional brain networks that underlie visual working memory in early development. They examined 4-month-olds, 1-year-olds, and 2-year-olds' performance on the preferential looking task to measure localised, task-specific activation of the visual working memory network. They reported localised task-specific activation within the fronto-parietal network. Specifically, they found localised task-related activation in the DLPFC and right inferior frontal gyrus (rIFG), irrespective of age or behaviour. Additionally, load-dependent modulation was found in the left intraparietal sulcus (lIPS), with decreasing activation with increasing load (medium to high loads). They also reported age-dependent modulation in the lIPS, left ventral occipital gyrus (lVOC) and rDLPFC. Specifically, there was a decrease in lVOC and rDLPFC activation and increase in lIPS activation, with age. Thus, by investigating the brain alongside behaviour, one can better understand mechanistic processes and identify individual differences in visual working memory processing. Additionally, as this period is critical, it is important to consider factors that may influence early neurocognitive development.

3.1.2. The caregiver's role in early infant development.

Caregivers play a key role in regulating these important cognitive systems in infancy. During the first few years of life, children are dependent on their caregivers for stimulation, nurturance, and regulation (Sameroff, 2010). Positive caregiver-child interactions support early attention development (Altenburger & Schoppe-Sullivan, 2021; Bernier et al., 2010; Cheng et al., 2018; Ribner et al., 2022). Further, emerging evidence suggests that caregivers' executive functions are closely linked to the development of these same skills in their children. For instance, Kao et al. (2018) examined parent and child executive functions using parallel lab-based tasks, when

children were aged 3.5 to 4.5 years. They reported a significant positive association between parent and child executive function performance, suggesting that children whose caregivers demonstrated stronger executive functioning also performed better themselves. Cuevas and colleagues (2014) examined how maternal executive function and maternal caregiving behaviours influenced child executive function. They reported that both maternal executive function and negative caregiving behaviours accounted for unique variance in child executive function at 36 months of age (Cuevas, Deater-Deckard, et al., 2014). Relatedly, Ribner and colleagues (2022) investigated to what extent maternal and paternal executive function predicted emergent executive function in toddlerhood. Each caregiver completed executive function assessments while the children completed an executive function battery at 14 and 24 months. They found that maternal executive function predicted child working memory and shifting at 24 months while paternal executive function only predicted child shifting at 24 months. Taken together, these findings indicate that caregiver executive function is a key contributor to early development, likely providing a cognitive foundation upon which children's own regulatory capacities emerge and grow.

3.1.3. The current study.

Some gaps in afore-mentioned research remain. First, it is unclear whether and how caregiver executive functions impact child visual working memory as early as infancy. Further, it is unknown whether any such impact is observable in both behaviour and brain function. Second, most prior research has focused on composite executive functioning scores in caregivers, rather than examining individual executive function sub-functions in relation to child outcomes. Composite scores are useful as they provide a broad understanding of how caregiver and child cognitive systems relate. However, they may obscure more nuanced relationships between specific executive function components. For instance, different executive function sub-functions, such as inhibitory control, cognitive flexibility, and working memory, may interact in distinct ways depending on the specific demands of a task or the child’s developmental stage. Examining these sub-functions separately could provide a more precise understanding of how caregiver executive function supports child visual working memory development. Importantly, from the perspective of developing caregiver-based interventions, it is more challenging to introduce

behavioural change based on global composite executive function scores compared to specific executive function sub-functions. For example, caregiver inhibitory control may be particularly relevant in early caregiver-child interactions. Inhibitory control, the ability to suppress automatic or impulsive responses to enable goal-directed behaviour (Diamond, 2013; Fiske & Holmboe, 2019), is crucial for effective caregiving. It allows caregivers to regulate their emotional responses, maintain patience, and provide structured guidance during play and learning activities (Gonzalez, 2015). Given its role in social interactions, inhibitory control is a strong candidate for understanding how caregiver executive function influences child cognitive development.

The current study aims to address some of these gaps by examining whether there is an association between caregiver inhibitory control and infant visual working memory – at the level of behavioural performance and brain function. To this end, inhibitory control was assessed in caregivers using a Go-NoGo task, and visual working memory was assessed in infants using the preferential looking task. fNIRS was used to record brain function from both caregivers and their infants as they engaged in their respective tasks. Concretely, the study posed three research questions. The first question inquired what brain regions were engaged during inhibitory control in caregivers, and how engagement in these regions varied with individual differences in regulating inhibitory control. Previous work has shown that the lIFG (Swick et al., 2008) and right middle frontal gyrus (rMFG) (Swick et al., 2011) are associated with successful inhibition of responses. Here, caregivers were expected to show increased activation in these regions alongside correct responses within the NoGo condition, i.e. when they have successfully inhibited their response. The second research question investigated whether better caregiver inhibitory control was associated with better visual working memory behaviour in their infants. Given previous associations between caregivers and toddlers, with caregiver executive function predicting child executive function at 24-months (Ribner et al., 2022), it was predicted that better caregiver inhibitory control would be directly linked to better infant visual working memory behaviour. The third research question investigated whether caregiver inhibitory control was linked to visual working memory-related brain function in infants. Previous work has shown that infant visual working memory behavioural performance was associated with activation in the left-

lateralised parietal cortex (Delgado Reyes et al., 2020; Wijeakumar et al., 2023). Therefore, it was predicted that better caregiver inhibitory control would be associated with greater visual working memory-related left-lateralised parietal activation in infants.

3.2. Methods.

3.2.1. Participants.

Families with infants between 6- to 10-months of age were recruited through social media (e.g., Instagram, Facebook), liaison with organisations (e.g., Banana Moon Nursery, Toddler's University), and public engagement events (e.g., Mum2Mum Markets, Buggy Babes Derby). Interested families contacted the research team and were screened to ensure they met the inclusion criteria. These criteria required that infants had normal or corrected-to-normal vision, a normal delivery term (37 – 42 weeks), no exposure to drug or alcohol use during pregnancy, no family history of mental illness, no neurological conditions, and had English as one of their primary languages. After confirmation, caregivers and infants were invited to visit the Infant and Toddler Lab in the School of Psychology at the University of Nottingham to take part in the study. Informed consent was obtained from caregivers prior to the commencement of the study. Caregivers gave consent for themselves and their infants. Ethical approval was granted by the University of Nottingham School of Psychology Ethics Committee (Approval Reference: F1415).

Prior to the commencement of the project, power calculations were performed with effect size of 0.15 (based on results from a one-factor Analysis of Variance (ANOVA) examining the effect of load on looking measures in (Delgado Reyes et al., 2020)), alpha = 0.05 and power = 0.80 (F-tests for linear multiple regression using the A priori method for four predictors). These calculations revealed that 85 families were required to participate in the study. The sample size was also in line with the recommendations for infant studies (Oakes, 2017).

A total of one-hundred and twelve families expressed interest in the study. Out of this sample, 4 families had infants who were not in the 6- to 10-month age-range, and a further 17 families withdrew from the study. Thus, a total of 91 caregivers (90 females, 1 non-binary, Mage = 33.5 years, SD = 4.5) and 91 infants

(46 females, Mage = 251.3 days, SD = 34.9) were recruited into the study. Data from 3 caregivers and their infants were excluded from analyses due to the presence of familial colour-blindness. Data from a further 2 infants were excluded due to an inconsistent number of experimental runs compared to the other infants. The final sample consisted of 88 caregivers (87 females, 1 non-binary, Mage = 33.4 years, SD = 4.4) and 86 infants (44 females, Mage = 250.6 days, SD = 35.8). Other demographic and socioeconomic status information is provided in Table 3.1. More details of sample sizes following other analysis criteria are specified in relevant sections.

Table 3.1. Socioeconomic and demographic information was collected via questionnaire shortly after the family visited the research facility. In some cases, the questionnaire was not filled out, as indicated by N in each case.

Measure	**N**	**Mean**	**SD**
Infant age (days)	86	250.6	35.8
Primary caregiver age (years)	88	33.4	4.4
Primary caregiver education (years)	78	16.1	2.6
Secondary caregiver education (years)	76	13.9	4.3
Primary caregiver income	70	£ 28,793	£ 12,372
Secondary caregiver income	49	£ 31,625	£ 6,101
Primary Caregiver's Ethnicity	**N**	**%**	
Asian	5	5.7	
Mixed	4	4.5	
Arab	1	1.1	
White British	67	76.1	
Other White	1	1.1	
Did not answer	10	11.4	

3.2.2. Caregiver Go-NoGo task.

Inhibitory control was assessed in the caregiver using a Go-NoGo task - see Figure 3.1(c). The task was created and run using PsychoPy v2021.2.3. Caregivers were asked to press a button when they saw a 'Go' stimulus and withhold their response when they saw a 'NoGo' stimulus. Caregivers completed practice and

experimental trials. In practice trials, two coloured stimuli were associated with the 'Go' response and a further two, coloured stimuli were associated with the 'NoGo' response. The caregivers completed four practice trials. If the caregivers understood the rules and successfully completed the practice trials, the experimental run ensued. In the experimental run, a set of four colours were associated with the Go response and an additional set of four colours with the NoGo response (the sets included the colours previously used for the practice trials along with an additional two colours for each type of response). Each trial started with the presentation of the fixation cross for 2500 ms, followed by the stimulus presentation for 1500 ms. Caregivers were instructed to respond as quickly as possible. If a response was not entered (i.e., within 3000 ms of stimulus presentation), the task would automatically move on to the next trial. The inter-trial interval was 1000 ms (50% of trials), 2500 ms (25%), or 3500 ms (25%). Each stimulus was displayed in the centre of the screen. Stimuli were coloured shapes that were all the same shape but varied in colour. The colours were equally distributed in CIELAB 1976 colour space, a perceptually uniform colour space and colour appearance model developed by the Commission Internationale de I'E`clairage. The shape was chosen from Drucker and Aguirre (2009). The colours were selected from a set of eight colours (RGB values: 66 129 179 (blue); 52 138 135 (teal); 111 136 81 (green); 166 123 41 (yellow); 217 99 48 (orange); 245 70 89 (red); 231 73 142 (pink); 170 102 183 (purple)). The experimental run consisted of 100 trials (75 Go trials and 25 NoGo trials). The task took around 10 minutes to complete.

3.2.3. Infant preferential looking task.

Infant visual working memory was assessed using an adapted version of the preferential looking task (Ross-Sheehy et al., 2003) - see Figure 3.1(a - b). The task was created and run using PsychoPy v2021.2.3. This task featured two flashing side-by-side square displays of coloured shapes. On one of the sides (the 'unchanging' side), the colours were always the same and on the other side (the 'changing' side), one random shape changed colour after each flash. The colours were selected from a set of 16 colours (RGB values: 0 0 0 (black); 255 255 255 (white); 255 0 0 (red); 0 255 0 (lime green); 0 0 255 (dark blue); 255 255 0 (yellow); 0 255 255 (light blue); 255 0 255 (pink); 128 0 0 (maroon); 128 128 0 (khaki green); 0 128 0 (green); 128 0 128 (purple); 0 128 128 (teal); 0 0 128 (ocean blue); 255 165 0 (orange); 222 184

135 (nude)). In a trial, the colours of the shapes differed from each other, but colours could be repeated between the displays (i.e., the same colour could appear on both displays). The positions of the shapes on each display were randomly selected from a 3-by-3 grid of possible positions. Each trial started with a dynamic audio-visual attentional cue. This cue was a rotating animated star with a smiley face accompanied with music. The attentional cue remained on the screen until the infant looked at the TV. Following this, the flashing displays were presented. Each trial consisted of alternate presentations of a flashing array and a blank grey screen (for a total of 14 flashes lasting 10.25 s). An inter-trial interval of 5000 ms was presented after each trial. Visual working memory load was manipulated across 1 (low load), 2 (medium load), or 3 (high load) coloured shapes. Each run consisted of 18 trials with 6 trials each (3 trials with the changing display on the left side, 3 trials with the changing display on the right side) at the low, medium, and high loads. Each run lasted approximately 5 minutes. Between 1 and 6 runs were collected, depending on the level of engagement across trials as not all infants attended to all trials of the runs (3.17 ± 1.29 runs).

One video camera was used to record the TV screen and another video camera was used to record the infants' face. Real-time recordings were presented on a laptop on the experimenter side of the room using Bandicam (https://www.bandicam.com/) and Movavi programs (https://www.movavi.com/). These recordings were presented in real-time to the experimenter to gauge infant engagement and proceed to further trials.

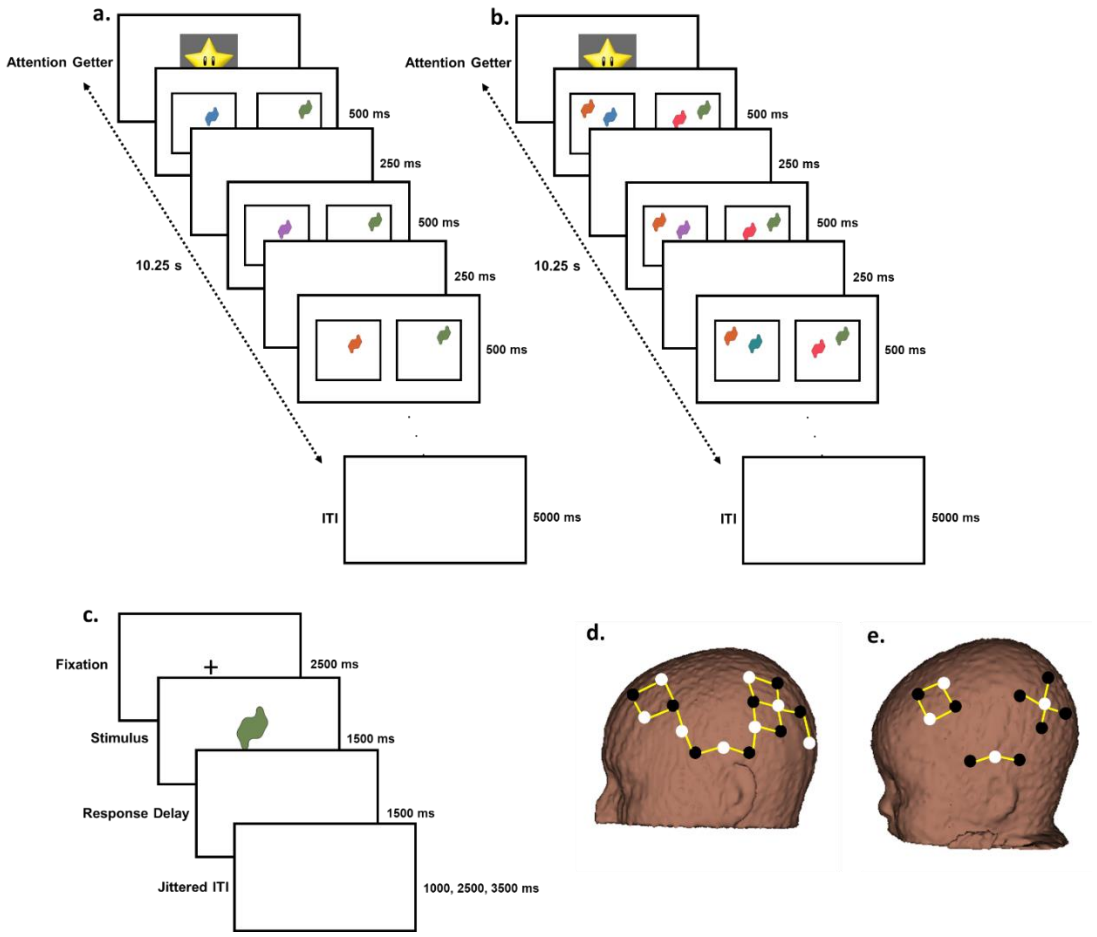


Figure 3.1. (a) Low load trial from the infant preferential looking task. Changing side showed on the left. (b) Medium load trial from the infant preferential looking task. Changing side showed on the left. (c) Go trial of the GNG task. (d) Caregiver probe geometry. (e) Infant probe geometry. Sources are shown in black, detectors shown in white, and channel connections show in yellow (Both caregiver and infant probe geometries covered the whole head but only left side shown in figure). Note that the backgrounds of experimental tasks were grey, however for improved image clarity, the figures show a white background. For clarity, it is best to view all figures in the original colour version.

3.2.4. fNIRS data acquisition.

A NIRScout device, containing 16 sources and 16 detectors, was used to measure brain activation during the caregiver and infant experimental tasks. Fibre optic cables transported infrared light from the machine to a tailored cap. Multiple cap sizes were used to accommodate the varying head sizes of the caregivers (54 cm, 56 cm, and 58 cm) and infants (42 cm, 44 cm, 46 cm, 48 cm, 50 cm, 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). Data was collected at 7.81 Hz using wavelengths of 760 nm and 850 nm. The caregiver probe geometry consisted of 36 channels - see Figure 3.1(d). The infant probe geometry

consisted of 20 channels - Figure 3.1(e). The probe geometries covered the entire head for both caregivers and infants. Fewer channels were present in the infant geometry to prevent discomfort for the infant from wearing a heavy cap. However, the 20 channels overlapped with the caregiver's probe geometry. The probe geometries were adapted using the 10 - 20 system of electrode placement (Wijeakumar et al., 2015).

3.2.5. Procedure.

Two researchers were present during each session. After the family was welcomed and escorted to the lab, the researchers explained the full procedure to the caregiver and obtained informed consent from the caregiver and assent from the infant. The head circumference of the infant was measured so that the researchers could select the appropriately sized fNIRS cap. The infant was placed into a highchair or sat on their caregiver's lap 100 cm from a TV screen which had a cartoon playing while the cap was fitted on their head. Following set-up, the researchers administered the preferential looking task. One researcher was responsible for administering the task and monitoring the video set-up and the other researcher monitored the quality of fNIRS signals. Cartoons were played during the attentional cue if the infant appeared to disengage from the TV. Breaks were also provided as per the convenience of the infant and caregiver. Once the preferential looking task was completed, the caregiver's head circumference was measured, and the appropriate fNIRS cap size was selected. Once the caregiver's cap was fitted, the Go-NoGo task was administered. A practice run was set up before the experiment was run. Families were renumerated with £10 for each visit to the lab.

3.2.6. Behavioural analyses.

Caregiver Go-NoGo behaviour. From the caregivers' responses to the task, four conditions were generated: correct responses on Go trials (Go Correct), incorrect responses on Go trials (Go Incorrect), correct responses on NoGo trials (NoGo Correct), and incorrect responses on NoGo trials (NoGo Incorrect). Reaction time (RT) was also recorded for each Go correct response. Go Correct, Go Incorrect, NoGo Correct, and NoGo Incorrect rates were calculated using the following formula:

$$\text{rate} = \frac{n}{t}$$

where n refers to the sum of the number of trials in a particular condition (i.e., number of Go Correct trials) and t refers to the total number of trials of a trial type (i.e., total number of Go trials). For example, Go Correct rate was calculated as the number of Go Correct trials divided by total number of Go trials. Go Correct rate and NoGo Correct rate were then averaged to create an overall Correct rate. An inverse efficiency score was calculated for each caregiver by dividing the average RT on correct Go trials by the overall Correct rate to provide an index of processing efficiency while considering possible speed-accuracy trade-offs. The efficiency score was then multiplied by -1 for the purpose of interpretability such that a less negative score indicated better performance on the task, i.e. better ability to regulate inhibitory control. Low-efficiency caregivers showed more negative values and high-efficiency caregivers showed lesser negative values. This approach was chosen over relying solely on average accuracy or reaction times, as prior research has demonstrated that efficiency scores can yield more nuanced and informative insights (e.g., Cascio et al., 2022; Tomlinson et al., 2020; Hirose et al., 2012).

The efficiency score was screened for outliers. Data-points were considered as outliers if they fell outside of $\pm$ 3 SDs from the mean. One data-point was identified as an outlier and excluded from further analyses. 87 caregivers contributed data for further analyses.

Infant visual working memory behaviour. Video recordings of the experimental task were coded using DataVyu (https://datavyu.org/). First, each trial was coded for load (low, medium, or high) and side of change (left or right). Then, this information was 'hidden' from the coder's view, and video recordings of the infant's face was coded. Looking data was manually coded by assigning each look to a 'left' or 'right' category based on whether the infant was looking to the left or right side of the screen. Looks were not coded if the infant looked away from the screen or looked at the centre of the screen. Three coders (AT, CD, GA) were rigorously trained on how to accurately code trials and looks for infant 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 three coders manually coded 23% of the data from infants. Kappa values from 0.81 to 0.99 indicate near perfect agreement. The mean Kappa was 0.94. From this data, four measures of visual cognition were estimated for the infant.

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. Mean look duration (MLD) for each trial was calculated as the total amount of time spent looking at the left and right displays divided by the total number of looks. 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. Change preference (CP) score was calculated for each trial. CP score was calculated as the time spent looking to the changing side divided by the total amount of time spent looking at both displays. To consider variability in the number of trials per load across infants, a weighted average score was calculated for each measure at each load for each infant.

All behavioural data were screened for outliers. Data-points were considered outliers if they fell outside of ± 3 SDs from the mean. Data-points from 7 infants were identified as outliers based on looking behaviours and removed from the dataset, 1 infant for SR at high load, 1 infant for MLD at low load, 2 infants for MLD at medium load, and 3 infants for CP at medium load. Thus, for TLD, 86 infants contributed data at all loads. For SR, 86 infants contributed data at the low load, 86 at the medium load, and 85 at the high load. For MLD, 85 infants contributed at the low load, 84 at the medium load, and 86 at the high load. For CP, 86 infants contributed data at the low load, 83 at the medium load, and 86 at the high load.

3.2.7. fNIRS brain analyses.

fNIRS Pre-processing. fNIRS pre-processing was completed 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). For caregiver data, 0.2% of channels were pruned. For infant data, 3.15% of channels were pruned. Intensity was converted to optical density units. Principal components analyses were conducted to identify and remove motion artifacts using hmrMotionCorrectPCArecurse (tMotion = 1, tMask = 1, STDEVthresh = 50, AMPthresh = 0.5, nSV = 0.97, maxIter = 5). Following this, the data were scanned again for motion artifacts using hmrMotionArtifactByChannel (tMotion = 1, tMask = 1, STDEVthresh = 50, AMPthresh = 0.5). Stimulus markers within specified

windows of uncorrected artifacts were removed using enStimRejection (For caregiver fNIRS data: tRange = -1 to 7; For infant fNIRS data: tRange = -1 to 18). These windows were chosen to capture the stimulus presentation, response, and intertrial interval for each trial for the two tasks. The data were band-pass filtered using hmrBandpassFilt (hpf = 0.016, lpf = 0.5).

Following pre-processing, 87 caregivers contributed fNIRS data for each condition. For this group, 0.2% of trials were lost. 85 infants contributed fNIRS data for the low load, 82 infants for medium load, and 85 infants for high load. Further, for this group, 7.55% of trials were lost at low load, 7.83% of trials were lost at medium load, and 6.96% of trials were lost at high load. Pre-processed data was used in further analyses described below.

fNIRS Image Reconstruction. The methodological pipeline used in the current study has been described in detail elsewhere (Forbes et al., 2021). The same pipeline can be used to analyse caregiver and infant data. Further, the pipeline uses existing fMRI tools to threshold reconstructed fNIRS image data, unlike conventional fNIRS studies that do not typically correct for the number of channels used. Here, each of the steps are briefly outlined. First, scalp landmarks and probe geometry were digitised using a Polhemus Patriot Motion Tracking System on an adult wearing a 58 cm size cap and a child wearing a 48 cm size cap. Next, these points were projected onto age-specific templates. Age-specific templates were obtained from a Neurodevelopmental database to represent approximate changes in head shape and head size across caregiver and infant age-groups (Richards et al., 2016). The chosen templates represented the following age-groups, for caregivers: 20-24 years, 25-29 years, 30-34 years, 35-39 years, 40-44 years, 45-49 years, and for infants: 6-months, 7.5-months, 9-months. The templates were segmented into four tissue types (scalp, cerebro-spinal fluid, grey matter, and white matter). Sensitivity profiles were generated for each channel and head volume by running Monte Carlo simulations with 1 million photons using AtlasViewerGUI in HOMER2. The head volumes and sensitivity profiles were then converted to NIFTI format. Pre-processed optical density time-series data (from the section above) were integrated with these volumetric sensitivity profiles using a novel image reconstruction technique (Eggebrecht et al., 2014; Forbes et al., 2021) to generate 3D images of time-series

data for each voxel, condition, chromophore, and participant. These reconstructed images were used for running linear mixed effects models described below.

Linear mixed effects modelling of individual fNIRS Data.

Caregiver fNIRS data. A linear mixed effects model with 4 regressors (2 trial conditions [Go and NoGo] and 2 accuracy conditions [correct and incorrect]) was run for each voxel, chromophore, and caregiver. A hemodynamic response function derived from diffuse optical tomography was used for HbO and HbR data (Eggebrecht et al., 2014). Each trial was modelled with a 1.5 s boxcar to capture the stimulus presentation and response time. This process generated beta coefficient maps for each of the 4 conditions. These beta coefficient maps were registered to the MNI space and used in group analyses described below.

Infant fNIRS data. A linear mixed effects model with 3 regressors (low, medium, and high load) was run for each voxel, chromophore, and infant. Each trial was modelled with a 10 s boxcar. To account for the variability in the number of trials per load across infants, a weighted average was computed for each load and infant. These resulting images were registered to the MNI space and used in group analyses described below.

Group Analyses of fNIRS Data.

Caregiver fNIRS data. A caregiver group mask was calculated by masking each age-specific beta map (representative of each age-specific atlas), summing these maps, and extracting voxels that contained data from 70% of the caregivers. Voxels from this mask were included for linear mixed effects modelling. The linear mixed effects model was run on the beta coefficient maps using the 3dLME function in AFNI (Chen et al., 2013), with fixed within-subjects factors of condition (Go and NoGo) and chromophore (HbO and HbR), and caregiver efficiency as a quantitative variable. Models only included beta coefficient maps for correct trials to account for successful inhibitory control. The model yielded an F-statistic image for main effects of, and interactions between caregiver efficiency, condition, and chromophore. Only effects that showed an interaction with chromophore were examined. Chromophore

was included to account for how HbO and HbR interacts with the other factors of interest. Note that typically, activation is represented by increasing HbO and decreasing HbR concentrations and suppression is represented by decreasing HbO and increasing HbR concentrations. Thus, the effects of interest were main effect of chromophore, interaction between condition and chromophore, interaction between caregiver efficiency and chromophore, and interaction between condition, caregiver efficiency and chromophore. Family-wise corrections were applied to these F-statistic images using 3dClustSim and 3dClusterize (voxel-wise p value of 0.01 and cluster size of 122 voxels). Beta values were averaged across voxels of each cluster and follow-up tests were ran in RStudio (RStudio Team, 2020). Note that MNI labels were extracted from AFNI for each brain region, all MNI coordinates have been featured within text and within figure legends (Forbes et al., 2021).

Infant fNIRS data. An infant group mask was calculated by masking each age-specific beta map (representative of each age-specific atlas), summing these maps, and extracting voxels that contained data from 70% of the infants. This group mask was used in the linear mixed effects model on the infant data. The model was run with fixed within-subjects factors of load (low, medium, and high) and chromophore (HbO and HbR), and infant CP score and caregiver efficiency as quantitative variables. Caregiver efficiency was included as a quantitative variable to determine if it had any impact on infant brain function. The model yielded an F-statistic image each for main effects of, and interactions between, load, chromophore, infant CP score, and caregiver efficiency. Only effects that showed an interaction with chromophore were examined. Chromophore was included to account for how HbO and HbR interacts with the other factors of interest. Thus, the effects of interest were main effect of chromophore, interaction between infant CP score and chromophore, interaction between load and chromophore, interaction between caregiver efficiency and chromophore, interaction between infant CP score, load, and chromophore, interaction between caregiver efficiency, load, and chromophore, interaction between caregiver efficiency, infant CP score, and chromophore, and interaction between caregiver efficiency, load, infant CP score, and chromophore. Family-wise corrections were applied to these F-statistic images (voxel-wise p value of 0.01 and cluster size of 213 voxels). Beta values were averaged across voxels of each cluster and follow-up tests were ran in RStudio (RStudio Team, 2020). Note that MNI labels

were extracted from AFNI for each brain region, all MNI coordinates have been featured within text and within figure legends (Forbes et al., 2021).

3.2.8. Statistical analyses.

Statistical analyses were carried out using RStudio (RStudio Team, 2020). To investigate how TLD, MLD, SR, and CP scores changed with increasing load, one-factor ANCOVAs were run, while controlling for infant age in days. To examine relationships between caregiver efficiency and infant preferential looking measures, regression models were run with infant age as a covariate. To examine brain function in caregivers and infants, separate linear mixed effects models were run. Note that this chapter has previously been published as a paper in *Infant Behavior and Development.* However, the analyses featured in the paper did not control for infant age. Therefore, for the purpose of the chapter and to remain consistent with the following chapters, the analyses here have been rerun to include infant age as a covariate. Please refer to Appendix A for the published results excluding infant age as a covariate.

3.3. Results.

3.3.1. Infant visual working memory behaviour.

One-factor ANCOVAs were run to investigate how TLD, MLD, SR, and CP scores changed with increasing load. To do this, ANCOVAs were run with load (low, medium, and high) as an independent variable, and infant age in days as a covariate, separately for each looking measure.

The one-factor ANCOVAs on infant TLD and SR scores revealed no significant effect of load.

The ANCOVA on infant MLD scores revealed a significant main effect of load ($F(2,251) = 3.716$, $p = .026$, $\eta 2 = 0.03$; low load = 1634.15 ± 625.46; medium load = 1819.41 ± 667.19; high load = 1912.09 ± 776.49), after controlling for infant age – see Figure 3.2a. Specifically, MLD score at the low load was significantly lower than MLD score at the high load ($p = .024$). MLD score at the low load did not differ from MLD score at the medium load, and medium load did not differ from high load.

Finally, the ANCOVA on infant CP scores revealed a main effect of load ($F(2,251) = 13.683$, $p < .001$, $\eta 2 = 0.10$; low load = 0.59 ± 0.08; medium load = 0.55 ± 0.07; high load = 0.54 ± 0.07), after controlling for infant age – see Figure 3.2b.

Specifically, CP score at the low load was significantly greater than CP score at the medium ($p < .001$) and high loads ($p < .001$). CP score at the medium load did not differ from CP score at the high load.

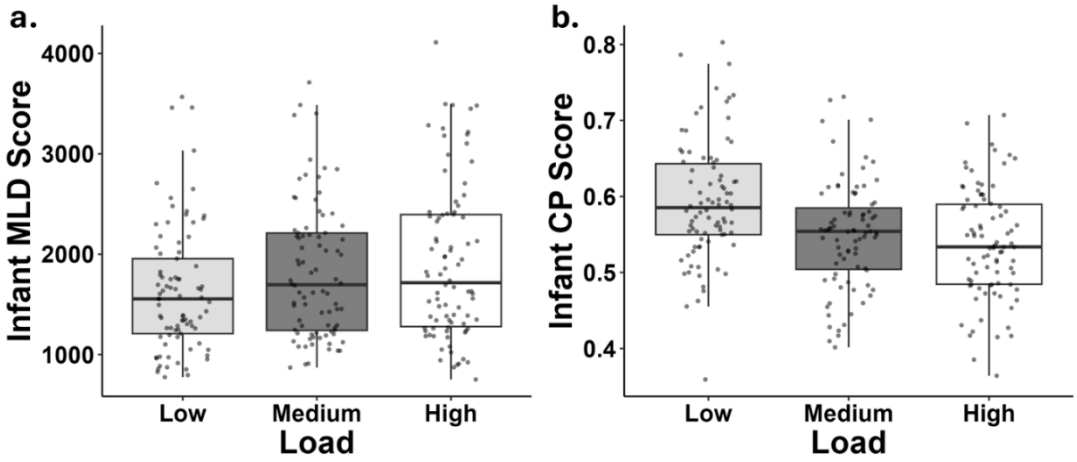


Figure 3.2. a) Main effect of load on infant MLD scores. b) Main effect of load on infant CP scores. Each box represents the interquartile range (IQR), with the horizontal line indicating the median. Whiskers extend to 1.5 times the IQR, and data points outside this range are plotted as outliers.

3.3.2. Association between caregiver efficiency and infant visual working memory behaviour.

Regression models were used to investigate whether caregiver efficiency of inhibitory control and load were associated with infant preferential looking measures, while controlling for infant age. Neither the main effect of caregiver efficiency nor the interaction between caregiver efficiency and load were significantly associated with infant CP scores, SR scores, TLD scores, or MLD scores.

Only infant CP scores were taken forward for the brain analyses, as this measure is the most indicative of visual working memory performance. CP score captures the extent to which infants preferentially attend to novel over familiar stimuli and is a widely used indicator of capacity in infancy research (e.g., Ross-Sheehy et al., 2003; Oakes et al., 2011).

3.3.3. Caregiver brain function.

To examine brain regions associated with caregiver inhibitory control, a linear mixed effects model with 4 regressors (2 trial conditions [Go and NoGo] and 2 accuracy conditions [correct and incorrect]) was run for each voxel, chromophore, and caregiver.

The linear mixed effects model of the caregivers' brain data revealed only a significant main effect of chromophore in four clusters – lIFG [MNI coordinates: 58.7 -7.9 16.4, 430 voxels, $F(1,255) = 10.76$, $p < 0.01$], right angular gyrus (rAG) [MNI coordinates: -57.3 56.5 36.4, 186 voxels, $F(1,255) = 20.80$, $p < 0.01$], rMFG [MNI coordinates: -43.9 -26.9 39.9, 180 voxels, $F(1,255) = 7.93$, $p < 0.01$] and left inferior parietal lobule (lIPL) [MNI coordinates: 57.4 54.0 39.2, 130 voxels, $F(1,255) = 12.88$, $p < 0.01$] – see Table 3.2 and Figure 3.3(a-d).

Follow-up tests, while controlling for infant age, revealed that HbO concentration was greater than HbR concentration in lIFG (lIFG: $p < .001$, $\eta_p^2 = .06$) and rMFG (rMFG: $p = .033$, $\eta_p^2 = .03$). In contrast, in rAG and lIPL, HbO concentration was lesser than HbR concentration (rAG: $p < .001$, $\eta_p^2 = .07$; lIPL: $p = .001$, $\eta_p^2 = .06$). Therefore, engaging in the inhibitory control task resulted in lIFG and rMFG activation, and rAG and lIPL suppression. Note that these caregiver brain results remained unchanged when caregiver age was included as a covariate.

*Table 3.2. Cluster information for significant effects in the caregiver brain model. * Indicates effects that yielded significant results after follow-up tests.*

Significant effects	**Cluster**	**Size (mm^3)**	**MNI coordinates**		
			Centre of Mass		
			x	**y**	**z**
Chromophore	Left inferior frontal gyrus (lIFG)*	430	58.7	-7.9	16.4
	Right angular gyrus (rAG)*	186	-57.3	56.5	36.4
	Right middle frontal gyrus (rMFG)*	180	-43.9	-26.9	39.9
	Left inferior parietal lobule (lIPL)*	130	57.4	54	39.2

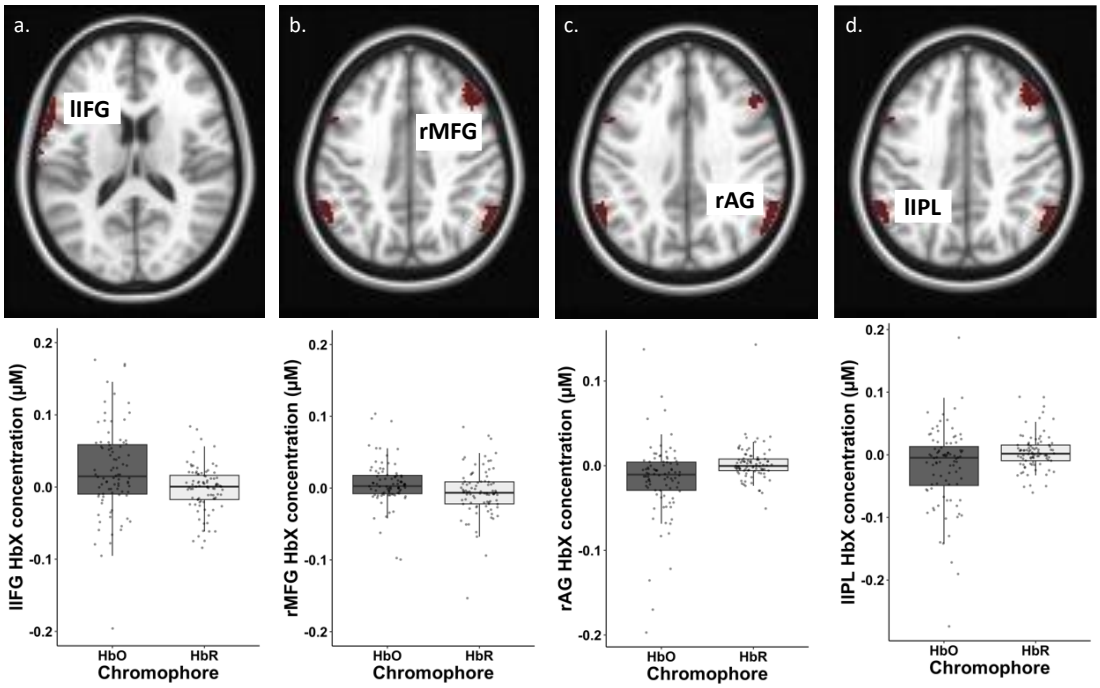


Figure 3.3. Brain images and boxplots for significant main effect of chromophore in (a) left inferior frontal gyrus (lIFG) - [MNI coordinates: 58.7 -7.9 16.4], (b) right middle frontal gyrus (rMFG) - [MNI coordinates: -43.9 -26.9 39.9], (c) right angular gyrus (rAG) - [MNI coordinates: -57.3 56.5 36.4], and (d) left inferior parietal lobule (lIPL) - [MNI coordinates: 57.4 54.0 39.2]. HbO concentration is shown in black and HbR concentration is shown in grey. Each box represents the IQR, with the horizontal line indicating the median. Whiskers extend to 1.5 times the IQR, and data points outside this range are plotted as outliers.

3.3.4. Infant brain function

To examine brain regions associated with infant visual working memory brain function, a linear mixed effects model with 3 regressors (low, medium, and high load) was run for each voxel, chromophore, and infant. The linear mixed effects model of the infants' brain data revealed significant main effects and interactions (Table 3.3). All follow-up analyses were run with infant age in days as a covariate.

A main effect of chromophore was observed in lIFG [MNI coordinates: 40.6 -37 26.8, 774 voxels, $F(1,397) = 16.94$, $p < 0.01$], right superior parietal lobule (rSPL) [MNI coordinates: -23.9 63.9 60.4, 360 voxels, $F(1,397) = 25.20$, $p < 0.01$] and left middle temporal gyrus (lMTG) [MNI coordinates: 62.2 33.6 8.2, 333 voxels, $F(1,397) = 17.50$, $p < 0.01$] - see Figure 3.4(a – c). Follow-up analyses, while controlling for infant age, found that in lIFG and rSPL, HbO concentration was greater than HbR concentration (lIFG: $p = .01$, $\eta_p^2 = .04$; rSPL: $p < 0.001$, $\eta_p^2 = .08$). There were no

significant differences between HbO and HbR for lMTG. Therefore, infants showed lIFG and rSPL activation during the preferential looking task.

A significant two-way interaction between infant CP score and chromophore was observed in a cluster in the lMFG [MNI coordinates: 37.8 -41.1 24.9, 318 voxels, $F(1,397) = 9.52$, $p < 0.01$] – see Figure 3.4(d). Follow-up tests were run for each chromophore separately, while controlling for infant age. Here, greater infant CP score was associated with greater HbO concentration ($p = .034$ $\eta_p^2 = .05$), but not HbR concentration in lMFG. Therefore, infants with better visual working memory performance, showed greater lMFG activation.

*Table 3.3. Cluster information for significant effects in the infant brain model. * Indicates effects that yielded significant results after follow-up tests when including infant age in days as a covariate (See Appendix A for published results, excluding infant age as a covariate). Note that there is no spatial overlap between the lMFG cluster showing an interaction between infant CP score and chromophore and the lMFG cluster showing an interaction between caregiver efficiency and chromophore.*

Significant effects	**Cluster**	**Size (mm^3)**	**MNI coordinates**		
			Centre of Mass		
			x	**y**	**z**
Chromophore	Left inferior frontal gyrus (lIFG)*	774	40.6	-37	26.8
	Right superior parietal lobule (rSPL)*	360	-23.9	63.9	60.4
	Left middle temporal	333	62.2	33.6	8.2

	gyrus (lMTG)				
Infant CP Score x Chromophore	Left middle frontal gyrus (lMFG)*	318	37.8	-41.1	24.9
Caregiver Efficiency x Chromophore	Left inferior parietal lobule (lIPL)	897	40.4	53.7	56.6
	Left middle frontal gyrus (lMFG)*	226	27.9	-48.6	29.8
Caregiver Efficiency x Load x Infant CP Score x Chromophore	Left inferior parietal lobule (lIPL)*	732	40.5	53.9	55.9

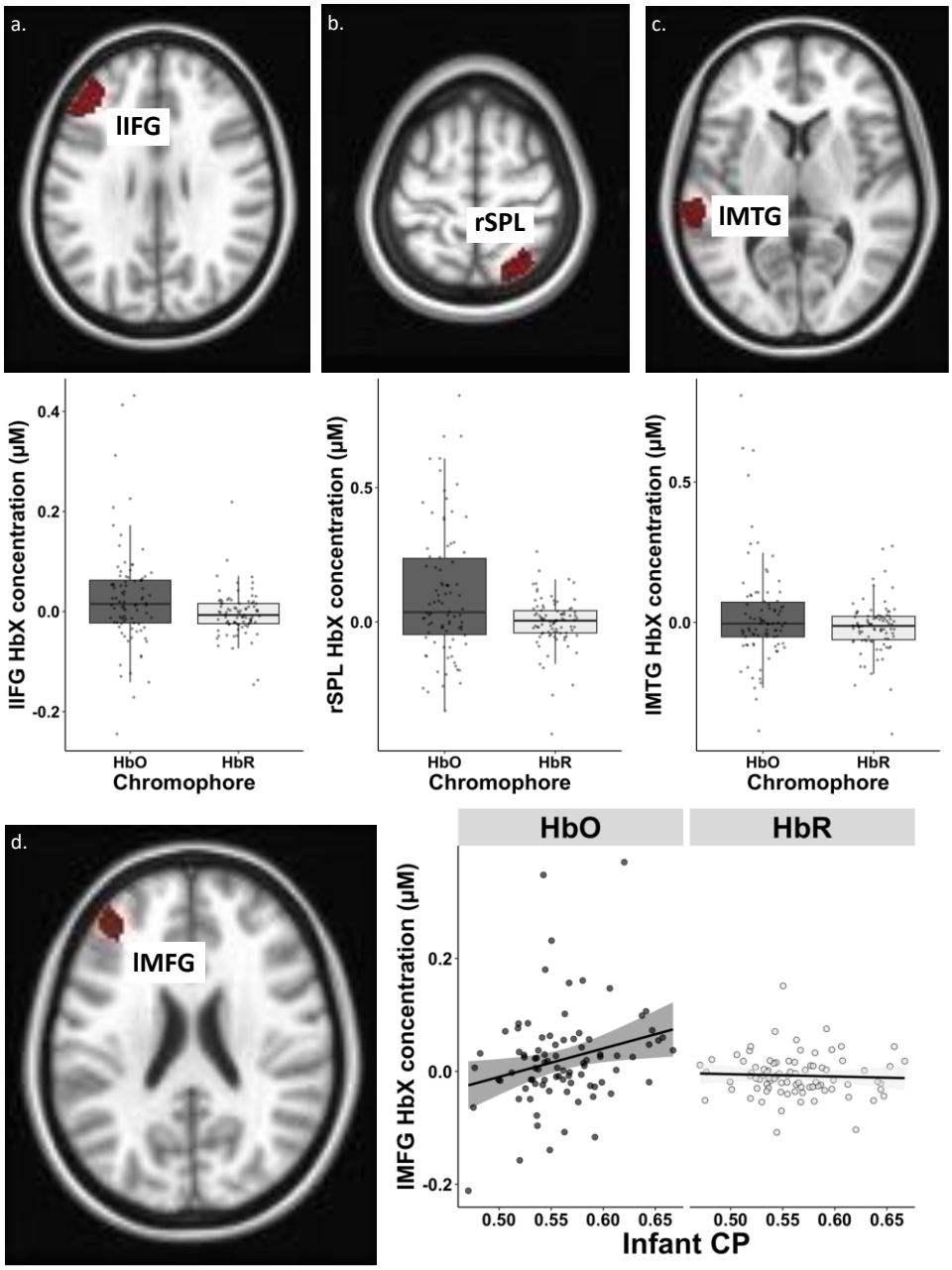


Figure 3.4. Brain images and boxplots for significant main effect of chromophore in (a) left inferior frontal gyrus (lIFG) - [MNI coordinates: 40.6 -37 26.8], (b) right superior parietal lobule (rSPL) - [MNI coordinates: -23.9 63.9 60.4], and (c) left middle temporal gyrus (lMTG) - [MNI coordinates: 62.2 33.6 8.2]. (d) Brain image and scatterplot for significant interaction between infant CP score and chromophore in left middle frontal gyrus (lMFG) - [MNI coordinates: 37.8 -41.1 24.9]. HbO concentration is shown in black and HbR concentration is shown in grey. Each box represents the IQR, with the horizontal line indicating the median. Whiskers extend to 1.5 times the IQR, and data points outside this range are plotted as outliers.

Lastly, there were two significant effects related to caregiver efficiency. A significant two-way interaction between caregiver efficiency and chromophore was observed in a cluster in the lMFG [MNI coordinates: 27.9 -48.6 29.8, 226 voxels,

F(1,397) = 8.88, p < 0.01] and lIPL [MNI coordinates: 40.4 53.7 56.6, 897 voxels, F(1,397) = 16.22, p < 0.01]. Follow-up tests were run for each chromophore and for each cluster, with infant age as a covariate. Findings revealed that in lMFG, greater caregiver efficiency was associated with lesser HbO concentration (p = .03, η_p^2 = .06), but not HbR concentration – see Figure 3.5. Therefore, infants of caregivers with better efficiency of inhibitory control exhibited increased suppression of lMFG. Note that this cluster did not spatially overlap with the lMFG cluster showing an interaction between infant CP score and chromophore (discussed in the previous paragraph). In lIPL, follow-up analyses did not reveal significant findings for either HbO or HbR concentration. Note, however, that this two-way interaction effect in lIPL was subsumed by a significant four-way interaction in the same region. This is discussed below.

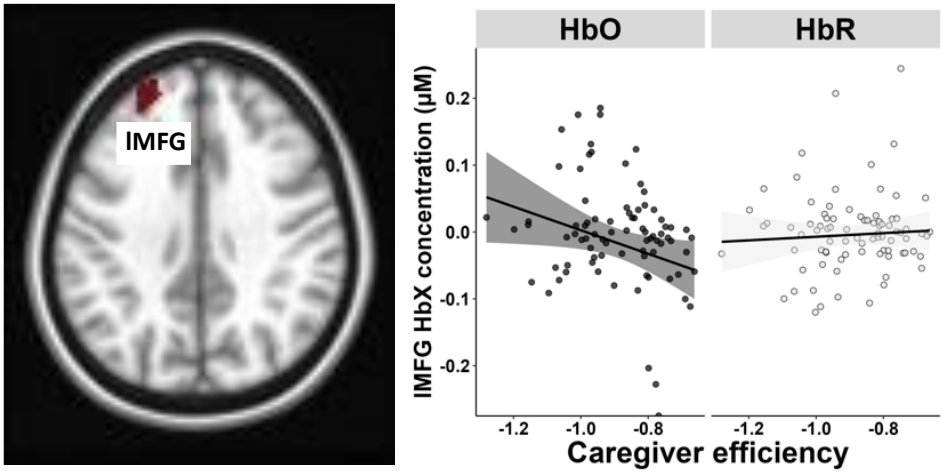


Figure 3.5. Significant two-way interaction between caregiver efficiency and chromophore in left middle frontal gyrus (lMFG) in infant brain data - [MNI coordinates: 27.9 -48.6 29.8]. HbO concentration is shown in black and HbR concentration is shown in grey in scatter plots.

There was also a significant four-way interaction between load, infant CP score, caregiver efficiency, and chromophore in lIPL [MNI coordinates: 40.5 53.9 55.9, 732 voxels, F(2,397) = 7.61, p < 0.01]. Follow-up tests were run for each chromophore and load separately, while controlling for infant age. There was a significant interaction between infant CP score and caregiver efficiency for lIPL HbR concentration at the medium load (p = .044, η_p^2 = .05) and lIPL HbO concentration at the high load (p = .005, η_p^2 = .09). For ease of understanding, the association between the three continuous variables (infant CP score, caregiver efficiency score and lIPL activation), caregiver efficiency was median-split into low efficiency and high

efficiency groups and a further follow-up test was run on each group separately, while still controlling for infant age. Results revealed that both interaction effects were driven by low efficiency caregivers only (lIPL HbR at medium load: $p = .029$, $\eta_p^2 = .13$; lIPL HbO at high load: $p < .001$, $\eta_p^2 = .46$) – see Figure 3.6(a – b). Specifically, at the medium load, infants of low efficiency caregivers showed increasing lIPL HbR concentration (interpreted as decreasing lIPL activation since directionality is reversed with HbR) with increasing CP scores. Similarly, at the high load, infants of low efficiency caregivers showed decreasing lIPL HbO concentration (interpreted as decreasing lIPL activation since directionality is preserved with HbO) with increasing CP scores. Thus, at the medium and high loads, infants with low efficiency caregivers showed decreasing lIPL activation with increasing CP scores, compared to infants with high efficiency caregivers, who did not demonstrate any CP score-dependent lIPL modulation.

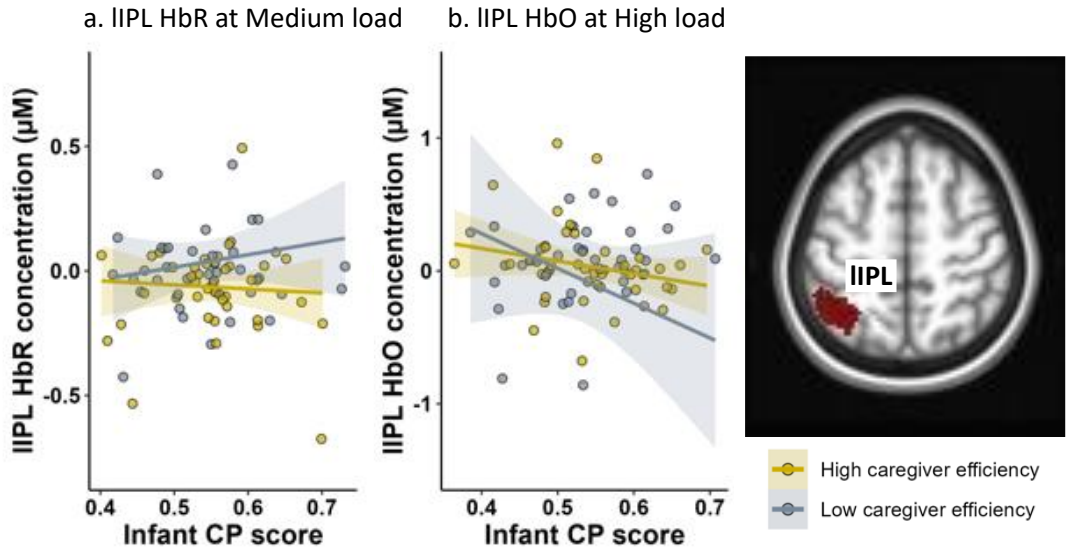


Figure 3.6. Significant interaction between infant CP score and caregiver efficiency in left inferior parietal lobule (lIPL) - [MNI coordinates: 40.5 53.9 55.9]. Specifically, for (a) lIPL HbR concentration at the medium load and (b) lIPL HbO concentration at the high load. Low efficiency caregivers are shown in grey and high efficiency caregivers are shown in yellow.

Finally, spatial overlap between significant clusters in the caregiver brain data and infant brain data was examined. There was no spatial overlap between caregiver and infant clusters.

3.4. Discussion

The current study posed three research questions to understand the association between caregiver efficiency of inhibitory control and visual working memory function in infants. The first question aimed to investigate what brain networks were linked to caregiver inhibitory control and how cortical engagement would vary with efficiency. Caregiver efficiency of inhibitory control did not modulate cortical function in the fronto-parietal network. However, four regions in this network showed overall engagement during the task. Specifically, activation in lIFG and rMFG and suppression in rAG and lIPL was observed. The second question inquired whether better caregiver inhibitory control was associated with better visual working memory behaviour in infants. However, there were no direct behavioural associations between caregiver efficiency of inhibitory control and infant visual working memory. The third question inquired whether caregiver inhibitory control was linked to visual working memory-related brain function in infants. Here, caregiver efficiency of inhibitory control impacted lMFG and lIPL engagement in infants during the visual working memory task. Importantly, infants with low efficiency caregivers showed decreasing lIPL activation with increasing CP scores at the challenging loads, compared to infants with high efficiency caregivers who did not show any CP score-dependent modulation of lIPL activation. These findings are discussed below.

3.4.1. Fronto-parietal network engaged during response selection and response inhibition in caregivers.

The Go-NoGo task elicited overall engagement of the fronto-parietal network. Specifically, caregivers showed lIFG and rMFG activation, and rAG and lIPL suppression. Previous work has shown that both lIFG and rMFG are involved in inhibition. Specifically, Edwards et al. (2012) found that the rMFG was actively engaged in a Go-NoGo task during error processing. Additionally, in a meta-analytical comparison of Go-NoGo and Stop-Signal tasks, Swick et al. (2011) reported that the rMFG was engaged more during Go-NoGo tasks and was associated with successful inhibition of automatic responses. Relatedly, Swick and colleagues (2008) had individuals with damage in the lIFG engage with a Go-NoGo task and found that they had higher error rates. Increased error rates indicate that lIFG is important for successful inhibition of motor responses (Swick et al., 2008).

However, contrary to predictions, activation in these regions did not vary with condition (Go or NoGo) or caregiver efficiency. Rather, these regions remained engaged throughout the task suggesting that there was equal engagement during Go and NoGo trials and consistent cortical engagement regardless of individual differences in caregiver efficiency. In the current study, it is possible that both regions were involved in general attentional control when associating response to stimuli. This interpretation is supported by previous findings linking both the lIFG and rMFG to attentional control. For example, during incongruent trials of the Stroop task, when greater attentional resources are needed to resolve interference, these regions show increased activation (Bench et al., 1993; Prakash et al., 2009). Complementing this, Tops and Boksem (2011) suggest that the IFG contributes not only to inhibition but also to more complex forms of attentional processing, such as adapting to task demands to facilitate accurate responding. Building on this, the current findings support the notion that the lIFG may be engaged throughout the Go-NoGo task to facilitate the broader allocation of attention to relevant stimuli, rather than being selectively recruited during inhibition-specific trials. Similarly, Japee et al. (2015) highlighted the role of the rMFG in reorienting attention, particularly in response to unexpected or salient stimuli. In the context of the current study, the sustained activation of the rMFG could reflect its involvement in continuously directing attention to the task, ensuring that caregivers remained engaged and responsive. Thus, recruitment of these regions throughout the Go-NoGo task may be due to this more general role of attentional control, which allowed caregivers to direct and regulate their attention.

Findings also revealed that two parietal regions, rAG and lIPL, showed suppression throughout the task. These findings were also contrary to expectations. Previous work found that the AG played a role in decision-making by guiding visuo-spatial attention toward relevant stimuli (Studer et al., 2014). Specifically, disrupting AG activity with repetitive transcranial magnetic stimulation affected decision latencies on visually demanding trials in a gambling task (Studer et al., 2014). Handy et al. (2005) reported that the lIPL is involved in implicit visuomotor processing influenced by visuospatial attention. In their study, participants engaged with a voluntary attentional orienting task that varied the category of an object (tool [e.g., a cup] vs non-tool [e.g., seahorse]) in the attended location. fMRI findings showed that

lIPL activity was modulated by the interaction between attended location and the presence of a tool in the visual field. This modulation indicates that visuospatial attention can influence not only perception but also action planning, highlighting IPL's role in linking attention with motor-related processing (Handy et al., 2005). Additionally, both rAG and lIPL have previously been linked to inhibitory control (see reviews - e.g., Criaud & Boulinguez, 2013; Simmonds et al., 2008). Cascio and colleagues (2022) reported that better inhibitory performance was associated with increased activity of rAG. This region is involved in interference control which involves the ability to suppress or inhibit inappropriate responses during Go-NoGo tasks (Seghier, 2013). In the current study, it is possible that attending to a single stimulus presented at the centre of the display across both Go and NoGo trials does not engage these regions, otherwise robustly engaged whilst allocating attentional resources across multiple stimuli and/or locations. Nonetheless, more research is necessary to probe the role of posterior regions during inhibitory control, as much of the focus remains on frontal cortex circuitry.

Finally, no association was found between caregiver efficiency and brain function. However, previous work using fMRI has reported such associations. For example, Cascio et al. (2022) reported a significant relationship between activity in the AG and the MTG and efficiency scores, such that increased activation in these regions were associated with better Go-NoGo task efficiency in adolescent males. A similar study by Tomlinson et al. (2020) found that children and adolescents, aged 7 to 18 years, who performed more efficiently on a Go-NoGo task had stronger inhibitory-related activation in the IFG. These findings were in line with prior adult work by Hirose and colleagues (2012) who also reported significant correlations between activation of the lIFG and efficiency. Given these prior findings, it is surprising that similar associations within the current cohort were not observed, particularly as caregivers demonstrated a good spread of efficiency scores. However, one possible explanation for this discrepancy is the variation in how efficiency was calculated across studies. Cascio et al. (2022) calculated efficiency as the average RT on correct Go trials divided by the proportion of correct NoGo trials. Tomlinson et al. (2020) calculated efficiency by dividing accuracy for NoGo trials by RT on correct Go trials. Hirose and colleagues (2012) took an alternative approach by using a regression model to establish a baseline relationship between RT and NoGo

accuracy across participants, then quantifying how much individual performance deviated from this expected efficiency. The current study calculated efficiency as the average RT on correct Go trials divided by overall accuracy (i.e. accuracy on both Go and NoGo trials). A commonality across these previous works is that they all focused on NoGo accuracy, whereas the current study incorporated overall accuracy (both Go and NoGo trials). Successful performance on a Go-NoGo task requires balancing inhibitory control with overall task performance, i.e. the ability to respond accurately to Go and NoGo trials. By using total accuracy, the measure used in the current study aimed to capture efficiency as a broader regulatory function that reflects both response execution and inhibition rather than isolating inhibitory control alone. This approach is particularly relevant when considering cognitive efficiency in real-world contexts, where adaptive control involves not just suppressing incorrect responses but also maintaining accurate and timely responses to relevant stimuli.

3.4.2. Caregiver efficiency is not directly linked to infant visual working memory behaviour.

There was no direct association between caregiver efficiency of inhibitory control and infant visual working memory behaviour. This finding is contrary to expectation and related evidence from previous work in older children. Ribner et al. (2022) reported that caregiver executive function was related to children's working memory at 24 months. Other studies have also shown similar caregiver-child behavioural associations in executive functioning tasks. Cuevas et al. (2014) reported that maternal executive function uniquely predicted child executive function at 36 months. While Kao et al. (2018) showed that parent and child executive functions were positively correlated when children were aged 3.5 to 4.5 years. Therefore, it may be that behavioural associations are not evident at this younger age range between 6 and 10 months. However, most studies have used an executive function composite score created by combining performance measures on tasks assessing executive function sub-functions. Thus, these studies have not assessed whether there is a direct behavioural link between caregiver and child executive function sub-functions.

3.4.3. Caregiver efficiency is associated with fronto-parietal activation in infants.

Caregiver efficiency was linked to fronto-parietal activation in infants as they engaged with the visual working memory task. In the first finding, better caregiver efficiency was associated with reduced lMFG activation in infants. The MFG is involved in distractor suppression in adults (D'Esposito & Postle, 1999). For instance, Yamasaki et al. (2002) examined the role of the MFG in attentional control, particularly in the presence of distractors. The authors showed that this region displayed increased activation when distractors were present, suggesting a role in maintaining goal-directed attention and resisting interference - highlighting the contribution to executive control, reinforcing its importance in sustaining attention and filtering out irrelevant information. In the current study, it is possible that infants with high efficiency caregivers recruited lesser lMFG activation compared to infants with low efficiency caregivers because they might have developed more efficient visuo-spatial attentional control, and thus, do not need to meet exceeding executive demands.

It is important to note that this cluster of the lMFG did not spatially overlap with the cluster showing an interaction between infant CP scores and activation in the lMFG. Therefore, the differences in findings regarding lMFG engagement likely reflect distinct roles of its subregions in cognitive processes. The region associated with greater infant CP scores may reflect active engagement in higher-order cognitive processes necessary for task success, particularly under demanding conditions. While the region associated with caregiver efficiency may indicate more efficient processing, reducing reliance on effortful executive resources. High efficiency caregivers likely foster environments that promote attentional regulation and streamlined cognitive strategies, allowing infants to perform well without excessive activation. Conversely, infants with higher CP scores may still require active recruitment of specific MFG subregions, possibly as a compensatory mechanism to sustain performance.

In the second finding, caregiver efficiency was related to infant visual working memory behaviour through left-lateralised parietal activation. The lIPL has been implicated in advanced socio-cognitive functions, such as the ability to infer

others' thoughts, beliefs, and behaviours (Bzdok et al., 2016). Under the umbrella of cognitive operations, this region is also involved in visuo-spatial attention and maintenance of items in visual working memory. Specifically, the IPL is implicated in attentional control mechanisms that enable the selection and prioritisation of relevant visual information (Corbetta et al., 2000). Previous work also demonstrates that activity in this region is heightened when individuals engage in spatial attention tasks, particularly during shifts of attention between locations or objects (Culham & Kanwisher, 2001). In the current study, more generally, load-dependent modulation of parietal activation was observed, in agreement with previous reports (Ambrose et al., 2016; Buss et al., 2014; Delgado Reyes et al., 2020; Jha & McCarthy, 2000; Linden et al., 2003; Wijeakumar, Magnotta, et al., 2017). However, only infants with low efficiency caregivers showed load- and performance-dependent lIPL modulation. Specifically, low CP infants with low efficiency caregivers recruited greater lIPL activation compared to high CP infants with low efficiency caregivers. Importantly, these low CP infants over-recruited lIPL activation even though they were less successful in detecting and sustaining attention to the changing side compared to their high CP counterparts – implying that this signature does not represent a compensatory mechanism. Instead, it is possible that these low CP infants might not efficiently direct visuo-spatial attention in the presence of challenging stimuli and shift between displays and/or away from the screen (reducing CP scores), thus, over-recruiting lIPL activation compared to high CP infants. This finding is in line with previous work in preschool-age children. McKay et al. (2021) investigated individual differences in behavioural performance and brain function in low- and high-performing similarly aged preschoolers on a change detection visual working memory task. They reported that while high-performing children did not show any load-dependent cortical modulation, low-performing children showed a change in left-lateralised parietal cortex activation with increasing load. This finding also aligns with previous work examining the impact of performance-based effects on brain function in adults (Honey et al., 2000; Jaeggi et al., 2008).

Note that while there was no significant performance- or load-dependent modulation of lIPL activation in infants with high efficiency caregivers, there is a visible trend for decreasing lIPL activation with increasing CP scores at the high load. Thus, some low CP infants with high efficiency caregivers might demonstrate a

similar trend to that of low CP infants with low efficiency caregivers but only at the more challenging conditions.

It is important to consider why only infants with low efficiency caregivers showed significant load- and performance-dependent lIPL modulation, whereas infants with high efficiency caregivers did not. It is speculated that low-efficiency caregivers might be less inhibitive and switch more frequently between objects and activities during their interactions. Therefore, their infants might adopt similar shifting behaviours while sustaining attention on tasks. On the other hand, high efficiency caregivers might be better at appropriately inhibiting and regulating their thoughts, behaviours, and actions more stably, thus, exhibiting less intrusive behaviours during interactions. These behaviours might promote uninterrupted bouts of infant sustained attention during active exploration and learning. Due to these differing exposures, it is possible that infants with high efficiency caregivers might be able to more consistently engage cortical regions necessary to sustain attention and show good visual working memory processing regardless of increasing task demands, compared to infants with low efficiency caregivers. Taken together, the findings suggest that caregiver efficiency of regulating inhibitory control might impact their children's visual working memory behaviour through fronto-parietal engagement, as early as the first year of life.

3.5. Conclusion.

The current study investigated whether caregiver efficiency of regulating inhibitory control was associated with visual working memory in infants. To this end, caregivers were presented with a Go-NoGo task wherein they had to either elicit or inhibit a response to certain stimuli. Using their behavioural performance, an efficiency score was extracted; a higher score represented better regulation of inhibitory control. Infants were presented with the preferential looking task and naturalistic looking behaviours were extracted while they engaged with the task. fNIRS was used to record brain function from caregivers and their infants as they engaged in their respective tasks. Results revealed no direct association between caregiver efficiency and infant visual working memory behaviour. However, there was an indirect association - caregiver efficiency was linked to infant visual working memory through left-lateralised parietal engagement. Specifically, infants with low

efficiency caregivers showed decreasing lIPL engagement with increasing CP scores at the challenging visual working memory loads, compared to infants with high efficiency caregivers who did not show any load- or performance-dependent modulation. These findings contribute to the growing body of literature examining the role that caregivers play in very early neurocognitive development.

3.6. Motivations for the next chapter.

The findings presented in this chapter suggest that caregivers with more efficient inhibitory control may be better equipped to regulate their own behaviours during interactions, potentially fostering more supportive environments for infant attention and learning. These caregivers may be less likely to interrupt or override the infant's focus, instead facilitating sustained, self-directed engagement with the environment. Such interaction patterns could play an important role in shaping how infants allocate attention and process visual information across varying demands. Building on this, the next chapter examines caregiver and infant behaviours during naturalistic play and how these relate to infant visual working memory. Specifically, the chapter examines the relationship between caregiver scaffolding and intrusiveness and infant object engagement and distractibility during distinct play interactions with different types of objects and instructions. These caregiving behaviours, especially intrusiveness, may reflect underlying differences in self-regulation, such as inhibitory control, and influence the quality of infant attention during play. The chapter further explores how these patterns relate to individual differences in infant visual working memory performance. By situating caregiver and infant behaviours within the context of dyadic interactions, Chapter 4 aims to clarify how early social environments shape emerging attentional control and cognitive functioning.

Chapter 4:

Experiment 2: Caregiver-infant interactions and infant visual working memory.

The following chapter has been submitted to Infant Behavior and Development. A modified version of this paper with additional content is included here.

4.1. Introduction.

Play interactions serve as a conduit for the transfer of socio-cognitive behaviours between caregivers and infants, leading to better socio-emotional development in childhood and later-life experiences (Hirsh-Pasek et al., 2008; Tronick, 1989). For example, children require playful learning opportunities under the guidance of caregivers to best prepare for academic success (Hirsh-Pasek et al., 2008). The history of the use of free-play interactions is rich and multifaceted, with earliest work using the Still-Face Paradigm wherein an infant interacts with a caregiver who suddenly becomes unresponsive, maintaining a still, expressionless face after a period of normal interaction (Tronick et al., 1978). During the Still-Face Paradigm, infants typically show increased gaze away from the caregiver, less smiling, and more negative affect (Gusella et al., 1988; Toda & Fogel, 1993). Such outcomes demonstrated that infants are highly sensitive to the emotional availability of their caregivers and that disruptions can lead to stress and affective changes. This work supports the notion that consistent and responsive interactions are critical for healthy emotional and cognitive development, emphasising the role of mutual regulation where both the caregiver and infant influence each other's states and behaviours (Mesman et al., 2009).

4.1.1. Naturalistic observation of caregiver-infant interactions in free-play contexts.

In recent work, researchers have increasingly focused on recording free-play interactions to study caregiver-infant dynamics. By instructing caregivers to 'play as they normally would' (Abels et al., 2017; Puura et al., 2019; Schneider et al., 2023),

this method allows for the observation of naturalistic behaviours and interactional styles. This approach is often used to identify differences between caregivers' interactional styles (Abels et al., 2017). A wide range of caregiver behaviours have been studied in this context. For example, studies have looked at how caregivers use gaze to direct attention to objects or activities (e.g., Deák et al., 2014; Franchak et al., 2018). Franchak and colleagues (2018) reported that caregivers frequently looked at both infants' faces and at objects, suggesting that caregivers monitored infant gaze direction towards objects to better engage in play. Caregivers often label objects and describe actions during play, which aids in vocabulary development and cognitive skills. Hoff (2006) demonstrated that the richness of a caregiver's language positively correlates with a child's linguistic development.

Asking questions and providing elaborate responses encourages critical thinking and problem-solving skills in children. Rowe and colleagues (2017) showed that the complexity of questions posed by caregivers influenced children's narrative skills and comprehension. Other work has focussed on negative caregiving behaviours during these interactions. For example, Landry et al. (2006) found that highly controlling behaviours were associated with less optimal cognitive and social outcomes in children. Further, Doyle and Cicchetti (2017) reported that children who experience adverse early caregiving are more likely to exhibit negative attachment behaviours, deficits in social-emotional competencies, and persisting difficulties in social functioning and relationship outcomes. While this work is beneficial for identifying differences between caregivers' interactional styles, much of the research tends to focus on specific categories of behaviours independently. For example, studies often examine attention behaviours, positive behaviours, or negative behaviours in isolation. However, examining multiple types of behaviours, both positive and negative, concurrently within the same interaction is crucial. This comprehensive approach can provide a deeper understanding of how these combined behaviours influence cognitive and socio-emotional outcomes in early development.

4.1.2. The influence of different play contexts on caregiver-infant interaction dynamics.

To fully understand a caregiver's influence on their infant's development, it is essential to observe caregiver-infant dyads in a variety of play interactions during the

critical first year of life (Leyendecker et al., 1997). Infants are exposed to multiple types of interactions, such as free play, structured play, and guided learning activities. The key question is whether these different types of interactions have distinct impacts on later cognitive and socio-emotional development. For example, Serra and colleagues (2020) analysed caregiver touch behaviours while they interacted with their 12-month-old infants in three types of interactions: free play with toys, free play without toys, and challenging object play. They found that maternal use of touch was most frequent during free play without toys. However, mothers touched their infants almost twice as often during challenging object play compared to free play with toys. Overall, maternal touch behaviour varied depending on the demands of the play task, changing not only in frequency but also in the type of touch used (Serra et al., 2020). Further, Puccini and colleagues (2010) found that the type of shared activity had a pervasive influence on both the verbal and non-verbal communication of caregivers and 12-month-old infants. Concretely, during free play contexts, dyads used a variety of showing, giving, and placing gestures but would rarely use pointing gestures. Whereas, in an exploratory context the dyad pointed more frequently to demonstrate their interest in objects (Puccini et al., 2010). Recently, Quinn and Kidd (2019) explored how early communicative behaviours differed during caregiver-infant interactions at 18-months in symbolic compared to functional play. Symbolic play involves the non-literal use of objects, actions, or persons (e.g., pretending to cook with a saucepan and lid, or having pretend conversations with a toy phone). Functional play involves objects with a specific function (e.g., using a hammer and peg set). Play interactions were coded and compared across these play conditions for joint attention and gesture use. Joint attention was established more often and sustained longer in symbolic play, and both caregivers and infants produced more gestures during symbolic play compared to functional play (Quinn & Kidd, 2019). These existing studies have predominantly focused on older infants and while they have yielded valuable insights into caregiver-infant interactions, their findings may not be applicable to interactions with younger infants. Thus, a detailed investigation into various free play contexts with younger infants could provide a deeper understanding of caregiver-infant interactions.

4.1.3. Caregiver behaviours and the development of attention and executive function.

Caregiver-child interactions have been shown to be directly linked to child cognitive development, particularly attention and executive function skills. For example, Hughes and Ensor (2009) reported that individual differences in the extent to which mothers engaged in scaffolding practices such as open-ended questions, praise, encouragement, or elaborations during a structured activity predicted individual differences in children's executive functions at 4-years-old. Further, Bernier et al. (2010) found that maternal sensitivity, mind-mindedness, and autonomy support from 12-15 months were all related to later child executive function at 18 and 26 months. In another study, Mermelshtine and Barnes (2016) explored the association between maternal responsive caregiving behaviours (contingent response, stimulating language, and autonomy-promoting speech) and infant object play at 10-months. Infant advanced object play was found to predict maternal responsive caregiving, such that infants who managed to succeed with the challenging objects elicited more responsive and lexically varied input from their mothers. More recently, Ribner and colleagues (2022) found that parental sensitivity during free-play interactions was positively related to child working memory and shifting at 24-months. Research also suggests that early caregiving influences emerging attention processes (Cicchetti & Dawson, 2002; Posner et al., 2014). Altenburger and Schoppe-Sullivan (2021) found that maternal parenting quality at 9 months was associated with better attention at 26 months. Further, Swingler and colleagues (2017) reported that maternal positive affect at 5 months was linked to better infant behavioural attention at 10 months. In contrast, maternal intrusiveness had a disruptive effect, with 10-month-old infants showing suboptimal neural activity during an attention task (Swingler et al., 2017). Li et al. (2022) found that infant attention at 4-months was related to 14-month working memory and that maternal sensitivity during toy play at 14-months was related to infant inhibition at 14-months. Other studies have shown that maternal behaviours during play, such as teaching and conjoint action, predict infant joint attention (Gaffan et al., 2010) and that maternal sensitivity supports cognitive development and symbolic play at 12-months (Feldman et al., 2004). Collectively, these findings highlight the importance of positive caregiving behaviours in supporting early attention and cognitive skills. However, more research is needed to understand how these caregiver behaviours

influence visual working memory, a foundational system that develops rapidly in the first year of life and plays a key role during caregiver-infant interactions.

4.1.4. The current study.

Despite extensive research on caregiver-child interactions, several key gaps remain. First, much of the existing literature tends to examine caregiver behaviours in isolation, focusing either on positive or negative behaviours, rather than considering how multiple behaviours co-occur and interact within the same play episode. Additionally, while studies have explored various cognitive outcomes such as attention, joint attention, and general executive function, visual working memory has received limited focus. Furthermore, research has largely centred on children 12 months and older, leaving a gap in understanding how younger infants engage in play and how these early interactions influence foundational cognitive processes. Although some studies have shown that caregiver behaviours vary depending on play context (e.g., free play vs. structured tasks), systematic comparisons between different types of object-based play are scarce. Finally, few studies combine detailed behavioural coding of caregiver-infant play interactions with experimental assessments of cognitive outcomes. Addressing these gaps could provide a more nuanced and developmentally grounded account of how different play contexts support early cognitive development.

To address these gaps, the current study investigated differences in caregiver and infant behaviours between two types of object-based play interactions, and whether these behaviours were associated with concurrent infant visual working memory. To this end, video recordings were collected from caregivers and their 6-to-10-month-old infants as they engaged in two types of dyadic play interactions that differed by the objects used, and instructions issued to the caregivers. Specifically, in one play interaction (referred to as single object [SO] play), caregivers were instructed to engage their infants with single representational objects (e.g. cup, car) as they normally would at home. In the other interaction (referred to as multi-component object [MO] play), caregivers were instructed to engage their infants with multi-component objects (e.g. stacking objects, sorting objects) as per their intended purpose. The decision to use SO and MO play as the interaction types was based on the differing demands the objects could have on cognitive and visual processing. MO

play was expected to place greater demands on visuo-cognitive processing functions due to the nature of the objects involved, which required infants to process multiple features (e.g., colour and shape) and to integrate information about spatial orientation and object-function associations to achieve a goal. These interactions typically require a sequence of coordinated actions guided by visual input, such as identifying the correct shape or size, matching components based on perceptual features, and manipulating objects in goal-directed ways. Such tasks likely engage visual attention, working memory, and problem-solving processes. In contrast, the objects used in SO play were comparatively less demanding in terms of visuo-cognitive integration. While they can elicit motor interaction (e.g., spinning, shaking, or mouthing), they lack the same level of structured, goal-oriented complexity. These objects tend to involve fewer distinct features, less spatial reasoning, and minimal requirements for matching or sequencing actions, thereby placing relatively lower demands on visual working memory and related cognitive processes.

The current chapter had four research objectives. The first objective was to examine whether there were differences in caregiver and infant behaviours between SO and MO play interactions. Based on the differing complexity of the play interactions, it was predicted that caregivers would show greater scaffolding and reduced intrusiveness, and infants would show greater object engagement and reduced distractibility during MO play compared to SO play. Specifically, the multi-component objects in MO play are expected to require more caregiver guidance and infant focus due to their increased complexity compared to the simpler, single objects in SO play. Further, previous work has shown that caregivers show scaffolding behaviours when engaging in structured categorisation tasks (Inan et al., 2024). The second objective was to examine whether there would be an association between caregiver and infant behaviours during SO play and the same behaviours during MO play interactions. Previous work has generally shown consistency in behaviours across interactions. For example, Neale and Whitebread (2019) reported that caregivers' propensity to scaffold was consistent across different objects and Kannass and colleagues (2006) found evidence of stability in distractibility between 9 and 31-months during multiple object free play. Based on this, it was speculated that caregivers who showed higher scaffolding and reduced intrusive behaviours and

infants who showed higher object engagement and reduced distractibility during SO play would also show similar trends during MO play interactions.

The third objective was to examine whether caregiver and infant behaviours during dyadic interactions were associated with infant visual working memory. There are mixed findings in the literature regarding contributions from caregivers and infants. Regarding caregiver-specific influences - caregiver intrusiveness has been associated with poorer infant attention (Swingler et al., 2017), caregiver scaffolding has been shown to support child development (Hughes & Ensor, 2009), and maternal sensitivity has been shown to predict child working memory (Ribner et al., 2022). Regarding infant- and caregiver-specific influences - infant sustained attention in the context of caregiver-infant joint attention was shown to predict later vocabulary (Yu et al., 2019). Further, both infants' willingness to initiate and caregiver responsivity has been shown to have different contributions to early language development (Paavola et al., 2005). Finally, regarding infant-specific influences, infants' engagement, and not caregiver responsiveness, has been shown to predict accuracy on an object search task (Clackson et al., 2019). Given these mixed findings on unique and joint caregiver-infant contributions, it was predicted that both caregiver and infant behaviours would be associated with infant visual working memory performance. There was no specific hypothesis about the exact behaviours or type of interaction. However, it was speculated that infant visual working memory would be linked to caregiver scaffolding and object engagement during MO play as infants might be exposed to better visuo-motor perception and working memory compared to SO play.

Finally, the fourth research question was to examine whether caregiver behaviours could explain associations between caregiver efficiency of inhibitory control and infant visual working memory brain function that were reported in Chapter 3. Specifically, caregiver efficiency was associated with infant lMFG engagement, such that greater efficiency was linked to reduced lMFG activation. Here, it was expected that caregiving behaviours would mediate the association between caregiver efficiency and infant lMFG brain function generally based on findings from Swingler et al. (2017) who found that maternal intrusiveness was associated with infant neural attention. Note that there was also an association

between caregiver efficiency and infant lIPL found in Chapter 3. However, the significance of that association was driven by specific subgroups within the data and including this in current analyses would have resulted in a largely reduced sample size. Thus, this was not considered within the current chapter.

4.2. Methods.

4.2.1. Participants.

Refer to section 3.2.1. in Chapter 3 for details of participant recruitment as the same sample was used for this study. A total of 91 caregivers (90 females, 1 non-binary, Mage = 33.5 years, SD = 4.5) and 91 infants (46 females, Mage = 251.3 days, SD = 34.9) participated in the study. Other demographic and socioeconomic status information is provided in Table 4.1. Task specific exclusions are presented in the following sections.

Table 4.1. Socioeconomic and demographic information was collected via questionnaires. Data was not available from all families (as indicated by N).

	N	Mean	SD
Child age (days)	91	251.3	34.9
Primary caregiver age (years)	91	33.5	4.5
Primary caregiver education (years)	80	16.1	2.6
Secondary caregiver education (years)	77	13.9	4.3
Primary caregiver income	72	£ 27,507	£ 13,296
Secondary caregiver income	49	£ 31,595	£ 11,564
Primary Caregiver's Ethnicity	**N**	**%**	
Asian	5	5.5	
Mixed	4	4.4	
Arab	1	1.1	
White British	69	75.8	
Other White	1	1.1	
Did not answer	11	12.1	

4.2.2. Dyadic play interactions.

Caregivers and infants were asked to engage in two types of play interaction. In SO play interactions, caregivers were instructed 'play as you normally would' with five single objects (i.e., car, cup, pop-it butterfly, gears, and rattle – see Figure 4.1c). In MO play interactions, caregivers were instructed 'play with these objects as their purpose intends' with three multi-component objects (i.e., shape sorter, rainbow stacker, and hide 'n' squeak eggs – see Figure 4.1d). To inform the labelling of these play interactions, detailed coding of the interactions was conducted to examine the extent to which the objects were used symbolically and/or functionally. A total percentage of whether each dyad played with the objects symbolically and/or functionally for each type of interaction was calculated and this was then averaged across dyads. In SO play interactions, objects were used symbolically on average 5.95% of the time (SD = 9.57%) and functionally 94.05% of the time (SD = 9.57%). In MO play interactions, symbolic use occurred on average 6.7% of the time (SD = 10.9%), while functional use occurred 93.3% of the time (SD = 10.9%). Thus, this coding confirmed the distinction between the play interactions was best characterised by the nature of the objects.

Each interaction lasted 7 minutes. Within the literature, lengths of interactions range from around 2 – 20 minutes. There were several constraints to consider when choosing the length of time for each play interaction. Firstly, there was the constraint of using fNIRS, not presented in the current chapter or overall thesis, during the interactions which could cause infants discomfort and result in them becoming fussy if worn for an extended period. Secondly, this work was part of an overarching study with a variety of tasks and questionnaires being administered within the same lab session. Ultimately, 7 minutes was deemed as a suitable interaction length given these constraints, particularly as this length has been used in previous studies (e.g., Maas et al., 2013; Sipos et al., 2013).

The start and end times of each interaction were signalled by an audible tone and a flash on a TV screen 150-200 cm away from the dyad (using PsychoPy v2021.2.3). Dyads were seated face-to-face with the caregiver sitting in a chair across from their infant in a highchair with a tray attachment. This arrangement was

chosen because fNIRS data was also recorded from the dyad, however, this data has not been presented in the current thesis. Objects were placed on a table beside the caregiver, and they were asked to move the objects to the highchair table during the interaction. Objects were often placed directly on the highchair table to occupy the infants during setup. For SO play, the interactions started with objects distributed between the white table and the highchair table in 88% of cases. For MO play, interactions started with objects distributed in 87% of cases. Importantly, however, all caregivers were made aware that they could use all of the objects. If infants were fussy and/or would not go into the highchair, the interactions were completed with the infant on the caregiver's lap with the objects on the white table in front of the dyad.

One video camera was placed atop the white table to capture a close-up view of the interaction, and another video camera was placed atop the TV to capture a wider view of the experimental area. Caregivers also wore head-mounted cameras; however, this view was only used to confirm any behavioural coding decisions. Real-time recordings from both cameras were presented on a laptop using Bandicam (https://www.bandicam.com/) and Movavi programs (https://www.movavi.com/) so that the experimenters could monitor the interactions.



Figure 4.1. a) Caregiver-infant dyad engaging in SO play. c) SO play objects. c) Caregiver-infant dyad engaging in MO play. d) MO play objects.

4.2.3. Infant preferential looking task.

Visual working memory was assessed in the infant using a preferential looking task – refer to section 3.2.3. in Chapter 3 for details.

4.2.4. Caregiver Go-NoGo task.

Inhibitory control was assessed in the caregiver using a Go-NoGo task – refer to section 3.2.2. in Chapter 3 for details.

4.2.5. Procedure.

Two researchers were present during each visit. After the family was welcomed and escorted to the lab, the researchers explained the full procedure to the caregiver and obtained informed consent. The infant was placed into a highchair or sat on their caregiver's lap. A cartoon was played on a TV screen 100-150 cm away while the infant was being set up. Following set-up, the researchers administered the preferential looking task. One researcher was responsible for administering the task and monitoring the video set-up. Cartoons were played during the attentional cue if the infant appeared to disengage from the TV. Breaks were also provided as per the convenience of the infant and caregiver. Next, caregivers were asked to engage their

infants during the SO and MO play interactions. The SO play interaction was completed first in 77% of the dyads, followed by the MO play interaction. It was not possible to counterbalance the interactions due to the practical constraints of the overarching project, which included multiple tasks and questionnaires conducted within the same session. Task order was also adjusted as per caregiver preference, and infant engagement and fussiness after they arrived in the lab. This has been included as a covariate in relevant analyses. As this study was part of an overarching study, the preferential looking task was typically completed in the families first visit to the lab because it is an attentionally-demanding task and data was required from multiple runs. The play interactions were typically completed at the second visit. In some cases, if caregivers stated that their infants were more likely to engage with the task after a play session, the researchers started with a play interaction. However, if the preferential looking task and/or the play interactions could not be completed at their visits, the family was invited back to the lab for further visits. Families were renumerated for each visit to the lab. Note that infant age was recorded at each visit and an average was calculated for use as a covariate in the analyses.

Please refer to section 3.2.5. in Chapter 3 for full procedural details for caregiver Go-NoGo task, infant preferential looking task, and infant fNIRS data collection.

4.2.6. Coding dyadic interactions.

Coding schemes were developed to analyse the SO and MO play interactions. Intrusiveness and scaffolding behaviours in caregivers and object engagement and distractibility in infants were coded during both interactions. Previous literature was surveyed using PubMed to extract information on the behaviours that were chosen to be coded, the epoch length used (if any), and the rating scale used (if any). See Appendix B for full lists of the articles identified for each behaviour.

For caregiver intrusiveness and scaffolding, the literature search focused on articles involving free-play interactions. For caregiver intrusiveness, the search terms ‘caregiver intrusiveness’, ‘maternal intrusiveness’, ‘play’, and ‘infant’ were used and 34 articles were identified. In these articles, free-play tasks lasted between 2 and 20 minutes. Regarding epochs, 25 articles did not split the interactions into epochs, 7

used 30-second epochs, 1 used 10-second epochs, and 1 used 1-second epochs. Regarding rating scales, 29 articles utilised a rating scale (e.g., 1 to 5) and 5 did not. 25 intrusive behaviours (e.g., interrupting child's activities) were identified from in-text examples across the 34 papers (Table 4.2). For caregiver scaffolding, the search terms 'caregiver scaffolding', 'maternal scaffolding', 'play', 'infant' were used and 23 articles were identified. In these articles, free-play tasks lasted between 5 and 20 minutes. Regarding epochs, 19 papers did not split the interactions into epochs, 2 used 2-minute epochs, 1 used 15-second epochs, and 1 used 5-second epochs. Regarding rating scales, 7 papers utilised a rating scale and 16 did not. 20 scaffolding behaviours (e.g., verbalises with physical demonstrations or miming how to use the object) were chosen from in-text examples across the 23 papers (Table 4.3).

For infant object engagement and distractibility, the literature search focused on papers involving free-play interactions and/or attention tasks. For infant object engagement, the search terms 'object engagement', 'sustained attention', 'focused attention', 'attention', 'joint attention', 'play', and 'infant' were used and 33 articles were identified. Regarding epochs, 28 articles did not use an epoch split, 1 used 10-second epochs, 1 used 5-second epochs, and 3 used 1-second epochs. Regarding rating scales, 4 articles utilised a rating scale and 29 did not. 8 object engagement behaviours (e.g., gaze intently focused on object) were identified from in-text examples across the 33 articles. These behaviours were categorised into two categories - 'with touch' and 'without touch' to distinguish between object engagement with and without active physical object handling. Thus, there were 13 object engagement behaviours in the coding scheme (Table 4.4). For infant distractibility, the search terms 'distractibility' and 'infant' were used and 18 articles were identified. Regarding epochs, 16 articles did not use an epoch split and 2 articles used 10-second epochs. Regarding rating scales, 3 articles used a rating scale and 15 did not. 2 distractibility behaviours (e.g., shifts interest across multiple objects, without staying fixated on one) were chosen from in-text examples (Table 4.5).

For this study, holistic caregiver and infant behaviours primarily related to object engagement were of interest, instead of general caregiving and infant socio-

emotional characteristics. Further, the aim was to code behaviours during defined epochs of the interaction and not rely on an overall global rating for the full interaction. Therefore, each interaction was split into 30 second epochs and each epoch was examined to identify all possible behaviours in a category. Each interaction video was imported into DataVyu software (https://datavyu.org/) and divided into 30 second epochs, resulting in a total of 14 epochs for interactions that lasted 7 minutes. For each epoch, the coder recorded how many behaviours were exhibited each for intrusiveness, scaffolding, object engagement, and distractibility. Epochs were not coded if the experimenter interrupted the interaction (e.g., by entering the room or speaking to the caregiver) or if the dyad engaged with anything other than the objects provided (e.g., highchair strap, snack box). One coder (CD) coded all the data, while another (AT) coded behaviours from both types of interactions and from both caregivers and infants of 10 dyads. Intraclass correlation (ICC) was used to assess reliability across all the epochs. For SO play, ICC was 0.828 for caregiver intrusiveness, 0.755 for caregiver scaffolding, 0.943 for infant object engagement and 0.873 for infant distractibility. For MO play, ICC was 0.715 for caregiver intrusiveness, 0.617 for caregiver scaffolding, 0.949 for infant object engagement and 0.881 for infant distractibility. The average ICC across all behaviours and interaction types was 0.82. ICC values above 0.8 indicate good reliability (Koo & Li, 2016).

Table 4.2. Caregiver intrusiveness behaviours and percentage of how often each behaviour was displayed for each interaction type. Total percentage was calculated as the percentage of behaviours observed across all epochs for all participants.

Caregiver Intrusiveness	**Total (%)**	
Behaviours	**SO Play**	**MO Play**
Non-contingent speech	0	0
Loud speech	0	0
Exaggerated, fake, facial expressions	0	0
Making developmentally inappropriate demands on the child	0.04	0.43
Breaking gaze while child is looking	0.85	0.34
Shifting focus of the task before child is ready	8.70	3.96

Taking objects away before child is ready	4.26	6.46
Ignoring or interrupting child's interest in an object or activity by introducing a different object	8.23	2.60
Not allowing child to touch an object that caregiver is holding	0.94	0.72
Not allowing child to play with or handle objects they reach for	2.52	4.53
Interrupting child's activities	14.71	14.57
Overstimulating child	4.05	3.47
Offering a continuous barrage of stimulation that overwhelms the child	0.47	0.05
Overwhelming with objects	4.95	6.22
Forcing objects or self on child	1.07	0.58
Overly caregiver-led	3.67	6.03
Not letting child set the tone and pace of play	15.57	22.72
Disregarding child signals	16.29	20.16
Failing to modulate the pace or intensity of her behaviour when the child withdrew or turned away	0.68	0.05
Intrusive physical interactions	7.51	3.47
Physical manipulation of child to complete a goal	1.75	1.25
Physically manipulating the child even when child objecting or already independently playing	0.17	0.29
Rough physical contact: tickling, poking, pulling, shaking, and using brisk movements	0.68	0.14
Physically grabbing or moving child	0.72	0.48
Pulling or controlling hands	2.17	1.45

Table 4.3. Caregiver scaffolding behaviours and percentage of how often each behaviour was displayed for each interaction type. Total percentage was calculated as the percentage of behaviours observed across all epochs for all participants.

Caregiver Scaffolding	**Total (%)**	
Behaviours	**SO Play**	**MO Play**
Questions or statements that associate objects and specific location	0.14	8.16
Relates object/activity that child is engaged with to a previous experience	0.51	0.34

States characteristics for an object that identifies its uniqueness, function, or specific features the child can use to problem solve	0.05	1.18
Specifies the function or activity that could be done with an object	2.88	4.07
Verbalises with physical demonstrations or miming how to use the object	12.02	9.80
Associates feelings or emotions with a reason for the emotion.	0.41	0.26
Teaches cause and effect or what you need to do to make an activity work	0.21	0.54
Links specifics objects with general categories	0.55	1.14
Helps child understand activities by linking two aspects of the activity	0	0.43
Suggesting object or activity to child whilst child disengaged	6.31	3.32
Labels objects	11.19	13.55
Describes objects	3.61	5.06
Labels own or child's actions	12.02	9.35
Reinforcing child's engagement with an object or activity	2.97	2.13
Allows child to lead while providing a supportive frame	2.88	2.69
Physically positions objects in such a way that child can engage in activities	12.11	13.14
Shows genuine interest and positive affect toward child	25.64	21.82
Reads child signals accurately and responds appropriately	1.91	1.42
Attends to and follows child's interest	2.88	1.19
Actively facilitates child's play through modelling or turn-taking	1.73	0.43

Table 4.4. Infant object engagement behaviours and percentage of how often each behaviour was displayed for each interaction type. Total percentage was calculated as the percentage of behaviours observed across all epochs for all participants.

Infant Object Engagement	**Total (%)**	
Behaviours	**SO Play**	**MO Play**
No touch – Child gazes intently and focusses on object without looking elsewhere.	18.87	17.81
No touch – Child shows facial signs of interest when engaging with an object (for e.g. furrowed brow).	7.21	7.25

No touch – Child looks at and babbles/vocalizes towards object.	1.37	1.38
No touch – Child shows interest in an object even though it has been hidden from view.	0.48	0.06
No touch – Child stays focussed on object even through any distractions.	0.13	0.04
Include touch – Child gazes intently and focusses on object without looking elsewhere.	19.97	17.90
Include touch – Child shows facial signs of interest when engaging with an object (for e.g. furrowed brow).	9.02	8.11
Include touch – Child looks at and babbles/vocalizes towards object.	2.64	1.74
Include touch – Child stays focussed on object even through any distractions.	1.10	0.75
Include touch/no touch – Child displays physical response towards object (for e.g. leaning, reaching, touching)	18.09	17.52
Include touch – Child directly brings object closer (without caregiver influence).	3.58	10.31
Include touch – Child explores object manually (for e.g. holding, mouthing, shaking, hitting, banging, swinging, rotating, orienting, shifting, pressing buttons, and poking fingers into holes, fingering, stroking)	17.52	17.06
Include touch – Child repeats an action with an object for a while until they are successful or close to successful. (5s+)	0	0.09

Table 4.5. Infant distractibility behaviours and percentage of how often each behaviour was displayed for each interaction type. Total percentage was calculated as the percentage of behaviours observed across all epochs for all participants.

Infant Distractibility	**Total (%)**	
Behaviours	**SO Play**	**MO Play**
Child shifts interest across multiple objects, without staying fixated on one.	63.60	67.84
Child is looking around the environment (for e.g. playing with the chair)	36.40	32.16

4.2.7. Behavioural analyses of the infant preferential looking task.

Please refer to section 3.2.6. in Chapter 3 for analyses details.

Only infant CP score at the low load was used for further analyses. Previous work has demonstrated that infant CP scores at low load, but not medium or high load, were significantly associated with caregiver CP scores at the same load (Theyer et al., 2024). Additionally, infant CP scores at low load have been linked to caregiver brain function during joint attention in dyadic interactions (Theyer & Wijeakumar, n.d.).

4.2.8. Behavioural analyses of caregiver Go-NoGo behaviour.

Please refer to section 3.2.6. in Chapter 3 for analyses details.

4.2.9. Outlier correction.

All behavioural data were screened for outliers using RStudio (RStudio Team, 2020). Data were considered outliers if they fell outside of ± 3 SDs from the mean. For play interactions, outlier corrections were carried out for the overall scores computed across epochs for each behaviour. For SO play interactions, there was one outlier for caregiver intrusiveness. Thus, for this play interaction, 74 caregivers provided intrusiveness data, 75 caregivers provided scaffolding data, 75 infants provided object engagement data, and 75 infants provided distractibility data. For MO play interactions, there were two outliers for caregiver scaffolding and one outlier for infant distractibility. Thus, for this play interaction, 85 caregivers provided intrusiveness data, 83 caregivers provided scaffolding data, 85 infants provided object engagement data, and 84 infants provided distractibility data.

For the infant preferential looking task, data from 3 infants were excluded due to the presence of familial colour-blindness and a further 2 infants were excluded due to fussiness. Thus, 86 infants contributed CP scores at the low load.

4.2.10. fNIRS brain analyses.

Please refer to section 3.2.7. in Chapter 3 for details on infant neuroimaging analyses.

4.2.11. Statistical analyses.

All statistical analyses were carried out using RStudio (RStudio Team, 2020). First, ANCOVAs were run, controlling for infant age, to test whether there were differences between epochs for each caregiver and infant behaviour. Next, to test whether there were differences in caregiver and infant behaviours between play interactions, ANCOVAs were run, controlling for infant age and order of play interaction. To examine whether caregiver and infant behaviours during SO play were predictive of the same behaviours during MO play, regression models were run with infant age as a covariate. To test whether caregiver and infant dyadic behaviours predicted infant visual working memory performance, regression models with infant age as a covariate were run. Mediations were used to examine whether caregiving behaviours influenced the association between caregiver efficiency of inhibitory control and infant lMFG engagement from Chapter 3. Finally, to examine whether there were any associations between caregiver efficiency and caregiver behaviours and/or infant lMFG and caregiver behaviours, correlations were run while controlling for infant age in days.

4.3. Results.

To examine if there were differences between epochs for each behaviour and play interaction, one-way ANCOVAs with epoch as the independent variable, and infant age in days as a covariate were run separately for caregiver intrusiveness, caregiver scaffolding, infant object engagement, and infant distractibility. Only caregiver scaffolding during MO play showed a main effect of epoch ($F(13,1188) = 1.972$, $p = .020$, $\eta 2 = .02$). However, follow-up comparisons were not significant. Given this, the number of codes were summed across epochs to generate an overall score for each behaviour, which was used in the following analyses to meet the research objectives.

The first objective was to investigate whether there were differences in caregiver and infant behaviours between play interactions. To do this, ANCOVAs were run with play interaction (SO/MO play) as an independent variable, and infant age in days and order of play interaction as covariates, separately for each caregiver and infant behaviour. For caregiver intrusiveness, there were no significant effects. For caregiver scaffolding, there was a significant main effect of play interaction ($F(1,154)$

= 18.471, p < .001, η2 = .11). Follow-up analyses revealed that caregivers engaged in more scaffolding behaviours during MO compared to SO play (p < .001) – see Figure 4.2b. For infant object engagement, there was a significant main effect of play interaction (F(1,156) = 59.852, p < .001, η2 = .28). Follow-up analyses revealed that infants engaged in more object engagement behaviours during MO compared to SO play (p < .001) – see Figure 4.2c. For infant distractibility, there were no significant effects.

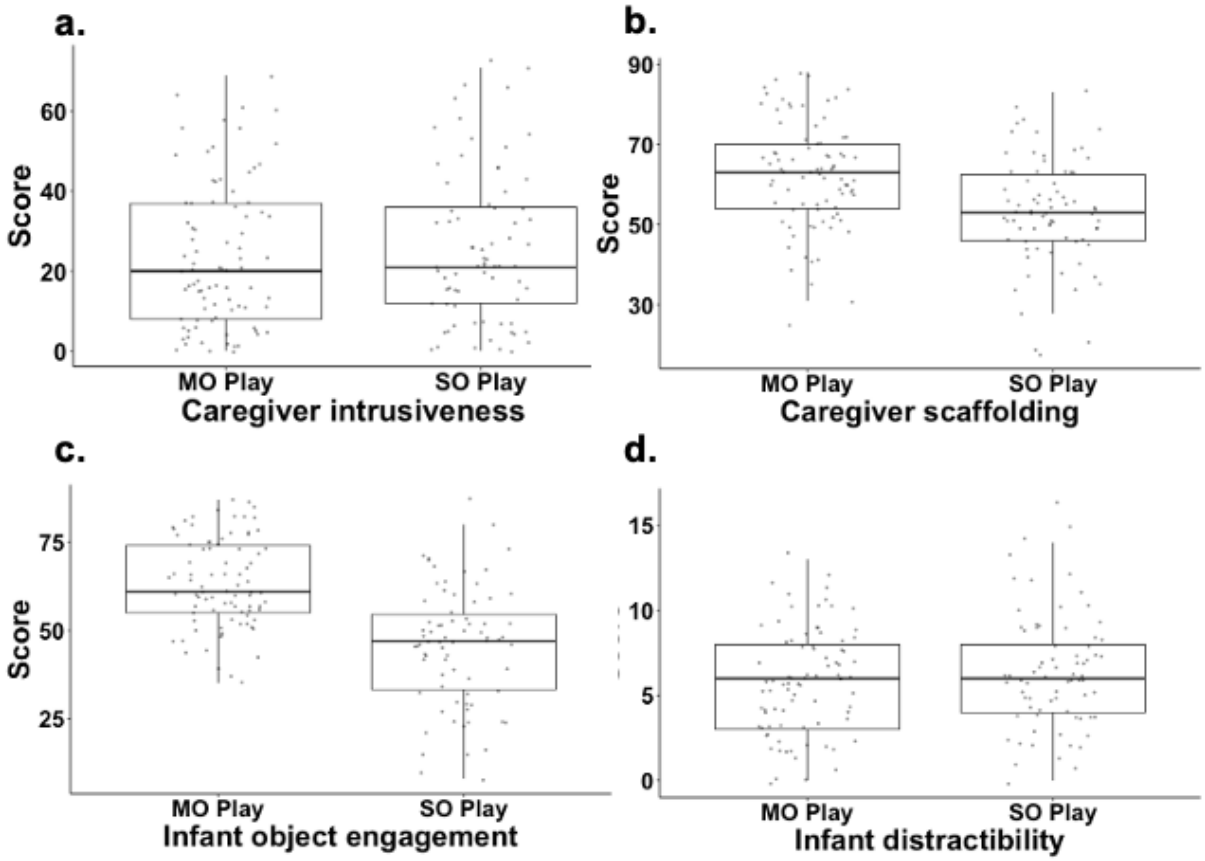


Figure 4.2. Difference between SO and MO play for (a) caregiver intrusiveness, (b) caregiver scaffolding, (c) infant object engagement, and (d) infant distractibility. Significant differences were observed only for caregiver scaffolding and infant object engagement. Each box represents the IQR, with the horizontal line indicating the median. Whiskers extend to 1.5 times the IQR, and data points outside this range are plotted as outliers.

The second objective was to examine whether caregiver and infant behaviours during SO play were associated with the same behaviours during MO play. Here, regression models were run with caregiver/infant behaviour for SO play as the predictor, and infant age in days as a covariate. These were run separately for each behaviour. Results revealed that caregiver intrusiveness (F(1,67) = 23.607, p < .001),

caregiver scaffolding ($F(1,66) = 52.949$, $p < .001$), and infant object engagement ($F(1,68) = 11.191$, $p = .001$) during SO play were associated with the same behaviours during MO play interactions (Figure 4.3). There was no significant association for infant distractibility.

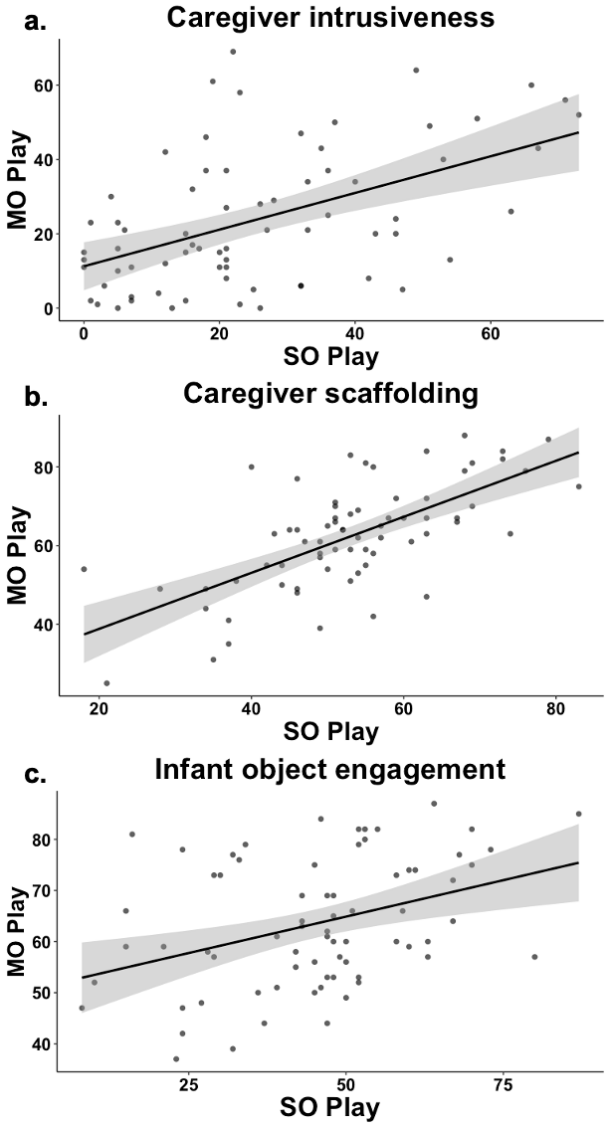


Figure 4.3. Association between SO play and MO play for (a) caregiver intrusiveness, (b) caregiver scaffolding, and (c) infant object engagement.

The third objective was to examine whether caregiver and infant behaviours during play interactions were linked to infant visual working memory performance. First, Pearson's correlations were run between caregiver and infant behaviours for each play interaction to identify behaviours that were significantly correlated with each other, and therefore, must not be included in the same model (see Table 4.6). Results revealed that, for SO play, caregiver scaffolding was significantly correlated

with caregiver intrusiveness ($r = -.38$, $p < .001$) and infant object engagement was significantly correlated with infant distractibility ($r = -.48$, $p < .001$). For MO play, infant object engagement was significantly correlated with infant distractibility ($r = -.63$, $p < .001$). There were no other significant relationships for either play interaction.

Following this, four regression models were run for each play interaction (SO and MO play). In all models, infant CP score at the low load was the outcome variable and infant age in days was a covariate. Centred caregiver and infant behaviour scores were predictors. In the first model, caregiver intrusiveness and infant object engagement were predictors. In the second model, caregiver intrusiveness and infant distractibility were predictors. In the third model, caregiver scaffolding and infant object engagement were predictors. Finally, in the fourth model, caregiver scaffolding and infant distractibility were predictors. Two significant associations were observed only for MO play. Specifically, there was a significant interaction between caregiver scaffolding and infant object engagement ($F(1,73) = 4.593$, $p = .04$). For ease of visualising three continuous variables, caregivers were median split into low and high scaffolding groups. As shown in Figure 4.4a, higher CP score in infants was associated with greater caregiver scaffolding and greater infant object engagement during MO play interactions.

There was also a significant interaction between caregiver scaffolding and infant distractibility ($F(1,72) = 5.293$, $p = .02$). As shown in Figure 4.4b, higher CP score in infants was associated with greater caregiver scaffolding and reduced infant distractibility during MO play interactions.

To account for multiple comparisons, Benjamini-Hochberg procedure with a false discovery rate of 0.1 was applied to p-values of the four interaction effects from the models run for MO play. Both significant interaction effects described above survived this threshold. There were no significant effects for SO play interactions.

*Table 4.6. Correlation between caregiver/infant behaviours for each play interaction. *** represents significance at p<.001.*

SO play				
	1	**2**	**3**	**4**
1. Caregiver scaffolding	-	-.38***	.20	-.20
2. Caregiver intrusiveness		-	.10	.03
3. Infant object engagement			-	-.48***
4. Infant distractibility				-
MO play				
	1	**2**	**3**	**4**
1. Caregiver scaffolding	-	-.12	.08	.00
2. Caregiver intrusiveness		-	-.10	.12
3. Infant object engagement			-	-.63***
4. Infant distractibility				-

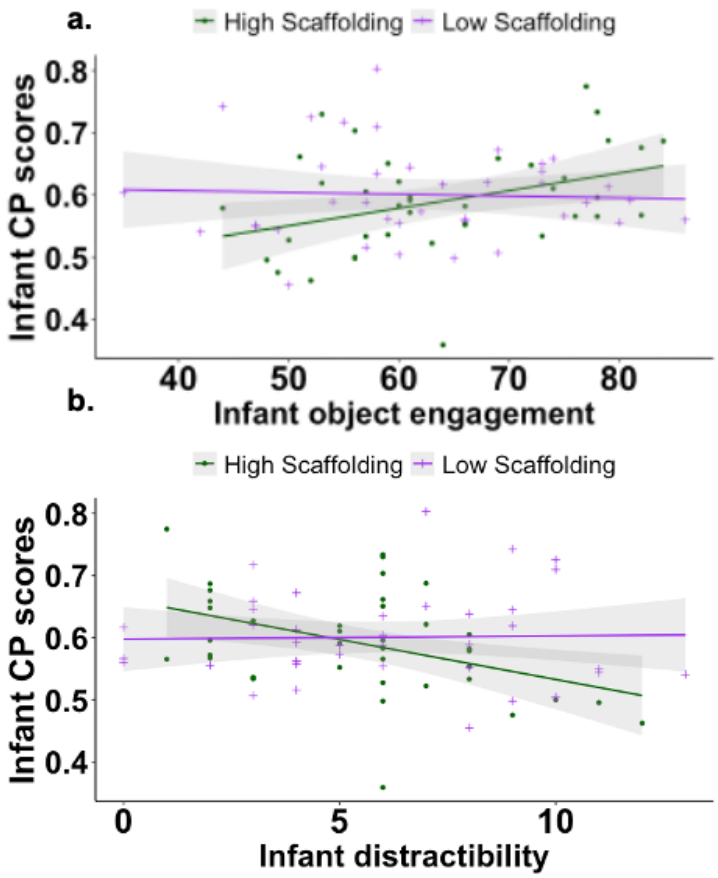


Figure 4.4. Infant CP score was associated with (a) caregiver scaffolding and infant object engagement during MO play, and (b) caregiver scaffolding and infant distractibility during MO play. Caregiver scaffolding was median-split into high and low groups for ease of visualising three continuous variables.

The fourth objective was to examine whether caregiver behaviours mediated the association between caregiver efficiency of inhibitory control and infant lMFG engagement from Chapter 3. Four mediation models were run. The first model examined whether caregiver scaffolding during SO play mediated this relationship, the second model examined caregiver scaffolding during MO play, the third model examined caregiver intrusiveness during SO play, and the fourth model examined caregiver intrusiveness during MO play. Findings revealed no significant mediations for the relationship.

Following this, exploratory correlational analyses were run to examine whether there were any associations between caregiving behaviours, caregiver inhibitory control and infant lMFG activation. Results revealed two significant correlations. Caregiver intrusiveness during SO play was positively correlated with infant lMFG ($r = .33$, $p = .006$), such that greater intrusiveness was linked to

increased lMFG activation – see Figure 4.5a. Further, caregiver scaffolding during MO play was negatively correlated with infant lMFG (r = -.26, p = .02), such that greater scaffolding was linked to reduced lMFG activation – see Figure 4.5b. Next, partial correlations were run to examine whether the link between caregiver scaffolding/intrusiveness and infant lMFG was still present after controlling for caregiver efficiency (as this was linked to infant lMFG in Chapter 3). Both associations survived, i.e. caregiver intrusiveness during SO play was still positively correlated with infant lMFG (r = .32, p = .007) and caregiver scaffolding during MO play was still negatively correlated with infant lMFG (r = -.23, p = .04).

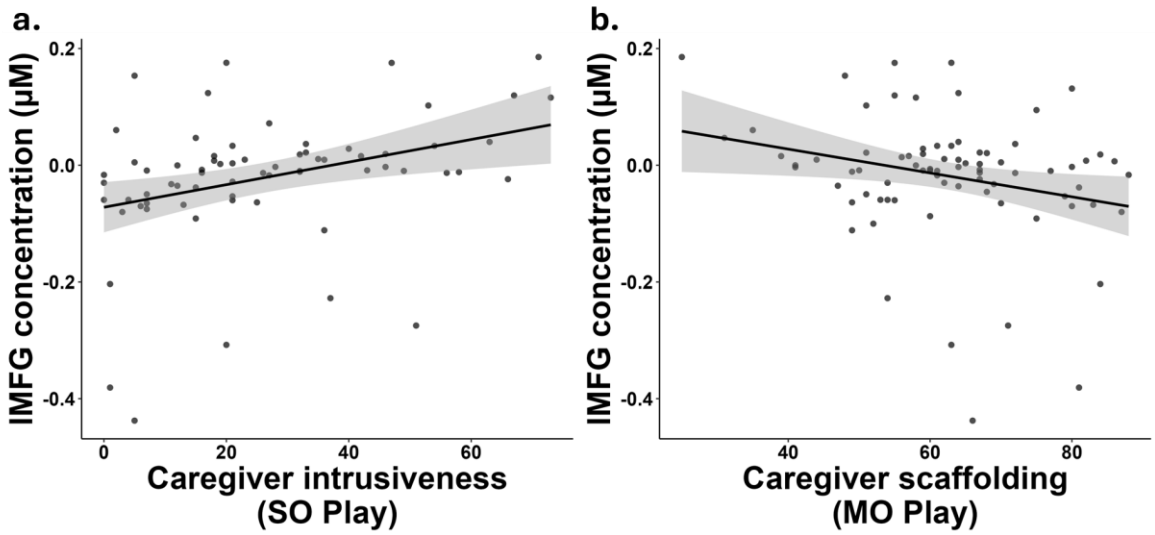


Figure 4.5. (a) Significant correlation between caregiver intrusiveness during SO play and infant left middle frontal gyrus (lMFG) HbO concentration. (b) Significant correlation between caregiver scaffolding during MO play and infant lMFG HbO concentration.

4.4. Discussion.

The current chapter posed four questions to investigate differences in caregiver and infant behaviours between two types of object-based play interactions, and whether these behaviours were associated with concurrent infant visual working memory. The first question inquired whether there were differences in caregiver and infant behaviours during SO and MO play. Caregivers showed greater scaffolding and infants showed greater object engagement during MO play compared to SO play. The second question inquired whether there would be an association between caregiver and infant behaviours during SO play and the same behaviours during MO play. Here, caregiver scaffolding, caregiver intrusiveness, and infant object engagement during SO play interactions were associated with the same behaviours

during MO play interactions. The third question inquired whether caregiver and infant behaviours during dyadic interactions were associated with infant visual working memory. Results showed that interactions between caregiver scaffolding and infant object engagement and caregiver scaffolding and infant distractibility during MO play were associated with infant visual working memory performance. The final question inquired whether caregiver behaviours would mediate the association between caregiver efficiency of inhibitory control and infant lMFG engagement from Chapter 3. Here, no significant mediations were reported but exploratory analyses revealed that caregiver scaffolding and intrusiveness were uniquely correlated with infant lMFG engagement during visual working memory processing. These findings are discussed below.

4.4.1. MO play elicits greater caregiver-infant behaviours compared to SO play.

The first objective was to investigate whether there were differences in caregiver and infant behaviours between SO and MO play interactions. Results revealed that caregiver scaffolding was greater during MO play compared to SO play. This finding was generally in line with previous work in older children. For example, Inan et al. (2024) explored strategies used by caregivers during a structured categorisation task with their preschool-aged children and found that interrogative approaches were positively associated with children's verbal responses. Concretely, key strategies included labelling, labelling questions, probing questions and perceptual cues. These strategies generally align with codes that were more frequently used during MO play compared to SO play in the current study (refer to Table 4.3) – these codes included the caregiver using questions or statements to link objects and a specific location, specifying the function or activity related to an object, and labelling and describing objects to their infant.

It was also found that infants showed greater object engagement during MO play compared to SO play. When examining codes, infants tended to physically bring objects closer to them without caregiver influence more frequently during MO play interactions compared to SO play interactions. This observation is generally in line with previous work showing that infants who demonstrated more advanced object manipulation during naturalistic play showed increased attention to changes in objects (Perone et al., 2008), and increased exploratory behaviours such as mouthing, looking, and fingering (Lobo & Galloway, 2013). Further, the

foundational motor abilities linked to infants of this age (e.g., object permanence (Bremner et al., 2015), motor coordination (Johnson & Blasco, 1997), and basic problem-solving abilities (Keen, 2011)) are more aligned with the objects used in the MO play interactions. Notably, Lobo and Galloway (2013) found that following the onset of reaching, infants not only increased the frequency of exploratory behaviours but also began to combine them in more complex and differentiated ways when interacting with objects. These findings suggest that the capacity to explore object properties emerges actively and selectively from earlier self-exploratory actions and becomes more refined with motor development. Thus, greater tendency for infants to independently bring objects closer during MO play may reflect their growing ability to act intentionally on multi-component objects, leveraging earlier-acquired sensorimotor routines to investigate their affordances in a more goal-directed and sophisticated manner. Concretely, in the current study, infants were able to reach out, grasp and manipulate the components of the objects used in MO play more easily than the objects used in SO play because they were smaller in size. It is also possible that greater caregiver scaffolding during MO play might have further motivated infants to reach out and physically engage with objects. Consequently, observations of increased infant engagement might motivate caregivers to continue to scaffold to maintain their attention on a specific goal during MO play.

It is important to consider why there were only interaction-based differences for scaffolding and object engagement and not for caregiver intrusiveness or infant distractibility. For both behaviours, there was a mixture in frequency of codes. For example, for caregiver intrusiveness, some codes, such as not letting the child set the tone and pace of play, were more frequent in MO play compared to SO play. On the other hand, other codes such as shifting focus on the task before child is ready were more frequent in SO play compared to MO play. Similarly, for infant distractibility, infants showed more instances of shifting interest across multiple objects without staying fixated on one object during MO play compared to SO play. On the other hand, they were more distracted towards their surroundings during SO play compared to MO play. These observations suggest that codes contributing to both behaviours might be heterogenous across play interactions in the first year of life, and so it might be important to examine whether these heterogenous patterns persist into toddlerhood. Additionally, caregiver intrusiveness may be less dependent on the

type of play and more related to the caregiver's general interaction style (H. Hunter et al., 2021). Similarly, infant distractibility may be more influenced by individual differences in temperament and environmental factors than by the type of play interaction itself (Hill-Soderlund & Braungart-Rieker, 2008). MO play involved more intricate activities that may have required higher levels of engagement and problem-solving. Here, caregivers might naturally provide more scaffolding to support their infant's engagement and understanding of complex tasks. Whereas SO play consisted of less demanding objects with fewer elements to focus on and may not have necessitated as much scaffolding from caregivers and object engagement from infants. These findings highlight the importance of considering multiple interaction types as they can provide unique insights into both caregiver and infant behaviours and communication.

4.4.2. SO play behaviours are associated with MO play behaviours.

The second objective was to examine whether caregiver and infant behaviours during SO play were related to the same behaviours during MO play. Findings revealed that caregiver intrusiveness, caregiver scaffolding, and infant object engagement during SO play were associated with the same behaviours during MO play. Previous research has not directly investigated whether behaviours in one type of play is linked to the same behaviours in another type of play within the same timepoint. However, Hunter et al. (2021) examined caregiver intrusiveness when infants were 5 and 10 months of age using a peekaboo task, and at 2 and 3 years of age, using a puzzle task. They reported that caregivers who displayed intrusive behaviours when their children were 10 months of age, were more likely to display the same behaviours when their children were 2 years of age. Similarly, Neale and Whitebread (2019) reported that caregiver propensity to scaffold was consistent across dyadic play interactions at 12-months and 24-months, with greater inclination to engage in goal-oriented play behaviours compared to less-structured play behaviours. Together, these findings suggest that individual differences in caregiver and infant behaviours are relatively stable across different types of play within a timepoint, consistent with broader evidence of behavioural continuity across contexts and developmental stages.

Cross-interaction associations in caregiver scaffolding might also be linked to similar cross-interaction associations observed for infant object engagement. It is

possible that episodes of caregiver scaffolding are temporally linked to episodes of infant engagement, as well as having an over-arching global effect on infant engagement – thus, leading to positive associations across play interactions. Interestingly, there were no cross-interaction associations for infant distractibility which were expected based on findings from Kannass and colleagues (2006) who found evidence of stability in distractibility between 9 and 31-months during multiple object free play. Specifically, they reported that children who were better at inhibiting responses to distracting stimuli in a distractibility task, were also better able to inhibit their response to distracting stimuli in the multiple object free play. However, this finding was observed in 31-month-old children; this sample was substantially older than the infants in the current study. Therefore, it is possible that positive cross-interaction effects for infant distractibility might emerge later in toddlerhood.

4.4.3. Caregiver-infant behaviours are associated with infant visual working memory.

The third objective examined whether caregiver and infant behaviours during both dyadic interactions were associated with infant visual working memory performance. Specifically, higher CP scores were observed in infants who showed better object engagement and reduced distractibility and had caregivers with better scaffolding abilities. This finding generally aligns with previous work, although findings are mixed regarding unique contributions from caregivers and infants, in most cases due to the examination of solely caregiver behaviours. For example, some studies have only reported links between caregiver behaviours during dyadic interactions, and infant attention and executive functions. For example, Swingler et al. (2017) found that caregiver positive affect when their infants were 5 months of age was associated with greater improvements in their infants' attention behaviours during an attention task between 5 and 10 months of age. Relatedly, caregiver scaffolding has been shown to support child executive function development (Hughes & Ensor, 2009), and maternal sensitivity to predict child working memory (Ribner et al., 2022). A few other studies have shown links between both caregiver and infant behaviours during dyadic interactions, and infant abilities. For example, infant sustained attention in the context of caregiver-infant joint attention, and not joint attention was shown to predict later vocabulary (Yu et al., 2019). Further, both

infants' willingness to initiate and caregiver responsivity has been shown to have different contributions to early language development (Paavola et al., 2005). Interestingly, the remaining studies have shown links between infant behaviours during interactions and infant cognition. For example, in one study, infant engagement, but not caregiver responsiveness represented by teaching duration and sensitivity, predicted infant accuracy in an object search task delivered in a naturalistic manner (Clackson et al., 2019). Another study examined the link between infant exploratory behaviours and later problem-solving and found that the extent of object exploration was predictive of more successful and sophisticated problem-solving skills (Caruso, 1993). Finally, more generally in line with the current findings, a recent study found that caregiver responsiveness positively affected infants' attention to social events, which in turn reduced their distractibility. This reduced distractibility mediated the relationship between caregiver responsiveness and improved language outcomes at 18 months (Testa et al., 2023). While these studies support findings from the current study, it is important to acknowledge that infants with better visual working memory might have been able to better engage with objects during MO play, motivating caregivers to increase scaffolding - thus, explaining the reported association. Future work should examine these links longitudinally to establish causality.

Interestingly, links between dyadic behaviours and infant visual working memory were only observed for MO play, and not for SO play. This might be explained by differences in the play interactions. During MO play, infants were able to reach out, grasp and explore the individual parts of the objects as they were smaller in size. Caregivers also encouraged them to physically manipulate these objects, stack them, sort them, or press them – true to the functional purpose of the objects. Increased infant engagement might have further motivated caregivers to continue to scaffold the interaction. Consequently, the structured nature of MO play interactions might have afforded more exposure to constructs such as numerosity (rings of varying sizes, shapes, counting etc.), object permanence (disappearing blocks into the sorter etc.), object irregularities (square blocks stopped by circular holes in the sorter etc.) and novelty detection (incorrect stacking etc.) – improving attention and visual working memory. On the other hand, during SO play, caregivers used objects in narrative play, potentially encouraging the emergence of

understanding abstract concepts and representations (Lockman & Tamis-LeMonda, 2021), but not necessarily to challenge low and high-level perceptual, attention and cognitive functions. These differences might explain why there were robust links between dyadic behaviours and infant visual working memory for MO play but not for SO play.

It is important to also consider why there was no link between caregiver intrusiveness and infant visual working memory performance, particularly because previous work suggests that caregiver intrusiveness affects cognitive outcomes. For example, caregiver intrusiveness during structured play when infants were between 5 and 10 months of age has been shown to predict preschool executive functions, and intrusiveness during unstructured play moderated the link between neural activation and later executive functions (Broomell et al., 2020). Additionally, from Chapter 3, it was hypothesised that high efficiency caregivers might be better at appropriately inhibiting and regulating their thoughts, behaviours, and actions, thus, exhibiting less intrusive behaviours during interactions. One possibility is that caregiver intrusiveness during the first year of life does not have profound impacts on concurrent infant visual working memory but might impact later cognitive outcomes. It may be that the cumulative effects of intrusive behaviours over time, or their influence on the development of self-regulatory processes, only become apparent as cognitive demands increase with age. Alternatively, early intrusiveness might shape emerging cognitive trajectories in more subtle ways that are not yet detectable in infancy.

4.4.4. Caregiver behaviours are associated with infant brain function during visual working memory processing.

The fourth objective was to examine whether caregiver behaviours could explain associations between caregiver efficiency and infant visual working memory brain function that were reported in Chapter 3. Specifically, better caregiver efficiency was associated with reduced lMFG activation in infants (Davidson et al., 2024), a region involved in attentional control and distractor suppression (D'Esposito & Postle, 1999). However, contrary to expectations, neither caregiver intrusiveness nor caregiver scaffolding mediated this association in either play context. Instead, exploratory analyses revealed that these dyadic behaviours were

independently associated with infant lMFG engagement, over and above caregiver efficiency. Specifically, higher caregiver intrusiveness during SO play was associated with increased infant lMFG activation, whereas greater caregiver scaffolding during MO play was associated with reduced infant lMFG activation. The link between intrusiveness and lMFG activation may reflect the additional cognitive effort required for infants to sustain attention in the face of controlling or disruptive input, consistent with prior research showing that intrusive caregiving is linked to suboptimal neural functioning during attention tasks (Swingler et al., 2017). In contrast, the association between scaffolding and reduced lMFG activation may indicate that supportive, contingent input from the caregiver helps infants engage more efficiently with the task, requiring less top-down attentional control. Importantly, these associations differed by play context, highlighting the role of interactional affordances. For example, the complexity of MO play may provide more natural opportunities for caregivers to engage in supportive scaffolding, helping infants to navigate more demanding interactional content. On the other hand, SO play might be mostly caregiver-led due to the size and shape of the objects, leaving little room for infant engagement, and/or caregivers to guide infants on engaging with the objects. These patterns underscore the importance of distinguishing between caregiver behaviours and recognising the unique influence of context when interpreting links with infant brain function. Collectively, the findings highlight that specific caregiver behaviours, not just global caregiving quality, play a critical role in shaping the development of infant attentional systems.

4.5. Conclusion.

The current chapter investigated whether caregiver and infant behaviours during dyadic play interactions were associated with infant visual working memory. Caregivers and their infants, aged between 6 and 10-months, engaged in two dyadic play interactions: SO play and MO play. Both interaction types were coded to extract caregiver intrusiveness, caregiver scaffolding, infant object engagement, and infant distractibility behaviours. Infants were also presented with a preferential looking task. Findings revealed that caregivers showed greater scaffolding and infants showed greater object engagement during MO play compared to SO play. Additionally, caregiver scaffolding and intrusiveness, and infant object engagement during SO play were positively associated with the same behaviours during MO

play. Critically, interactions between caregiver scaffolding and infant object engagement, and caregiver scaffolding and infant distractibility during MO play were associated with infant visual working memory. Specifically, for infants with higher CP scores, increased object engagement and reduced distractibility was associated with greater caregiver scaffolding. Here, caregiver scaffolding behaviours might encourage active exploration and learning and thus result in more engagement and less distractibility in infants during play interactions. Finally, caregiver behaviours did not mediate previously-reported associations between caregiver efficiency and infant lMFG engagement (from Chapter 3). Instead, caregiver intrusiveness and caregiver scaffolding were uniquely associated with infant lMFG engagement directly. Overall, this chapter provides a foundation for understanding how caregivers and their infants engage in dyadic play interactions during early development, offering insight into the behaviours observed at 6–10 months.

4.6. Motivations for next chapter.

The findings presented here demonstrate that specific caregiver and infant behaviours during dyadic play are associated with infant visual working memory. Differences in behaviours between SO and MO play highlight how the content and organisation of play interactions shape infant visual cognition. Moreover, caregiver behaviours during play were associated with infant brain function, suggesting that everyday play interactions offer a meaningful context for supporting early cognitive development. These findings suggest that the impact of caregiver–child interactions may vary depending on the context of the interaction and the child's developmental stage. The next chapter builds on this by examining how these dyadic behaviours evolve longitudinally, exploring stability and change as the children reach 18–22 months and begin to demonstrate more advanced social, cognitive, and play-related skills. This developmental window marks a period of rapid change in self-regulation, communicative intent, and goal-directed behaviour, capacities that may reshape the way children engage in and influence dyadic play. By using the same play interactions (SO and MO play) and focusing on the same caregiver and child behaviours (intrusiveness, scaffolding, object engagement, and distractibility), the chapter aims to investigate the stability of early interaction patterns. This longitudinal approach provides critical insight into early caregiving processes and their alignment with children's emerging developmental capacities.

Chapter 5:

Experiment 3: Longitudinal caregiver-child dyadic interactions.

5.1. Introduction.

Understanding longitudinal stability in caregiver-child play interactions is essential for appreciating the dynamic nature of caregiving in response to a child's evolving needs. While stable, positive interactions, such as sustained responsiveness and emotional attunement, provide a secure base that supports early social, emotional, and cognitive development (Bornstein & Suess, 2000; Kochanska & Aksan, 2004), caregiving must also adapt over time. Children's developmental trajectories, including changes in socio-motor engagement and autonomy, require that caregivers modify their behaviours to remain appropriately supportive (Kopp, 1982; Perea-Velasco et al., 2023). For instance, as children gain motor competence and social initiative, caregivers must shift from direct guidance to scaffolding that encourages independence while still offering support. Investigating the balance between stability and flexibility in social interactions can uncover how both consistency and adaptability contribute to resilience, social competence, and optimal long-term developmental outcomes (Blair et al., 2015).

5.1.1. Caregiver-child behaviours during dyadic interactions in toddlerhood.

Toddlerhood is a critical period of development in which significant changes in social and emotional functioning occur (Sroufe, 2002). It is typically characterised by improved motor ability, language, cognition, and emotional competence (Denham, 1998). Examining caregiver-child behaviours within social interactions during this particular period offers a unique lens through which to observe the moment-to-moment exchanges that shape early learning and relationship quality. For instance, Keren et al. (2005) explored how the nature of parent-child interactions during play influenced toddlers' symbolic play abilities, using observations of toddlers with their mothers and fathers in both dyadic (one parent and child) and

triadic (both parents and child) play settings. The authors found that parents' facilitative-creative interaction style during dyadic play predicted toddlers' symbolic abilities. Within triadic play, a coparenting style marked by cooperation and autonomy was found to predict toddlers' symbolic expression. These findings suggest that the presence and coordinated involvement of both parents during play can foster greater symbolic development in young children. In line with the importance of facilitative behaviours, Wilson and Durbin (2013) investigated parent-child interactions by examining the types of bids (e.g., for social contact, influence, or mood regulation) and responsiveness between mothers, fathers, and their young children aged between 3 and 6 years. Using structured observational tasks and detailed event-based coding, the study assessed how interaction patterns varied between mother–child and father–child dyads. Results showed that mothers made more social and emotional bids and were generally more responsive than fathers, who made more influence-oriented bids. Children's bids also changed with age, with the older children initiating more influence bids and fewer negative affect bids. Notably, there were significant within-family consistencies. Specifically, children were similarly responsive to both parents, and mothers' and fathers' responsiveness levels were moderately correlated, emphasising the bidirectional nature of caregiver-child interactions.

Research examining the quality and flexibility of caregiver-child interactions has shown that both the emotional tone and the caregiver's role can differentially shape children's behavioural and developmental outcomes. Lunkenheimer et al. (2011) examined how dyadic flexibility and positive affect in early parent–child interactions predicted the development of externalising behaviour problems in children. Using observational data from mother–child and father–child dyads engaged in a challenging task at age 3, the researchers measured dyadic flexibility (defined by range, dispersion, and transitions among emotional states) and positive affect. After controlling for child effortful control, gender, task time, and negative affect, the authors found that the interaction between high dyadic flexibility and positive affect predicted lower externalising behaviours at age 5.5. Interestingly, mother–child flexibility alone was linked to higher behaviour problems, while father–child flexibility predicted lower issues, suggesting differing implications based on parent gender. The findings suggest that dynamic, emotionally positive

interactions offer real-time opportunities for children to practice regulation skills, contributing to better adjustment in school settings. Additionally, it highlights that different caregivers can play varying roles in shaping children's behavioural development. In a similar vein, Klein and Feldman (2007) compared the quality of interactions between toddlers and their mothers versus those with daycare workers, focusing on sensitivity, teaching behaviours, and the role of child temperament and development. The study used standardised developmental assessments and behavioural coding while toddlers were observed during one-on-one play at home and in daycare. Although mothers and daycare workers demonstrated similar levels of sensitivity and intrusiveness overall, the daycare workers were more likely to use "affecting" behaviours (i.e., endowing things with meaning or expressing enthusiasm) and exert more control through commands. Importantly, maternal sensitivity was positively linked to children's mental development scores, while daycare worker intrusiveness was negatively related, particularly for toddlers rated as fussy or unpredictable. The findings highlight the influence of child characteristics on adult interaction styles, suggesting that while daycare workers may strive to provide quality care, their responses can be more reactive to child temperament compared to mothers' generally more consistent and developmentally attuned behaviour. This work underscores the importance of considering different contexts, as they reveal how various caregiving styles and the nuances of parent-child dynamics can distinctly influence child development. However, to fully understand the breadth of caregiver-child interactions, it is essential to examine different types of interactions.

The structure and nature of play contexts can significantly influence the quality of caregiver–child interactions and the developmental opportunities they afford, particularly in the areas of communication and engagement. For example, Quinn and Kidd (2019) showed that symbolic play, compared to functional play, promoted more frequent and sustained joint attention episodes and increased gesture use, particularly gestures that supported shared meaning-making. Such communicative behaviours are central to early social-cognitive development and align with socio-cultural theories highlighting the role of collective intentionality in symbolic play (Rakoczy, 2008). Relatedly, Kwon et al. (2013) examined how the social context of parent–toddler interactions, specifically, structured tasks versus free

play, shaped parenting quality, child engagement, play behaviours, and language use. Both mother–child and father–child dyads were observed during laboratory-based sessions involving a structured problem-solving task and an unstructured free play period. The study found that free play elicited higher-quality parenting behaviours, such as greater cognitive scaffolding and fewer negative interactions, alongside richer and more complex language use by both parents and toddlers. Toddlers also showed greater engagement and a wider variety of play behaviours during free play than during structured tasks. These effects were consistent across parent gender, with minimal differences between mothers and fathers. The findings underscore the importance of unstructured play contexts in supporting sensitive, developmentally appropriate caregiver–child interaction, and suggest that free play offers a more naturalistic and enriching environment for fostering early cognitive and communicative development. Such research emphasises how different interaction types, such as play activities and task structures, can shape behaviours and developmental outcomes. However, to fully understand the trajectory of these interactions, it is crucial to explore how such dynamics evolve over time and contribute to longitudinal changes in both caregiver and child behaviours.

5.1.2. Longitudinal changes in caregiving behaviours.

A growing body of longitudinal research has illuminated how caregivers dynamically adjust their behaviours in ways that both reflect and support children's developmental progression, highlighting a nuanced interplay between behavioural stability and context-sensitive change. For example, Bornstein and colleagues (2008) investigated the structure, variability, and continuity of maternal responsiveness across early childhood. Maternal responsiveness refers to prompt, contingent, and appropriate reactions to children's behaviours, which are essential for child development (Bornstein & Manian, 2013). Mothers were asked to engage their children in natural home-based free play interactions at three time-points, i.e. 10, 14, and 21 months. Results revealed that maternal responsiveness showed a mix of stable and changing patterns. For example, while overall responsiveness to the child's behaviours was stable, specific types of responsiveness (such as the frequency of questions or play prompts) changed to match the child's growing cognitive and social abilities. This result aligns with findings that parents naturally adjust their interactions as children develop more complex social and cognitive skills

(Tamis-LeMonda et al., 2001). These results highlight the role of dynamic, tailored parenting; as children's social and communicative abilities evolve, effective parenting involves adjusting responsiveness in ways that are developmentally relevant (Bornstein et al., 2008). This dynamic interaction aligns with developmental theories that emphasise bidirectional influences in parent-child relationships, where children's behaviours elicit specific maternal responses (Bell, 1979). Such adaptability in responsiveness supports children's emotional and social development, fostering a responsive parent-child relationship that evolves over time (Landry et al., 2001). Extending this finding, Neale and Whitebread (2019) examined longitudinal changes in maternal scaffolding behaviours with children at 12, 18, and 24 months. A strength of this study was its use of multiple toy types (ring toys and stacking cups), allowing for investigation of both temporal and cross-contextual consistency in caregiver behaviours. The findings showed that propensity to scaffold, the amount of time mothers spent engaging in structured, goal-oriented support, was relatively stable across both time and toy contexts. Maternal contingency, or how appropriately mothers adjusted their level of help based on the child's success or failure, showed consistency across toys but not across time. Importantly, maternal contingency at 12 months predicted children's effortful control at 24 months, even when early effortful control was accounted for. Further, maternal contingent interventions often led directly to children's successful actions, suggesting a developmental mechanism by which early caregiver behaviour shapes emerging self-regulation. Furthermore, mothers who consistently used contingent scaffolding over time had children who performed significantly better on measures of effortful control and cognitive development, highlighting the value of sustained, sensitive support (Neale & Whitebread, 2019). This study underscores the importance of examining caregiver behaviours not only over time but across different toy types to determine their stability and developmental significance. More recently, Perea-Velasco et al. (2023) examined longitudinal changes in mother-child interactions during the first 18 months of life, focusing on maternal sensitivity and response latency. The research centred on two main constructs: maternal response appropriateness and promptness in real-time interactions, assessing whether maternal behaviours supported the child's autonomy and developmental needs across key age milestones (6, 12, and 18 months). They found that sensitive responses increased significantly over time, with mothers being most sensitive at 18-months. In contrast, intrusive behaviours, which

interrupt the child's actions or invade their space, steadily decreased, suggesting that mothers became less intrusive as children gained more independence (Perea-Velasco et al., 2023). Further, the promptness of maternal responses to child-initiated behaviours remained relatively stable across all age groups. However, the latency of maternal responses to play behaviour increased over time, indicating that mothers allowed more time for independent play as children matured, promoting autonomy and exploration. Together, these works highlight the complexity of caregiver-child interactions and the importance of scaffolding and sensitive caregiving in fostering positive developmental outcomes. However, each of these studies focused on a single type of play interaction at each timepoint. While Neale and Whitebread (2019) included two toy types in their study, both were presented within a single play session, potentially making it difficult to disentangle the specific caregiver and child behavioural responses each toy individually elicited. This observation highlights the importance of longitudinally examining behaviours across distinct types of play interactions, as it can more clearly reveal whether these behaviours are stable or vary depending on the nature of the interaction.

5.1.3. Longitudinal changes in child behaviours.

Previous work tracking child development over time highlights substantial changes in attentional processes and exploratory play from infancy through toddlerhood. As children mature, their ability to focus, persist, and selectively attend to relevant stimuli becomes increasingly sophisticated (Hanania & Smith, 2010; Plebanek & Sloutsky, 2019). Evidence from longitudinal studies suggests that even within the first two years, attentional capacities evolve in ways that influence how children interact with objects and people in their environment. Kannass and Oakes (2008) provided a clear developmental trajectory of attention by following children from 9 to 31 months across different play contexts. Their findings suggested that early attentional behaviours were sensitive to task structure and evolved distinctly depending on whether children were engaging with a single object or multiple objects. At 9 months, infants exhibited relatively undifferentiated attention patterns across both contexts, whereas by 31 months, toddlers showed more sustained and efficient attention, particularly in structured, single-object play. In more complex multiple-object scenarios, toddlers displayed fewer distractions and longer episodes of focused looking, indicating emerging goal-directed attentional control. These

changes suggest that over time, children become better equipped to manage attentional demands during free play, which has implications for how they will come to engage with objects in increasingly autonomous and selective ways (Kannass & Oakes, 2008). Similarly, Schneider and Scher (2011) examined changes in exploratory behaviours across the second half of the first year, focusing on how infants engage with objects during semi-structured play at home. Their work revealed consistent developmental increases in attention, persistence, and complexity of play behaviour between 10 and 14 months. Of note, 12 months of age was a potential turning point - infants began to show more deliberate and sustained interactions with their environment. These behavioural shifts were not only related to age, but also predictive of later developmental competencies, suggesting that early object exploration reflects emerging cognitive and motivational capacities. Importantly, infants who were more attentive and persistent also demonstrated more advanced object play, indicating that engagement is shaped by growing self-regulation and purposeful exploration (Schneider & Scher, 2011). Along a similar vein, McQuillan et al. (2021) examined sustained attention in a large longitudinal sample of toddlers between 30 and 42 months, using both unstructured free play and structured sorting tasks. In the free play context, they found moderate stability in attentional performance over time, with particularly strong associations between 30 and 36 months. Notably, there was observed growth in toddlers' capacity to engage in more focused, goal-directed attention during play as they aged, even in the absence of external guidance. These changes were interpreted as part of a broader developmental shift towards greater attentional control and self-regulation. Importantly, sustained attention during free play was not only predictive of later attention outcomes but also influenced by other developmental factors such as language ability and sleep consistency. Together, these findings reinforce the view that sustained attention during naturalistic play undergoes marked, measurable improvements in toddlerhood, contributing directly to children’s growing ability to engage with their environment in deliberate and persistent ways (McQuillan et al., 2021). Overall, this research points to a developmental arc wherein children gradually move from reactive, stimulus-driven attention to more controlled and intentional engagement with objects. As such, one can expect children’s engagement with objects and tasks to become increasingly organised and sustained over time.

These arguments also imply that the structure of the environment may differentially impact these changes across infancy and into toddlerhood.

5.1.4. The current study.

Although considerable research has explored caregiver–child interactions, important gaps remain in understanding how dyadic behaviours develop and change longitudinally from infancy through toddlerhood. Most existing longitudinal studies examine a single type of play interaction at each timepoint, limiting the understanding of how behaviours evolve across different contexts. Although studies like Neale and Whitebread (2019) included multiple toy types, all were presented within a single session, making it difficult to distinguish behavioural patterns specific to each context. Moreover, research that examines multiple interaction types (e.g., Quinn & Kidd, 2019) often does so at a single timepoint, resulting in a lack of longitudinal evidence on how caregiver and child behaviours differ between play types over time. In addition, inconsistencies in how constructs such as intrusiveness are measured, particularly the use of different coding schemes across studies and timepoints, make it challenging to synthesise findings and identify nuanced developmental patterns. Longitudinal research that applies a consistent coding approach across multiple interaction types and ages is therefore well positioned to provide clearer insights into how caregiver–child behaviours shift over time and context. Addressing these gaps could yield a more comprehensive understanding of how dyadic behaviours evolve across early childhood.

The current study investigated whether there are longitudinal changes in caregiver-child dyadic behaviours from infancy to toddlerhood. To achieve this, caregivers and infants from the sample described in Chapter 4 were followed up one year later. Caregivers were asked to engage their child in SO play and MO play interactions. Concretely, in the first-year, children were between 6 and 10 months of age, and in the second year, children were between 18 and 22 months of age. Following the methodology described in Chapter 4, caregiver intrusiveness, caregiver scaffolding, child object engagement, and child distractibility were coded during these interactions.

The current study had five research objectives. The first two objectives were focussed on caregiver-infant behaviours from the second year of life. The first

objective was to examine whether there were differences in caregiver and toddler behaviours between both types of play interactions in the second year. In the previous chapter, there was greater caregiver scaffolding and infant object engagement during MO play compared to SO play. Current predictions focused on scaffolding and object engagement because these behaviours showed clear differences between play interactions in infancy, suggesting they are particularly sensitive to play context. In contrast, intrusiveness and distractibility did not show consistent variation previously, so no strong expectations were formed for these behaviours here. The second objective was to examine whether caregiver and toddler behaviours during SO play would be associated with the same behaviours during MO play, in the second year of life. In the previous chapter, there were positive associations between SO play and MO play for caregiver scaffolding, caregiver intrusiveness, and infant object engagement. Similar associations were predicted here, while no specific prediction was made for distractibility, as it did not show consistent cross-context links previously.

The third objective was to examine whether there were differences in caregiver-child behaviours between the first to the second year of life. Based on findings from Perea-Velasco and colleagues (2023) showing that maternal intrusiveness decreased as children grew older, it was expected that caregiver intrusiveness would reduce from the first to the second year . As scaffolding has shown consistency across developmental timepoints in previous work (Neale & Whitebread, 2019), it was unclear whether there would be differences in the current study. Regarding child behaviours, it was expected that object engagement would increase, and distractibility would decrease in the second year. This prediction was based on findings from Schneider and Scher (2011) who reported developmental increases in child attention, persistence, and complexity of play from 10 to 14 months.

The fourth objective was to determine whether caregiver-child behaviours in the first year would predict the same behaviours in the second year. For example, does caregiver scaffolding during SO play in the first year predict caregiver scaffolding during SO play in the second year, and so on. Previous work has shown that caregiver scaffolding demonstrated longitudinal stability from 12 to 24 months (Neale & Whitebread, 2019). Therefore, it was expected that caregiver scaffolding during the first year would be predictive of scaffolding in the second year.

Additionally, based on previous research showing consistent increases in child attention across developmental timepoints (Schneider & Scher, 2011), it was predicted that child object engagement in the first year would predict object engagement in the second year. Further, as previous work has shown stability in distractibility from 9 to 31-months during play (Kannass et al., 2006), predictability was also expected across timepoints for this child behaviour. Similarly, predictive relationships were expected for caregiver intrusiveness, given findings that showed caregivers who were intrusive at 10 months were also intrusive at 2 years (Hunter et al., 2021).

The final research objective was to examine whether caregiver behaviours in the first year were predictive of child behaviours in the second year for each play interaction. Previous work has shown that contingent and sensitive scaffolding may influence the development of child self-regulation and attentional control. For instance, Neale and Whitebread (2019) found that maternal contingency at 12 months predicted children's effortful control at 24 months. Well-timed scaffolding during early play interactions may therefore play a critical role in supporting the development of regulatory skills that enable sustained object engagement in children. On the other hand, while McQuillan et al. (2021) acknowledged caregiver involvement as a potential influence, they reported that that development of sustained attention was predominantly shaped by child-based factors such as language. Given these mixed findings, no strong predictions were made. Instead, these relationships were examined using exploratory analyses.

5.2. Methods

5.2.1. Participants.

Refer to section 3.2.1. in Chapter 3 for full participant recruitment details.

The recruited families from the previous chapter were followed a year later when their children were between 18 and 22-months of age. Additionally, new families with children between the ages of 18 and 22-months of age were also recruited in line with other objectives of the larger project. The same criteria were followed for the new families. Throughout this chapter, Year 1 will be represented as Y1 and Year 2 will be represented as Y2. Ethical approval was granted by the School of Psychology Ethics Committee (Y1 Approval Reference: F1415, Y2 Approval Reference: F1395).

At Y1, a total of 91 caregivers (90 females, 1 non-binary, Mage = 33.5 years, SD = 4.5) and 91 infants (46 females, Mage = 251.3 days, SD = 34.9) participated in the study. At Y2, 67 families from Y1 and 5 newly recruited families contributed data. The final sample at Y2 consisted of 72 caregivers (71 females, 1 non-binary, Mage = 34.3 years, SD = 4.4) and 72 toddlers (40 females, Mage = 614.9 days, SD = 24.5). A schematic representation of inclusion at Y1 and Y2 is shown in Figure 5.1. Other demographic and socioeconomic status information is provided in Table 5.1. Task specific exclusions for Y1 and Y2 are presented in the following sections.

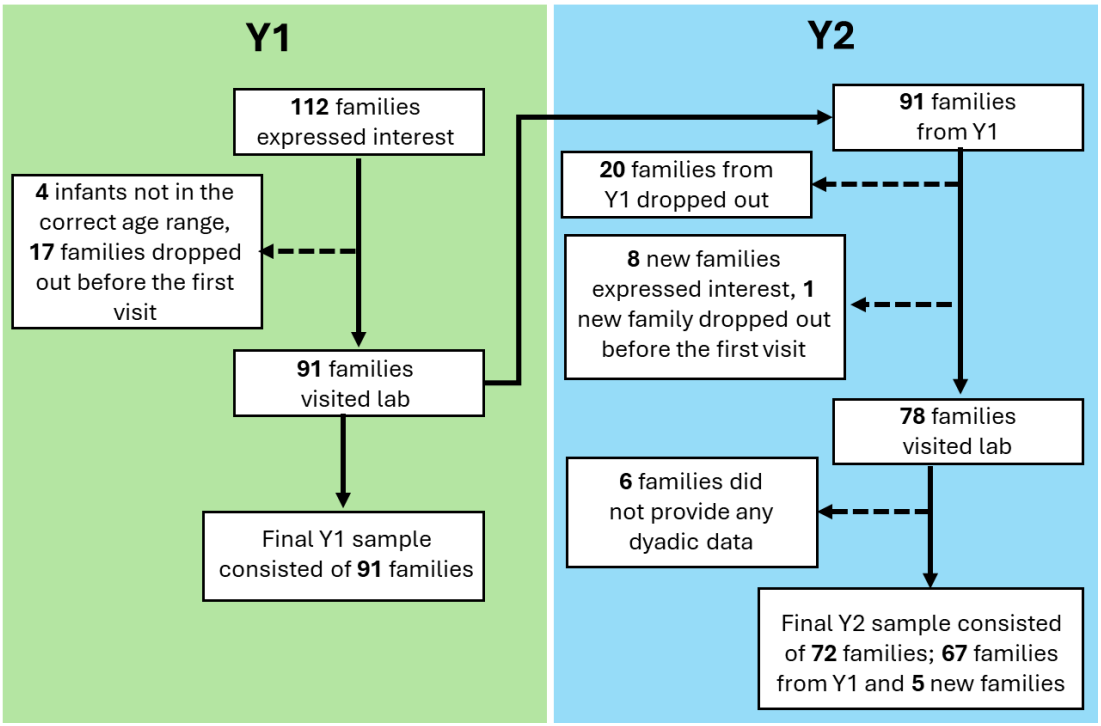


Figure 5.1. Schematic for recruitment and inclusion across Y1 and Y2.

Table 5.1. Socioeconomic and demographic information was collected via questionnaire shortly after the family visited the research facility. In some cases, the questionnaire was not filled out, as indicated by N in each case.

Measure	Y1			Y2		
	N	Mean	SD	N	Mean	SD
Child age (days)	91	251.3	34.9	72	614.9	24.5
Primary caregiver age (years)	91	33.5	4.5	72	34.3	4.4
Primary caregiver education (years)	80	16.1	2.6	65	16.3	2.7
Secondary caregiver education (years)	77	13.9	4.3	63	13.9	4.1
Primary caregiver income	72	£ 27,507	£ 13,296	59	£ 27,695	£ 12,570
Secondary caregiver income	49	£ 31,595	£ 11,564	43	£ 30,343	£ 10,829
Primary Caregiver's Ethnicity	**N**	**%**		**N**	**%**	
Asian	5	5.5		4	5.5	
Mixed	4	4.4		3	4.2	
Arab	1	1.1		1	1.4	
White British	69	75.8		56	77.8	
Other White	1	1.1		1	1.4	
Did not answer	11	12.1		7	9.7	

5.2.2. Dyadic play interactions.

Please refer to section 4.2.2. in Chapter 4 for full play interaction details. Note that some Y1 details from this section will be repeated here for clarity.

Detailed coding of the interactions revealed that, for Y1, in SO play interactions, objects were used symbolically on average 5.95% of the time (SD = 9.57%) and functionally 94.05% of the time (SD = 9.57%). In MO play interactions, symbolic use occurred on average 6.7% of the time (SD = 10.9%), while functional use occurred 93.3% of the time (SD = 10.9%). For Y2, in SO play interactions, objects were used symbolically 6.44% of the time (SD = 11.79%) and functionally 93.56% of the time (SD = 11.79%). In MO play interactions, objects were used symbolically 6.25% of the time (SD = 12.10%) and functionally 93.75% of the time (SD = 12.10%). Both interaction types lasted for 7-minutes in both years.

There was a difference in seating arrangement between Y1 and Y2 (Figure 5.2a-d). In Y1, dyads were seated face-to-face with the caregiver sitting in a chair across from their infant in a highchair with a tray attachment. A white table was placed beside the caregiver to hold the objects when not in use. In Y2, dyads were seated face-to-face with the caregiver sitting in a chair across from their child in a highchair. A white table was positioned between them with the objects placed within arm's reach of the caregiver. The differences in seating arrangements between the two years were due to several reasons. First, the highchair table was used in Y1 to avoid infants feeling separated and becoming upset by allowing for closer proximity between dyads. Second, the white table was used in Y2 to allow more room for playing with the objects. In both years, if children were fussy and/or would not go into the highchair, the interactions were completed with the children on the caregiver's lap with the objects on the white table in front of the dyad. PsychoPy v2021.2.3 was used to instruct the caregiver of the start and end times of the interaction, signalled by a 'beep' sound and a white flash on a TV screen.

Real-time recordings were presented on a laptop on the experimenter side of the room using Bandicam (https://www.bandicam.com/) and Movavi programs (https://www.movavi.com/). These recordings were presented in real-time to the experimenters so they could monitor the interactions. In Y2, both video cameras were on tripods, with one facing toward the child and the other facing toward the caregiver. Caregivers also wore head-mounted cameras; however, this view was only used to confirm codes when necessary.

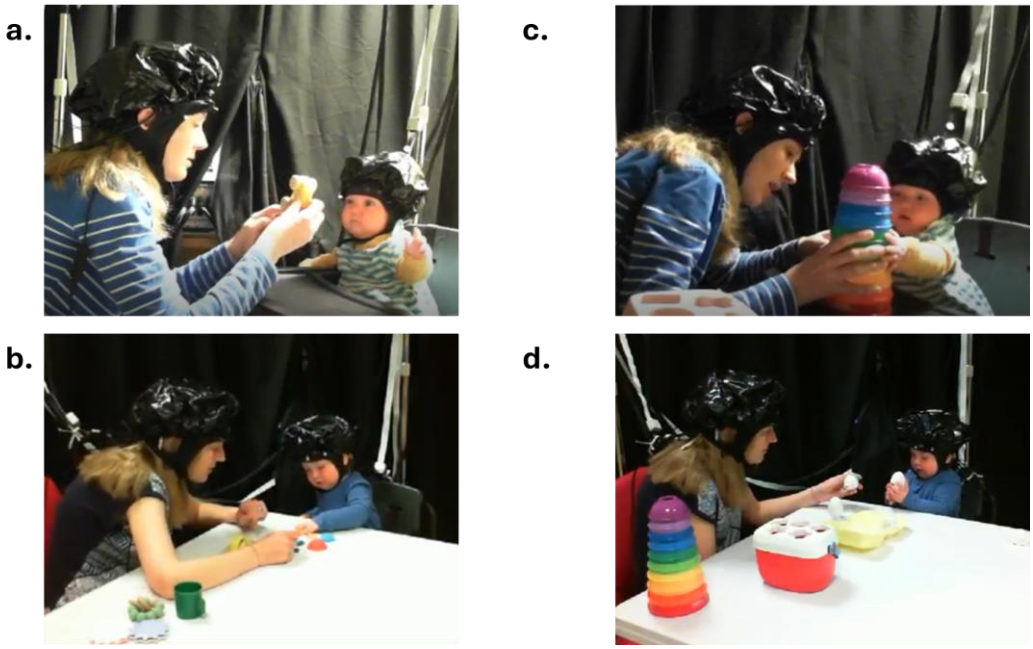


Figure 5.2. a) Caregiver-infant dyad engaging in SO play in Y1. b) Caregiver-toddler dyad engaging in SO play in Y2. c) Caregiver-infant dyad engaging in MO play in Y1. d) Caregiver-toddler dyad engaging in MO play in Y2.

5.2.3. Procedure.

Refer to section 4.2.5. in Chapter 4 for full procedural details.

In Y1, the SO play interaction was completed first in 77% of the dyads, followed by the MO play interaction. In Y2, the SO play interaction was completed first in 79% of the dyads, followed by the MO play interaction.

5.2.4. Coding dyadic interactions.

Intrusiveness and scaffolding behaviours in caregivers and object engagement and distractibility in children were coded during both interactions in Y2 (following identical procedures from Y1). Refer to section 4.2.6. in Chapter 4 for details on coding scheme development. As the coding from Y1 showed high inter-coder reliability between two coders (CD and AT), one coder (CD) coded all the data for Y2. Tables 5.2 – 5.5 show all behaviour codes and the percentage of how often each behaviour was displayed for each play interaction in each year.

Table 5.2. Caregiver intrusiveness behaviours and percentage of how often each behaviour was displayed for each interaction type in each year. Total percentage was calculated as the percentage of behaviours observed across all epochs for all participants.

Caregiver Intrusiveness	**Total (%)**			
Behaviours	**Year 1**		**Year 2**	
	SO Play	**MO Play**	**SO Play**	**MO Play**
Non-contingent speech	0	0	0	0
Loud speech	0	0	0	0.09
Exaggerated, fake, facial expressions	0	0	0	0
Making developmentally inappropriate demands on the child	0.04	0.43	0	0
Breaking gaze while child is looking	0.85	0.34	0.10	0.09
Shifting focus of the task before child is ready	8.70	3.96	12.95	7.30
Taking objects away before child is ready	4.26	6.46	2.18	4.68
Ignoring or interrupting child's interest in an object or activity by introducing a different object	8.23	2.60	11.81	2.43
Not allowing child to touch an object that caregiver is holding	0.94	0.72	0.10	0.56
Not allowing child to play with or handle objects they reach for	2.52	4.53	1.87	2.15
Interrupting child's activities	14.71	14.57	17.31	19.38
Overstimulating child	4.05	3.47	0.52	1.31
Offering a continuous barrage of stimulation that overwhelms the child	0.47	0.05	0.10	0.09
Overwhelming with objects	4.95	6.22	1.24	0.94
Forcing objects or self on child	1.07	0.58	1.14	0.84

Overly caregiver-led	3.67	6.03	5.70	10.11
Not letting child set the tone and pace of play	15.57	22.72	18.45	23.78
Disregarding child signals	16.29	20.16	18.13	20.88
Failing to modulate the pace or intensity of her behaviour when the child withdrew or turned away	0.68	0.05	0.10	0.37
Intrusive physical interactions	7.51	3.47	3.73	2.15
Physical manipulation of child to complete a goal	1.75	1.25	1.04	0.94
Physically manipulating the child even when child objecting or already independently playing	0.17	0.29	0.52	0.28
Rough physical contact: tickling, poking, pulling, shaking, and using brisk movements	0.68	0.14	1.55	0.19
Physically grabbing or moving child	0.72	0.48	0	0.28
Pulling or controlling hands	2.17	1.45	1.45	1.12

Table 5.3. Caregiver scaffolding behaviours and percentage of how often each behaviour was displayed for each interaction type in each year. Total percentage was calculated as the percentage of behaviours observed across all epochs for all participants.

Caregiver Scaffolding	**Total (%)**			
Behaviours	**Year 1**		**Year 2**	
	SO Play	**MO Play**	**SO Play**	**MO Play**
Questions or statements that associate objects and specific location	0.14	8.16	2.99	11.26
Relates object/activity that child is engaged with to a previous experience	0.51	0.34	0.36	0.24

States characteristics for an object that identifies its uniqueness, function, or specific features the child can use to problem solve	0.05	1.18	0.07	1.72
Specifies the function or activity that could be done with an object	2.88	4.07	3.39	3.96
Verbalises with physical demonstrations or miming how to use the object	12.02	9.80	9.24	3.96
Associates feelings or emotions with a reason for the emotion.	0.41	0.26	0.02	0.08
Teaches cause and effect or what you need to do to make an activity work	0.21	0.54	0.75	0.38
Links specifics objects with general categories	0.55	1.14	1.14	1.33
Helps child understand activities by linking two aspects of the activity	0	0.43	0.02	0.53
Suggesting object or activity to child whilst child disengaged	6.31	3.32	3.35	1.37
Labels objects	11.19	13.55	12.04	13.77
Describes objects	3.61	5.06	2.35	4.55
Labels own or child's actions	12.02	9.35	9.81	6.29
Reinforcing child's engagement with an object or activity	2.97	2.13	6.16	6.25
Allows child to lead while providing a supportive frame	2.88	2.69	8.89	8.67
Physically positions objects in such a way that child can engage in activities	12.11	13.14	15.17	12.07
Shows genuine interest and positive affect toward child	25.64	21.82	18.54	18.86

Reads child signals accurately and responds appropriately	1.91	1.42	2.42	2.65
Attends to and follows child's interest	2.88	1.19	1.51	0.83
Actively facilitates child's play through modelling or turn-taking	1.73	0.43	1.78	1.23

Table 5.4. Child object engagement behaviours and percentage of how often each behaviour was displayed for each interaction type in each year. Total percentage was calculated as the percentage of behaviours observed across all epochs for all participants.

Child Object Engagement	**Total (%)**			
Behaviours	**Year 1**		**Year 2**	
	SO Play	**MO Play**	**SO Play**	**MO Play**
No touch – Child gazes intently and focusses on object without looking elsewhere.	18.87	17.81	13.71	13.31
No touch – Child shows facial signs of interest when engaging with an object (for e.g. furrowed brow).	7.21	7.25	12.85	9.44
No touch – Child looks at and babbles/vocalizes towards object.	1.37	1.38	4.40	4.64
No touch – Child shows interest in an object even though it has been hidden from view.	0.48	0.06	0.02	0
No touch – Child stays focussed on object even through any distractions.	0.13	0.04	0.02	0.07
Include touch – Child gazes intently and focusses on object without looking elsewhere.	19.97	17.90	14.63	13.38
Include touch – Child shows facial signs of interest when engaging	9.02	8.11	14.25	11.53

with an object (for e.g. furrowed brow).				
Include touch – Child looks at and babbles/vocalizes towards object.	2.64	1.74	9.73	8.36
Include touch – Child stays focussed on object even through any distractions.	1.10	0.75	0.36	0.39
Include touch/no touch – Child displays physical response towards object (for e.g. leaning, reaching, touching)	18.09	17.52	13.01	13.29
Include touch – Child directly brings object closer (without caregiver influence).	3.58	10.31	2.44	11.02
Include touch – Child explores object manually (for e.g. holding, mouthing, shaking, hitting, banging, swinging, rotating, orienting, shifting, pressing buttons, and poking fingers into holes, fingering, stroking)	17.52	17.06	14.59	13.19
Include touch – Child repeats an action with an object for a while until they are successful or close to successful. (5s+)	0	0.09	0	1.37

Table 5.5. Child distractibility behaviours and percentage of how often each behaviour was displayed for each interaction type in each year. Total percentage was calculated as the percentage of behaviours observed across all epochs for all participants.

Child Distractibility	**Total (%)**			
Behaviours	**Year 1**		**Year 2**	
	SO Play	**MO Play**	**SO Play**	**MO Play**
Child shifts interest across multiple objects, without staying fixated on one.	63.60	67.84	69.92	74.63
Child is looking around the environment (for e.g. playing with the chair)	36.40	32.16	30.08	25.37

5.2.5. Outlier corrections.

All behavioural data were screened for outliers using RStudio (RStudio Team, 2020). Data were considered outliers if they fell outside of ± 3 SDs from the mean. For play interactions, outlier corrections were carried out for the overall scores computed across epochs for each behaviour.

In Y1, for SO play interactions, there was one outlier for caregiver intrusiveness. Thus, for this play interaction, 74 caregivers provided intrusiveness data, 75 caregivers provided scaffolding data, 75 infants provided object engagement data, and 75 infants provided distractibility data. For MO play interactions, there were two outliers for caregiver scaffolding and one outlier for infant distractibility. Thus, for this play interaction, 85 caregivers provided intrusiveness data, 83 caregivers provided scaffolding data, 85 infants provided object engagement data, and 84 infants provided distractibility data.

For Y2, for SO play interactions, there were two outliers for caregiver intrusiveness, one outlier for caregiver scaffolding, and one outlier for toddler distractibility. Thus, for this play interaction, 59 caregivers provided intrusiveness data, 60 caregivers provided scaffolding data, 61 toddlers provided object engagement data, and 60 toddlers provided distractibility data. For MO play interactions, there was one outlier for caregiver intrusiveness, one outlier for toddler object engagement, and one outlier for toddler distractibility. Thus, for this play interaction, 70 caregivers provided intrusiveness data, 71 caregivers provided

scaffolding data, 70 toddlers provided object engagement data, and 70 toddlers provided distractibility data.

Across Y1 and Y2, 52 families were common for SO play interactions and 62 families were common for MO play.

5.2.6. Statistical analyses.

All statistical analyses were carried out using RStudio (RStudio Team, 2020). To test whether there were epoch differences between interaction types in the second year, ANCOVAs were run with toddler age as a covariate. To examine whether there were differences in caregiver and toddler behaviours between both types of play in the second year, ANCOVAs with toddler age and order of play interaction as covariates were run. To test whether caregiver and toddler behaviours during SO play were associated with the same behaviours during MO play, regressions models were used. Next, to examine whether there were differences in caregiver-child behaviours between the first and second years, ANCOVAs were run with play interaction (SO/MO play) and year (Y1/Y2) as within-subject factors, and infant age in days as a covariate, separately for each caregiver and child behaviour. To examine whether caregiver and child behaviours in the first year predicted the same behaviours in the second year, regression models were used with infant age as a covariate. Finally, to test whether caregiver behaviours in the first year were predictive of child behaviours in the second year, regressions models were used with infant age as a covariate.

5.3. Results.

To examine if there were differences between epochs for each behaviour and play interaction in Y2, one-way ANCOVAs with epoch as the independent variable, and toddler age in days as a covariate were run separately for caregiver intrusiveness, caregiver scaffolding, toddler object engagement and toddler distractibility. There were no significant effects of epoch for any behaviour for any play interaction. Given this, the codes were summed across epochs to generate an overall score for each behaviour, which was used in the following analyses to meet the research objectives.

The first objective was to investigate whether there were differences in caregiver and toddler behaviours between play interactions in Y2. To do this, ANCOVAs were run with play interaction (SO/MO play) as an independent variable, and toddler age in days and order of play interaction as covariates, separately for each caregiver and toddler behaviour. For caregiver intrusiveness and scaffolding, there were no significant effects. For toddler object engagement, there was a significant main effect of play interaction ($F(1,127) = 88.565$, $p < .001$, $\eta 2 = .41$). Follow-up analyses revealed that toddlers showed greater object engagement during MO compared to SO play ($p < .001$) – see Figure 5.3c. For toddler distractibility, there was a significant main effect of play interaction ($F(1,126) = 6.714$, $p = .011$, $\eta 2 = .05$). Follow-up analyses revealed that toddlers were more distractible during SO compared to MO play ($p = .009$) – see Figure 5.3d.

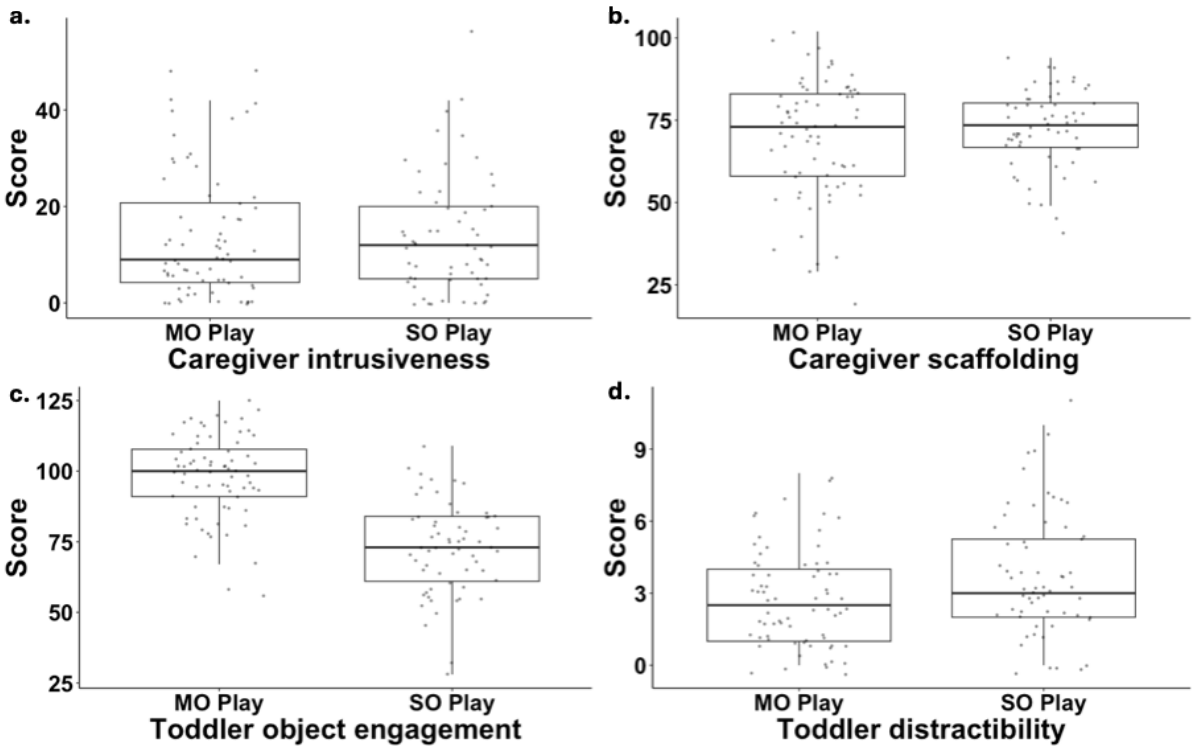


Figure 5.3. Difference between SO and MO play for (a) caregiver intrusiveness, (b) caregiver scaffolding, (c) toddler object engagement, and (d) toddler distractibility. Significant differences were observed only for toddler object engagement and toddler distractibility. Each box represents the IQR, with the horizontal line indicating the median. Whiskers extend to 1.5 times the IQR, and data points outside this range are plotted as outliers.

The second objective was to examine whether caregiver and toddler behaviours during SO play would be associated with the same behaviours during MO

play. To do this, regression models were run with caregiver/toddler behaviour for SO play as the predictor, and toddler age in days as a covariate. These were run separately for each behaviour. Results revealed that caregiver intrusiveness ($F(1,55) = 8.344$, $p = .006$) and caregiver scaffolding ($F(1,56) = 8.847$, $p = .004$) during SO play were associated with the same behaviours during MO play interactions (Figure 5.4). There were no significant associations for toddler behaviours.

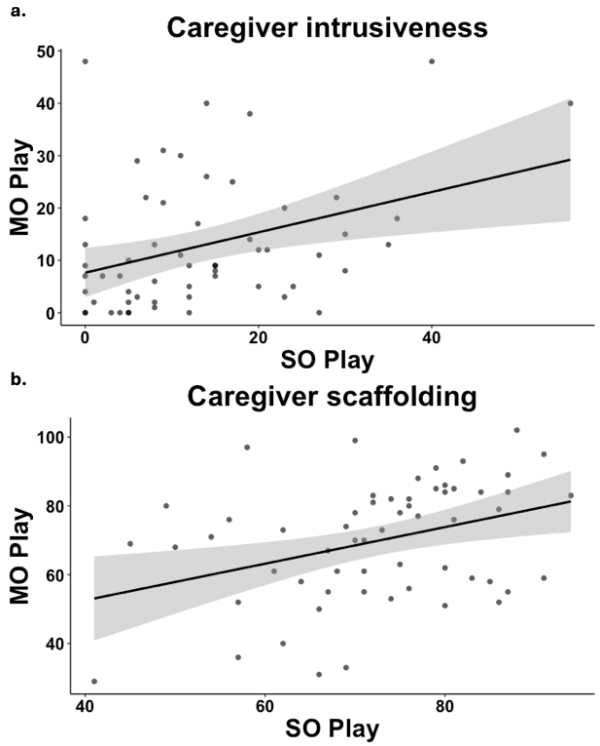


Figure 5.4. Association between SO play and MO play for (a) caregiver intrusiveness and (b) caregiver scaffolding

The third objective was to examine whether there were differences in caregiver-child behaviours from Y1 to Y2. Here, ANCOVAs were run with play interaction (SO/MO play) and year (Y1/Y2) as independent variables, and infant age in days as a covariate, separately for each caregiver and child behaviour. Note that infant age was used as a covariate rather than toddler age to maintain consistency across the thesis. This also reflected the scheduling approach for families' Y2 visits, which were arranged to occur one year after the Y1 session. To ensure this decision did not impact the results, analyses were also run using the difference in age between Y1 and Y2 as a covariate. These analyses confirmed that using age difference did not alter the findings, supporting the decision to use infant age as the covariate.

For caregiver intrusiveness, there was only a significant main effect of year ($F(1,276) = 32.292$, $p < .001$, $\eta 2 = .11$), i.e. caregivers showed less intrusive behaviours in Y2 compared to Y1 ($p < .001$) – see Figure 5.5a. For caregiver scaffolding, there were significant main effects of year ($F(1,277) = 52.278$, $p < .001$, $\eta 2 = .16$) and play interaction ($F(1,277) = 4.601$, $p = .033$, $\eta 2 = .02$), as well as a significant interaction between year and play interaction ($F(1,277) = 13.342$, $p < .001$, $\eta 2 = .05$) – see Figure 5.5b. Posthoc analyses revealed that caregivers exhibited more scaffolding behaviours in Y2 compared to Y1 during both SO play ($p < .001$) and MO play ($p = .006$). Further, caregivers exhibited more scaffolding behaviours during MO play compared to SO play in Y1 ($p < .001$).

For child object engagement, there were significant main effects of year ($F(1,279) = 293.652$, $p < .001$, $\eta 2 = .51$) and play interaction ($F(1,279) = 138.961$, $p < .001$, $\eta 2 = .33$), and a significant interaction between year and play interaction ($F(1,279) = 4.570$, $p = .033$, $\eta 2 = .02$) – see Figure 5.5c. Posthoc analyses revealed that children exhibited more object engagement behaviours in Y2 compared to Y1 during both SO play ($p < .001$) and MO play ($p < .001$). Further, children exhibited more object engagement behaviours during MO play compared to SO play in Y1 ($p < .001$) and Y2 ($p < .001$). For child distractibility, there were significant main effects of year ($F(1,277) = 66.601$, $p < .001$, $\eta 2 = .20$) and play interaction ($F(1,277) = 5.873$, $p = .016$, $\eta 2 = .02$) – see Figure 5.5d. Posthoc analyses revealed that children were more distractible in Y1 compared to Y2 ($p < .001$) and children were more distractible during SO play compared to MO play ($p = .034$).

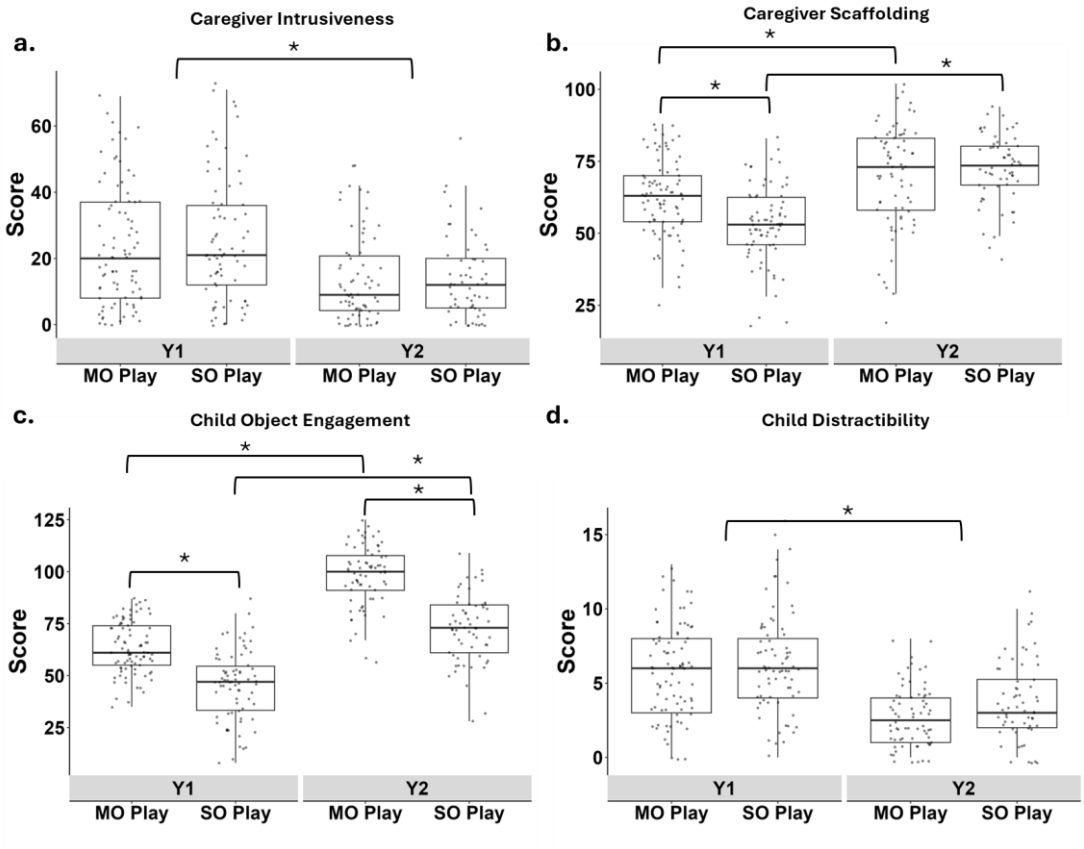


*Figure 5.5. Differences between SO and MO play across Y1 and Y2 for (a) Caregiver Intrusiveness, b) Caregiver Scaffolding, c) Child Object Engagement, and d) Child Distractibility. * Indicates significant results. Each box represents the IQR, with the horizontal line indicating the median. Whiskers extend to 1.5 times the IQR, and data points outside this range are plotted as outliers.*

The fourth objective was to determine whether caregiver-child behaviours in Y1 predicted the same behaviours in Y2. To do this, regression models were run for each behaviour and play interaction separately, while controlling for infant age in days. Centred caregiver and child behaviour scores from Y1 served as predictors, and caregiver and child behaviours from Y2 as the outcome. For SO play, caregiver intrusiveness ($\beta = 0.232$, SE = 0.11, $t = 2.142$, $p = .037$), caregiver scaffolding ($\beta = 0.296$, SE = 0.12, $t = 2.547$, $p = .014$), child object engagement ($\beta = 0.321$, SE = 0.13, $t = 2.430$, $p = .019$), and child distractibility ($\beta = 0.399$, SE = 0.10, $t = 3.872$, $p < .001$) in Y1 were predictive of the same behaviours in Y2 (Figure 5.6a-d). For MO play, there were no predictive effects from Y1 to Y2 for any behaviour. For comparison purposes and to examine any visible trends, results from MO play have also been visualised in red in Figure 5.6a-d.

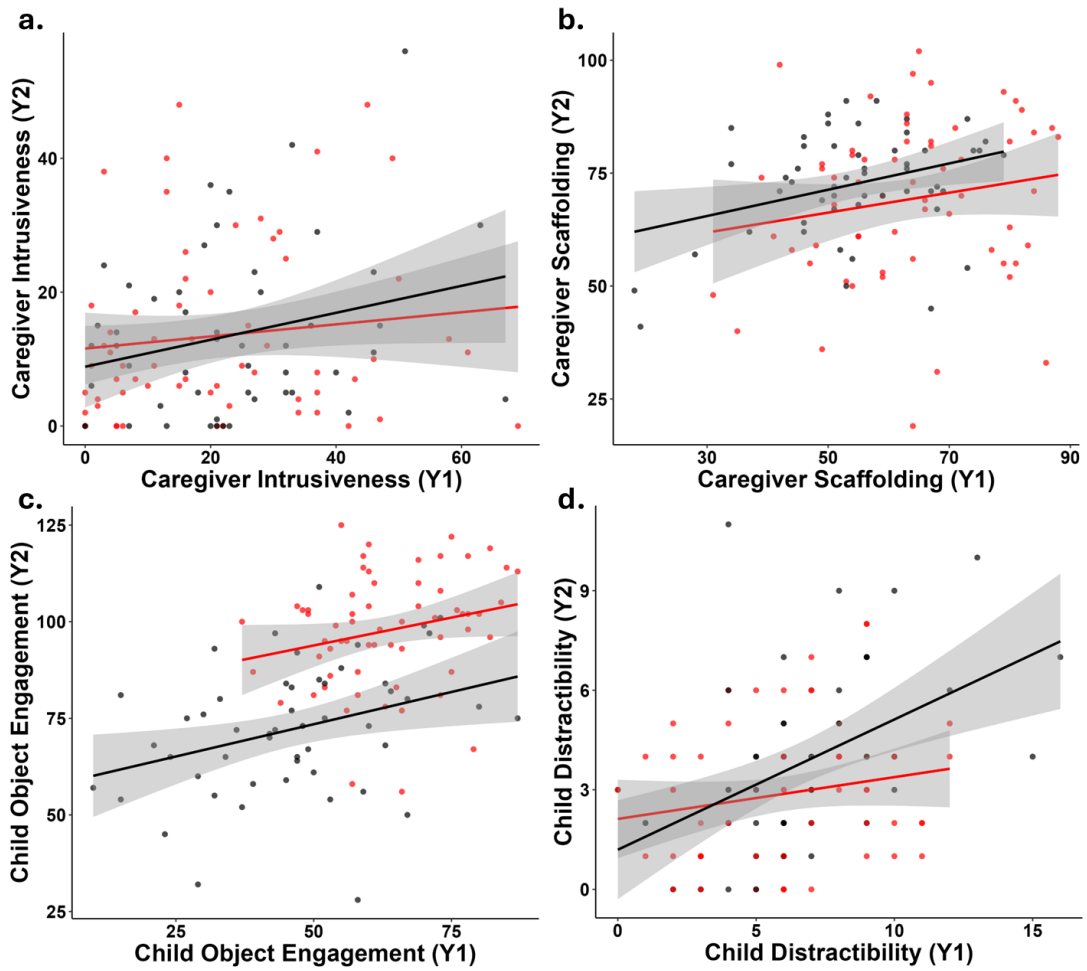


Figure 5.6. Behaviours in Y1 predicting the same behaviours in Y2 - SO play shown in black and MO play shown in red: a) Caregiver intrusiveness, b) Caregiver scaffolding, c) Child object engagement, and d) Child distractibility. Note that there were no developmental predictions for MO play (red), but this has been included to visualise trends, as an exception.

The final objective was to examine whether caregiver behaviours in Y1 were predictive of toddler behaviours in Y2 for each play interaction. Here, regression models were run with centred caregiver behaviour scores from Y1 as the predictor, and toddler behaviours in Y2 as the outcome, after controlling for infant age in days. There were four models for each play interaction, i.e. caregiver scaffolding as predictor and toddler object engagement as outcome, caregiver scaffolding as predictor and toddler distractibility as outcome, caregiver intrusiveness as predictor and toddler object engagement as outcome, and caregiver intrusiveness as predictor and toddler distractibility as outcome.

For SO play, caregiver scaffolding in Y1 was predictive of toddler object engagement ($\beta = 0.430$, SE = 0.16, $t = 2.633$, $p = .011$) and toddler distractibility ($\beta = -0.070$, SE = 0.03, $t = -2.702$, $p = .009$) in Y2. Specifically, greater caregiver

scaffolding in Y1 was associated with greater toddler object engagement and lesser toddler distractibility in Y2 (Figure 5.7a-b). To account for multiple comparisons, Benjamini-Hochberg procedure with a false discovery rate of 0.05 was applied to p-values of the four models run for SO play. Both significant results described above survived this threshold. There were no other significant associations.

Following this, partial correlations were run to test whether afore-mentioned predictive relationships between caregiver scaffolding in Y1 and toddler behaviours in Y2 for SO play remained after controlling for child behaviours in Y1. This step was required as findings from the fourth objective showed that child object engagement and distractibility in Y1 were associated with the same behaviours in Y2. Concretely, to test the predictive relationship between caregiver scaffolding in Y1 and toddler object engagement in Y2, a partial correlation was run controlling for infant object engagement in Y1. The relationship between caregiver scaffolding in Y1 and toddler object engagement in Y2 was still significant, after controlling for infant object engagement in Y1 ($r = .28$, $p = .045$). Next, to test the predictive relationship between caregiver scaffolding in Y1 and toddler distractibility in Y2, a partial correlation was run controlling for infant distractibility in Y1. The relationship between caregiver scaffolding in Y1 and toddler distractibility in Y2 was still significant after controlling for infant distractibility in Y1 ($r= -.29$, $p = .041$).

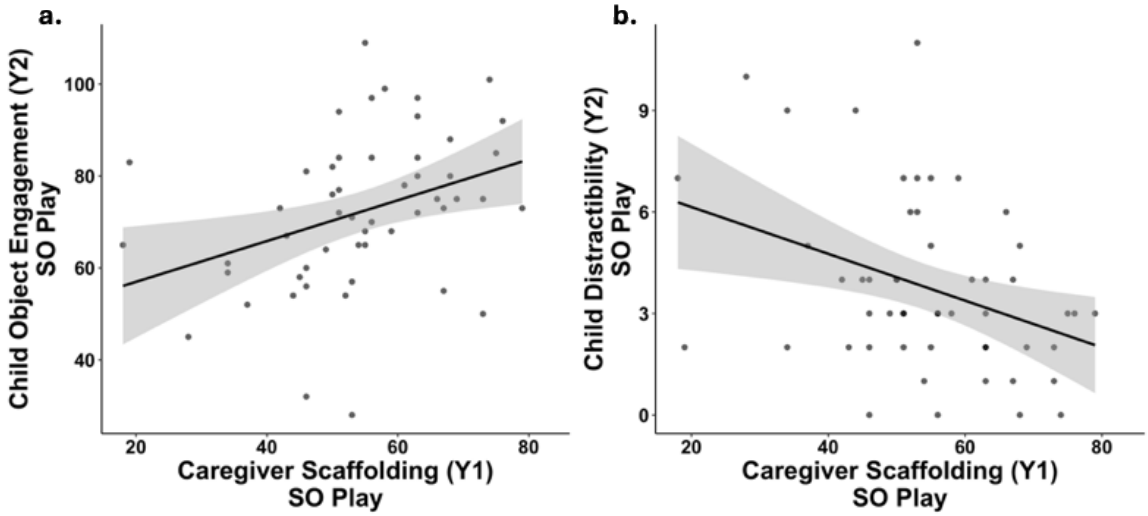


Figure 5.7. Caregiver behaviours in Y1 predicting child behaviours in Y2: a) Caregiver scaffolding in Y1 predicting child object engagement in Y2 during SO play, and b) Caregiver scaffolding in Y1 predicting child distractibility in Y2 during SO play.

5.4. Discussion.

The current chapter posed five research questions to examine longitudinal changes in caregiver-child dyadic play interactions from infancy to toddlerhood. The first question inquired whether there were differences in caregiver and toddler behaviours between both types of play interactions in Y2. Toddlers exhibited higher object engagement during MO play compared to SO play and higher distractibility during SO play compared to MO play. However, there was no difference between SO or MO play interactions for caregiver behaviours. The second question inquired whether caregiver and toddler behaviours during SO play would be associated with the same behaviours during MO play in Y2. Here, only caregiver intrusiveness and scaffolding in SO play were associated with the same behaviours in MO play. The third question inquired whether there were differences in caregiver-child behaviours from Y1 to Y2. Caregiver intrusiveness and child distractibility reduced from Y1 to Y2 while caregiver scaffolding and child object engagement increased from Y1 to Y2. The fourth research question examined whether caregiver-infant behaviours in the first year predicted the same behaviours in the second year. All dyadic behaviours during SO play in Y1 predicted the same behaviours during SO play in Y2. However, for MO play, there were no predictive relationships for any of the behaviours. The fifth question inquired whether caregiver behaviours in Y1 were predictive of toddler behaviours in Y2 for each play interaction. Here, better caregiver scaffolding in Y1 was associated with better toddler object engagement and reduced distractibility in Y2. These results were only found for SO play, and there were no predictive effects for MO. These findings are discussed below.

5.4.1. Greater toddler engagement during MO compared to SO play interactions.

The first objective was to examine whether there were differences in caregiver and toddler behaviours between both types of play interactions in the second year. There were interaction-based differences for both object engagement and distractibility in toddlers. Concretely, toddlers showed greater object engagement and reduced distractibility during MO play compared to SO play. When examining codes related to object engagement, in agreement with the previous chapter, toddlers tended to physically bring objects closer to them without caregiver influence more frequently during MO play compared to SO play. Relatedly, when examining codes related to distractibility, the distribution appears to be split across

the two codes contributing to this behaviour, with toddlers showing more instances of shifting interest across multiple objects without staying fixated on one object during MO play compared to SO play, and showing more instances of looking around the environment during SO play compared to MO play. Collectively, these observations align with Artemova et al. (2023), who reported that young children are particularly attracted to objects with bright colours and multiple features, including those that make sounds (e.g., hide ‘n’ squeak eggs). These object properties were shown to increase both the duration and quality of children’s engagement. Further, MO play offers more opportunities for exploration and control, motivating children to independently manipulate, bring closer, and interact with the objects in more sustained and purposeful ways. Thus, MO play provides a more engaging and structured play experience, sustaining toddlers’ attention for longer periods. Even periods of distractibility are driven by shifting interest between different objects used in MO play. In contrast, SO play was associated with more frequent disengagement from the play objects altogether, reflected in increased looking around the environment. While these objects may still offer opportunities for focussed play, toddlers might struggle to engage with SO objects, as they are larger, afford fewer opportunities for exploration and manipulation, thus reducing engagement and orienting to extraneous stimuli, altogether. This finding is consistent with Ruff and Capozzoli (2003), who emphasised that sustained attention in toddlers is more likely when play materials are both novel and appropriately stimulating. While SO objects, such as the pop-it butterfly or gears, are novel and can be stimulating, they typically offer limited affordances for sequential actions or open-ended exploration. In contrast, MO objects like the shape sorter or hide 'n' squeak eggs not only capture attention through features like vibrant colours and sounds but also invite goal-directed behaviours (e.g., matching shapes, uncovering hidden elements, stacking in sequence). These built-in affordances support varied, purposeful interaction and maintain engagement over time, thereby more effectively meeting the criteria outlined by Ruff and Capozzoli (2003). The developmental literature further supports this interpretation. Although attentional control is still maturing in the second year of life (Garon et al., 2008; Moyano et al., 2023), Kannass et al. (2006) highlight that distractibility is especially sensitive to environmental features that encourage engagement, such as novelty, complexity, and interactivity. In this light, MO play objects may help support attention by offering multisensory feedback and

opportunities for goal-directed manipulation, while SO play objects may leave children more susceptible to environmental distractions.

5.4.2. Caregiver behaviours show stability across play interactions in toddlerhood.

The second objective was to examine whether caregiver and toddler behaviours during SO play would be associated with the same behaviours during MO play, in the second year of life. Only caregiver intrusiveness and scaffolding in SO play was associated with the same behaviours in MO play. There were no such associations for toddler behaviours. These caregiver effects in toddlerhood are consistent with findings reported in Chapter 4 when the same children were between 6 and 10 months. Specifically, during infancy, caregivers who were intrusive or scaffolded frequently during SO play were also more likely to display similar tendencies during MO play. Together, these findings suggest that caregiver tendencies are relatively stable traits, observable from late infancy through toddlerhood. This finding aligns with longitudinal research by Hunter et al. (2021), who found that caregivers who exhibited high levels of intrusiveness with their infants at 10 months were more likely to maintain these behaviours when their children were 2 and 3 years of age, even across different play tasks. This stability suggests that caregiver interaction patterns may be shaped by enduring factors such as parenting beliefs, responsiveness thresholds, or perceptions of the child's capabilities. Similarly, the consistency in caregiver scaffolding is in line with work by Neale and Whitebread (2019), who reported that caregivers' inclination to scaffold was evident across different dyadic play situations from 12 to 24 months. Their findings showed that caregivers who adopted a more goal-directed, structured style with one type of object were likely to maintain this approach even when interacting with another object type. In the current study, the continuity in scaffolding between SO and MO play suggests that caregivers who are attuned to their toddler's developmental level and regularly engage in support strategies, such as verbal prompts, spatial guidance, and demonstration, apply these behaviours consistently across play situations, even when object complexity differs.

In contrast to the stability observed in caregiver behaviours, there was no association in toddler behaviours between SO and MO play in Y2. This result goes against the finding in Chapter 4 showing cross-interaction associations for infant object engagement in Y1. This finding may reflect greater contextual sensitivity and

developmental variability in toddler engagement and attention, compared to the first year of life. For example, in toddlerhood, MO objects may offer more opportunities for varied interactions, which may have shaped toddlers' engagement patterns differently than SO play, which might offer more constrained exploration. This flexibility in toddler behaviour could reflect growing autonomy and exploratory drive, rather than a lack of consistency. Reflections on differences between infancy and toddlerhood are covered in the sections below when developmental differences are discussed.

5.4.3. Developmental shifts in play behaviours from the first and second year of life.

The third objective was to examine whether there were differences in caregiver-child behaviours from Y1 to Y2. There were differences across all behaviours for both play interactions - specifically, there was greater caregiver scaffolding and child object engagement and reduced caregiver intrusiveness and child distractibility in Y2 compared to Y1. The observed increase in caregiver scaffolding from Y1 to Y2 was characterised by more frequent and developmentally-tuned verbal support strategies. Specifically, when examining the codes, there was increased engagement for the code 'Questions or statements that associate objects and specific location'. This code related to verbal prompts such as "Where does this go?", "Put the square shape in the square hole", or "This one goes on top", which provided spatial cues to children about placement of objects during play. This shift might suggest not only a change in the quantity of scaffolding but also a shift toward more structured and goal-directed support with caregivers adapting their guidance to match children's emerging abilities to understand and act on spatial and relational information. Between 18 and 23 months, children become increasingly capable of encoding spatial relationships and understand the use of relational terms like "in," "on," and "under" (Casasola et al., 2006). Caregivers may intuitively respond to this progression by offering scaffolding that integrates spatial concepts with object use, helping children not only interact with the object but also organise and sequence their actions more purposefully. Further, the observed increase also likely reflects better attunement to their child's developmental needs and preferences, enabling more effective scaffolding (Bornstein et al., 2008; Tamis-LeMonda et al., 2001). Increased scaffolding may also reflect the caregivers' confidence and experience in facilitating more complex interactions as toddlers gain independence and require

more nuanced support during play. Previous work suggests that effective scaffolding behaviours, such as prompting and demonstrating, become more prominent as children approach two years of age, coinciding with advancements in toddlers' goal-directed behaviours and sustained attention (Landry et al., 2008). The reduction in intrusiveness from Y1 to Y2 suggests that caregivers might have become more attuned to their toddlers' autonomy and learning cues, leading to fewer interruptions in the child's exploration. This result aligns with findings that intrusive behaviours tend to diminish as caregivers learn to balance involvement with allowing independence (Perea-Velasco et al., 2023). Intrusiveness may also decrease because toddlers' increasing independence reduces the need for controlling behaviours (Perea-Velasco et al., 2023). When considering the codes, the reduction from Y1 to Y2 was characterised by a decline in specific behaviours that interfered with the child's agency during play. Notably, there were less frequent instances of 'Overwhelming with objects', fewer instances of 'Taking objects away before child is ready', and a decrease in caregivers 'Not allowing child to play with or handle objects they reach for'. These changes suggest that by the second year of life, caregivers have become more attuned to their toddlers' signals of readiness, interest, and engagement, allowing children greater autonomy in directing the flow of interactions. These shifts align with a more responsive and child-led approach to interaction, which has been linked to better outcomes in early cognitive, emotional, and self-regulatory development (Bernier et al., 2010). These findings indicate a developmental shift towards more supportive, attuned, and autonomy-respecting caregiver behaviours in the second year, reflecting both the child's growing capabilities and the caregiver's increased responsiveness and confidence during play.

The observed increase in child object engagement likely reflects improved motor coordination, attentional focus, and cognitive understanding of play materials (Lockman & Tamis-LeMonda, 2021). Between 12 and 24 months, toddlers undergo dynamic changes in executive functions that enhance their ability to maintain attention and manipulate objects with purpose (Garon et al., 2008). More specifically, two specific codes were more frequent in toddlerhood, i.e. 'Facial signs of interest when engaging with an object' and 'Looking at and babbling or vocalising towards an object', both with and without touching the object. These observations suggest a shift from primarily physical, exploratory interaction with objects towards affective and verbal language-driven communication in toddlerhood, compared to

infancy. Facial expressions such as furrowed brows or concentrated gazes often signal focused attention and mental effort (Babaei et al., 2020; Holler, 2022), indicating that toddlers might not only perceive the object but are also processing its properties, functions, relations to other objects and space and/or novelty. Moreover, increased caregiver scaffolding likely reinforces toddlers' object engagement by providing structure and guidance during play (Lockman & Tamis-LeMonda, 2021). Finally, the observed reduction in distractibility from Y1 to Y2 was characterised by the decline in off-task behaviour (i.e., 'Child is looking around the environment'), suggesting that in toddlerhood, children become better able to sustain focus on the current task and perhaps, also learn to inhibit shifting attention to task-irrelevant stimuli. This shift aligns with established developmental trajectories in attention regulation and executive function from experimental work. Improvements in working memory and inhibitory control help toddlers stay focused for longer periods (Garon et al., 2008). As these processes develop, children become more capable of ignoring irrelevant inputs and prioritising task-relevant actions, which is critical for meaningful engagement in play and learning contexts. This developmental improvement may also be reinforced through caregiver scaffolding, which, as discussed earlier, appears to become more targeted and object-focused in Y2. By naming, describing, and providing cues about object use and placement, caregivers help toddlers attention within the play episode, further reducing the likelihood of disengagement. These patterns likely reflect a developmental progression in toddlers' attention, communication, and object engagement, supported by increasingly structured and responsive caregiver scaffolding that fosters sustained focus and purposeful interaction during play.

5.4.4. Longitudinal stability for behaviours during SO play.

The fourth objective was to determine whether caregiver-child behaviours in the first year predicted the same behaviours in the second year. Only for SO play, caregiver intrusiveness, caregiver scaffolding, child object engagement, and child distractibility in Y1 predicted the same behaviours in Y2. Interestingly, there were no predictive associations for any behaviours for MO play, although all behaviours showed positive trends. These findings suggest that SO play may foster more stable patterns over time, potentially because of the constrained nature of the objects. That is, when a caregiver and child engage with single objects, the play content may be

simpler and more repetitive, enabling consistent behavioural patterns to emerge and persist across development. This interpretation aligns with findings from Schneider (2009), who observed that infants' task-directed play behaviours increased significantly with age, indicating a developmental progression in how infants engaged with objects. Along a similar vein, Neale and Whitebread (2019) found that maternal scaffolding behaviours showed consistency across different toys and over time, suggesting that certain interaction patterns may be more stable in less complex play contexts. The lack of longitudinal continuity in MO play may reflect the greater complexity of this play type: engaging with multiple objects may place greater demands on developing skills such as spatial reasoning (Jung et al., 2018; Uhlenberg & Geiken, 2021), working memory (Gilmore et al., 2018), and motor coordination (Denham, 1998; Lockman & Tamis-LeMonda, 2021), all of which undergo rapid and dynamic changes in the second year of life. For instance, research by Cheng et al. (2019) demonstrated that the ability to track multiple object identities in dynamic environments emerges around 25 months of age, suggesting that the cognitive demands of MO play may outpace capacities in the first year, leading to less behavioural continuity over the first two years of life, at least.

Furthermore, the current findings may also reflect changes in the caregiver's role across time. During SO play, caregivers might adopt consistent interactional strategies because the play context remains relatively static, thus reinforcing stable behaviour patterns. However, in MO play, caregivers might need to adjust their involvement in response to the child's rapidly changing skills and interests. Research on autonomy-supportive caregiving supports this interpretation, showing that caregivers often engage in autonomy-promoting behaviours (e.g., positive guidance, responsiveness) during the toddler years (Hughes et al., 2018; Linkiewich et al., 2021). For instance, an infant's limited ability to combine or manipulate multi-component objects may initially require more directive scaffolding, while a toddler's greater autonomy may shift caregiver behaviour toward more passive observation or higher-level prompting. This adaptive responsiveness could reduce behavioural continuity in MO contexts even when there is a developmental increase in behaviours.

These findings have broader implications for our understanding of the conditions under which developmental stability in early interactions can be expected. The contrast between SO and MO play suggests that behavioural continuity may be

more likely in contexts that are relatively constrained and place fewer demands on rapidly developing systems. Conversely, in contexts that require integration of emerging cognitive or motor skills, variability may be a natural and even adaptive feature of development. Therefore, longitudinal stability may not always signal optimal development, nor is change necessarily indicative of disruption - it may instead reflect normative adaptation. Overall, these findings highlight the importance of considering the complexity of play contexts and the developmental trajectories of underlying cognitive functions when examining the stability of caregiver-child interactions over time.

5.4.5. Caregiver scaffolding in infancy is predictive of toddler object engagement and distractibility.

The final objective was to examine whether caregiver behaviours in Y1 were predictive of toddler behaviours in Y2 for each play interaction. Interestingly, only for SO play, caregiver scaffolding in Y1 predicted toddler object engagement and distractibility in Y2. Specifically, greater caregiver scaffolding in Y1 was associated with greater toddler object engagement and lesser distractibility in Y2. Scaffolding behaviours, such as modelling and verbal encouragement, facilitate children's ability to maintain focus on play activities (Yogman et al., 2018). By consistently engaging in scaffolded play, children might begin to internalise the strategies caregivers use, gradually developing their ability to sustain engagement independently (Mendez et al., 2024). Additionally, scaffolding provides structure, reducing the likelihood of distraction by keeping the child focused on task-relevant actions. For example, a caregiver's verbal cues can help redirect attention back to the task when a child's focus wanders. Existing research suggests that high-quality caregiver scaffolding fosters better self-regulation and attentional control in toddlers, as they learn to sustain focus and manage distractions within guided interactions (Yogman et al., 2018). Scaffolding also promotes self-regulation by modelling behaviours such as persistence, goal-directedness, and managing frustration during challenging tasks (Landry et al., 2006), thus, leading to improved attention regulation and reduced distractibility over time. These findings can be further interpreted in light of the specific caregiver scaffolding codes observed during SO play in infancy. Behaviours such as verbalising with physical demonstrations or miming how to use the object likely supported infants in learning how to interact with objects in purposeful,

sustained ways, laying the groundwork for later behaviours such as manual exploration (e.g., banging, rotating, pressing buttons) and focused gazing. Labelling actions may have helped direct the infant's attention to relevant aspects of the play, reinforcing cognitive associations between language, action, and object affordances, which could explain the higher frequency of facial signs of interest and intense object focus observed in toddlerhood. Additionally, when caregivers showed genuine interest and positive affect, this likely enhanced the emotional salience of shared play, increasing the child's motivation to remain engaged and reducing tendencies to look around the environment - an indicator of distractibility. Thus, the specific forms of scaffolding provided during SO play may have shaped both the cognitive and emotional foundations of toddlers' object engagement and attentional control. The current findings also align with broader developmental work showing that early caregiver scaffolding positively influences later child outcomes. For example, Dilworth-Bart et al. (2010) reported that higher maternal attention scaffolding at 16-months predicted better verbal working memory at 24-months. Hammond and colleagues (2012) found that parental scaffolding of problem solving at age 3 was directly associated with executive functioning at age 4. Further, Meins et al. (2003) showed that mothers' use of mental state language (i.e., comment on internal experiences) with their 6-month-old infants positively predicted theory of mind ability at 45 and 48-months. This evidence collectively highlights that early scaffolding provides toddlers with a supportive framework that aids them in sustaining attention and reducing distractibility during play interactions.

It is important to consider why these predictive associations were observed for SO play and not for MO play, especially when caregiver-infant behaviours show developmental shifts for the latter. There is greater behavioural stability in SO play over time – this stability may stem from the constrained nature of SO interactions: when a caregiver and infant engage with single-component objects, the interaction tends to be simpler, more repetitive, and more easily shaped by consistent scaffolding strategies. These qualities may provide a developmentally-stable framework in which infants can internalise caregiver support over time, leading to observable longitudinal effects in toddlerhood. By contrast, MO play introduces greater complexity, both in terms of the number of objects and the variability of potential interactions, which likely contributes to the absence of predictive

associations. While caregiver behaviours in MO contexts may still be supportive, they may not exert the same stable developmental influence due to shifting interactional dynamics in relation to child autonomy (Hughes et al., 2018; Linkiewich et al., 2021). For example, caregiver scaffolding in MO play may be more prominent in infancy, as infants require assistance navigating the increased demands of multi-component object manipulation. However, as children's working memory, motor coordination, and spatial reasoning develop in the second year (e.g., Gilmore et al., 2018; Lockman & Tamis-LeMonda, 2021; Uhlenberg & Geiken, 2021), they may take more initiative in MO play, reducing the continuity of earlier caregiver-infant dynamics. This shift in play leadership from more caregiver-led to more child-driven likely disrupts the predictability of outcomes based on early scaffolding strategies. Thus, the discrepancy in predictive associations across SO and MO play highlights the importance of play context in shaping the stability, and developmental impact, of early caregiver scaffolding.

5.5. Conclusion.

The current chapter investigated longitudinal changes in caregiver-child dyadic play interactions from infancy to toddlerhood. Caregivers and their children engaged in two dyadic play interactions (SO and MO play) across two years. Children were aged between 6 and 10-months in the first year and between 18 and 22-months in the second year. Both play interactions were coded to extract caregiver intrusiveness, caregiver scaffolding, child object engagement, and child distractibility behaviours at both timepoints. In Y2, toddlers exhibited higher object engagement during MO play compared to SO play and higher distractibility during SO play compared to MO play. These patterns indicate that MO play may offer more engaging and stimulating opportunities for toddlers, allowing them to sustain focus more effectively. However, there was no difference between SO and MO play interactions for caregiver behaviours, indicating that caregivers may approach both play contexts with similar strategies. Caregiver intrusiveness and scaffolding in SO play were associated with the same behaviours in MO play but there were no such effects for toddler behaviours. These associations suggest that caregiver interaction styles may be more stable and generalisable than children's behaviours, which appear to be more sensitive to contextual complexity and developmental change. Caregiver intrusiveness and child distractibility reduced from Y1 to Y2 while

caregiver scaffolding and child object engagement increased from Y1 to Y2. These developmental trends point to an overall improvement in the quality of caregiver-child interactions and growing child capacities for focused, goal-directed play - likely reflecting the maturation of regulatory and attentional systems during the second year of life. Further results revealed that all dyadic behaviours during SO play in Y1 predicted the same behaviours in Y2. However, there were no predictive relationships within MO play. This pattern suggests that SO play offers a more structured and stable interactional context, which may support the development and continuity of behavioural patterns over time. In contrast, the longitudinal stability of behaviours during MO play may be disrupted as toddlers' rapidly developing motor, cognitive, language, and autonomy skills interact with the diverse affordances of MO objects. These developmental shifts can lead to increasingly varied ways of engaging with the same objects over time, resulting in less consistent behavioural patterns across timepoints. Finally, higher caregiver scaffolding in SO play during infancy predicted higher toddler object engagement and lower distractibility one year later - an effect not observed for MO play. The presence of this predictive relationship in SO play underscores the importance of early structured scaffolding in supporting attentional control and sustained engagement, particularly in contexts where the interaction remains relatively consistent over time. Overall, the findings underscore the importance of high-quality caregiver scaffolding during early play interactions for fostering cognitive and attentional development. This chapter highlights how dyadic play behaviours evolve over time, shedding light on the developmental changes in caregiver-child interactions as children transition into toddlerhood.

5.6. Motivations for next chapter.

The current chapter focussed on how caregiver-child dyadic play behaviours change from infancy to toddlerhood. The findings highlighted developmental shifts in both caregiver and child behaviours. Crucially, toddlers showed greater object engagement and reduced distractibility during MO play, compared to SO play. These behavioural differences were linked to the richer affordances of the multi-component objects, which encouraged exploration, manipulation, and sustained attention. From infancy to toddlerhood, caregivers showed increased scaffolding and reduced intrusiveness during MO play, shifting toward more structured, spatially-guided, and autonomy-supportive interactions. These changes occurred alongside greater child

object engagement and reduced distractibility, reflecting a developmental progression in both caregiver responsiveness and toddler attentional control. In the next chapter, this perspective is inserted into experimental assessments of visual cognition. Specifically, the next chapter will examine how stimulus type influences toddlers' ability to retain and process information, and how these cognitive processes are associated with real-world dyadic interactions. Concretely, the chapter will compare behaviour and brain function in toddlers between two preferential looking tasks, one using coloured shapes (as used in Chapter 3) and the other using images of real-world objects. Given that real-world objects are more closely linked to toddlers' everyday environments, a critical question is whether one should expect to observe better performance and respective underlying brain function while engaging with real-world objects compared to coloured shapes. Moreover, by examining links between toddlers' visual working memory in these tasks and play interactions with caregivers at the same stage, the chapter seeks to bridge the gap between controlled assessments of visual cognition and naturalistic measures of social experience.

Chapter 6:

Experiment 4: Impact of stimulus type on toddler visual cognition and associations with dyadic interactions.

6.1. Introduction.

In developmental research, the choice of stimuli plays a critical role in shaping our understanding of cognitive and social processes. There are differences between the simplified stimuli commonly employed in experimental tasks (e.g., Davidson et al., 2024) and the rich, dynamic nature of real-world objects often used in dyadic interactions, such as in caregiver-child play (e.g., Quinn & Kidd, 2019). While real-world stimuli provide a more ecologically valid context, simple stimuli such as shapes and colours standardise assessments of perception and cognition (Sonkusare et al., 2019). This divergence raises an important question about the ecological validity of experimental findings and their relevance to real-world learning and early development (Sonkusare et al., 2019). Concretely, do some children who show poorer performance when engaging with conventional experimental stimuli such as colours or shapes, perform better when engaging with real-world stimuli in experimental tasks – suggesting that contextual cues and episodic memories for objects and their likeness can boost performance. These considerations are especially relevant in light of previous and current investigations of concurrent and predictive links between dyadic behaviours and child cognition.

6.1.1. Use of stimuli in experimental paradigms in early childhood.

The selection of stimuli is particularly important for developmental research, as it directly influences how children engage with tasks and how their behaviour is interpreted. For early developmental research, stimuli must be age-appropriate, visually engaging, and capable of eliciting meaningful responses. For example, Kidd and colleagues (2012) conducted experiments with 7 and 8-month-old infants, measuring their visual attention to event sequences varying in complexity. They found that infants were more likely to look away from the screen when stimuli were

either too simple (highly predictable) or too complex (highly unexpected). Instead, they were most likely to attend towards stimuli that had an intermediate level of complexity, suggesting that infants sought to avoid allocating cognitive resources to either overly predictable or surprising events. However, certain types of stimuli may lead to what is known as "sticky attention", where children become overly focused on a particular object or feature, limiting their exploration of other aspects of the task (Dwyer et al., 2024; Hanania & Smith, 2010). For example, Kulke et al. (2015) examined the occurrence of "sticky fixations", instances where infants fail to disengage attention from a central stimulus (a schematic face), in infants aged 1 to 9 months using eye-tracking. Sticky fixations were significantly more common in younger infants (under 4 months) and in a competition condition, where the central stimulus remained visible when a peripheral target (black and white rectangular bars) appeared. This pattern supports previous findings that younger infants have difficulty disengaging attention, particularly when competing visual stimuli are present. The low rate of sticky fixations in older infants suggests developmental improvements in attentional control within the first few months of life. Their findings confirmed that even subtle difficulties in disengagement can be observed reliably in early infancy, highlighting the potential for identifying atypical attention development. Notably, infants who exhibit prolonged persistence of sticky fixation are at increased risk for later difficulties with executive attention (Hitzert et al., 2014). More recently, Dwyer and colleagues (2024) studied “sticky attention” using a gap-overlap task involving abstract, black, and white shapes alongside colourful pictures of stuffed animals. They proposed that children’s “sticky attention” towards the colourful stuffed animal pictures could be interpreted as simply a response to their engaging stimulus properties as some of them featured smiling facial expressions which could have aroused social interest. This finding highlights the need to identify and account for stimulus characteristics that may induce “sticky attention”, as such effects can distort measures of children's attention and cognition, leading to biased or misleading experimental outcomes. In line with this, Hanania and Smith (2010) suggest that such perseverative attentional behaviours may stem from immature or incomplete attentional processes that are still developing during the preschool years. Their work underscores the importance of considering how attentional biases interact with developmental limitations in cognitive flexibility, particularly in tasks requiring attention to shift across competing dimensions.

There are several studies that have incorporated real-world stimuli into experimental tasks to assess various aspects of visual cognition. Spriet et al. (2022) examined the development of visual object categorisation in infants aged 4 to 19 months using eye-tracking. They found a shift from low-level feature-based looking at 4 months to animacy-based categorisation by 10 months, followed by a "category spurt" by 19 months, with infants distinguishing between more nuanced categories like human vs. nonhuman faces. These findings suggest a progressive recruitment of feature spaces across the visual cortex and highlight infants' early preferences for socially relevant stimuli. Building on categorisation, Smith (2009) explored toddlers' object recognition, revealing a developmental shift from recognition based on local features to recognition based on global geometric structure. By 24 months, toddlers could identify both detailed and abstract object forms, with vocabulary size predicting success. Supporting this, research shows that manual exploration and goal-directed action help toddlers build three-dimensional shape representations, reinforcing the link between action and perception (Örnkloo & von Hofsten, 2007; Smith, 2005). More recently, Gerhard et al. (2021) used both real objects and their pictorial counterparts to examine visual preferences in 7-month-old infants. The primary aim of the study was to assess whether a visual preference for real objects was related to the assumption that infants perceive them as providing the opportunity to interact with and grasp them. The study found that infants displayed a stronger preference for real objects over pictures, a behaviour that was significantly linked to their manual exploration skills. This finding suggests that real-world stimuli are more effective in eliciting attention and engagement in infants, highlighting the importance of tangible, three-dimensional objects in research on early perceptual development (Gerhard et al., 2021). Together, these findings highlight the value of using real-world, richly detailed stimuli in developmental research. Such stimuli not only enhance ecological validity but also align more closely with infants' natural experiences and emerging cognitive abilities.

While studying how real-world stimuli influences visual cognition is valuable, it is also important to understand how conventional, simplified stimuli relate to real-world objects, as this can help bridge findings from controlled experiments to naturalistic settings. Mitsven and colleagues (2018) conducted a study to explore whether 10-month-old infants' visual attention was influenced by

information stored in visual short-term memory. They carried out two experiments using a cued visual search task. In this task, infants were first shown a sample stimulus, followed by a test array containing two items: one matching the sample stimulus and one that did not. The first experiment used coloured circles as the stimuli, while the second experiment used images of real-world objects to determine whether the findings extended beyond simple geometric shapes. The results demonstrated that infants could rapidly store information in their visual short-term memory and use it to guide their attention for both simple shape and complex real-world stimuli. In both experiments, infants showed a first-look preference for the non-matching item and spent significantly more time focusing on it, indicating a preference for novelty (Mitsven et al., 2018). A major limitation of this work is that it did not include a direct statistical comparison of infant performance across the two cued visual search tasks. Although the authors highlight the consistency of findings between experiments using simple versus complex stimuli, this descriptive approach stops short of formally testing whether stimulus complexity impacts infants' use of visual short-term memory, leaving a key question open for future research. Comparing visual cognitive performance could determine whether cognitive processes when engaging with simple stimuli, such as geometric shapes, are generalisable to more complex, real-world situations. Real-world objects often contain more visual details and semantic associations, which may place additional demands on cognitive systems such as memory and attention. By testing both, researchers can assess whether cognitive abilities are adaptable to different levels of complexity. This comparison also provides insights into developmental processes, revealing whether children's cognitive systems are mature enough to handle diverse stimuli. Additionally, using real-world objects increases ecological validity, ensuring the findings are more applicable to everyday experiences. Finally, such comparisons can highlight task-specific strategies, showing how children may approach different types of stimuli, thereby offering a more comprehensive understanding of their early cognitive development.

6.1.2. Brain function involved in processing visual stimuli.

As the visual system matures, the brain mechanisms that support visual processing do not operate in isolation, nor do they respond uniformly across all types of input. Instead, evidence suggests that the nature of the stimulus, its complexity,

familiarity, emotional salience, and task relevance, can modulate the recruitment of specific brain regions. For instance, Kim et al. (2010) investigated how the human brain responds to visual stimuli depicting contrasting environments. Using fMRI, they examined neural activation in adults while they viewed still photographs of rural and urban environments. Although both types of images activated primary visual areas, rural scenes elicited stronger engagement in emotion- and reward-related regions, including the anterior cingulate cortex, globus pallidus, putamen, and caudate. In contrast, urban scenes more strongly recruited the amygdala, hippocampus, and parahippocampal gyrus - regions associated with arousal and memory encoding. These neural differences were consistent with participants' subjective ratings, which characterised rural imagery as more peaceful and urban imagery as more suffocating. The findings suggest that visual stimuli rich in emotional or ecological relevance engage extended networks beyond early sensory areas, highlighting how context and affective associations modulate visual processing (Kim et al., 2010). More recently, Mencarelli et al. (2019) conducted a comprehensive meta-analysis of n-back task studies to examine how different stimulus types modulate brain activation during working memory tasks. By comparing brain function elicited by verbal (letters, numbers, words), spatial (locations), and nonverbal (faces, objects, images) stimuli, they identified both shared and stimulus-specific patterns of activation. Across all stimulus types, a common fronto-parietal network, including the DLPFC and parietal lobes, was consistently recruited, supporting the idea of a domain-general executive system (Owen et al., 2005; Rottschy et al., 2012). However, verbal tasks preferentially activated left-hemisphere language regions and the parietal cortex (Gelfand & Bookheimer, 2003; Jonides et al., 1998), spatial tasks recruited bilateral parietal areas (Corbetta et al., 1995), and nonverbal stimuli engaged additional subcortical and insular regions. Importantly, the study also identified load-dependent activity, with higher working memory demands (e.g., 3-back vs. 1-back) eliciting increased activation in regions such as the anterior cingulate cortex and subcortical structures, including the thalamus. These regions are associated with increased executive effort, inner speech, and cognitive control (Cipolotti et al., 2025; Wolff & Halassa, 2024). These results demonstrate that while core working memory processes are supported by common neural substrates, stimulus properties shape the broader network involved in visual and cognitive processing.

Recent work has investigated how both adults and young children perceive and process geometrically regular shapes, revealing key developmental insights into the brain's symbolic reasoning abilities (Sablé-Meyer et al., 2024). Sablé-Meyer et al. (2024) emphasised a fundamental distinction between two neural systems involved in geometric shape perception: an early visual system (ventral pathway) that responds more to visual complexity and a later, symbolic system (involving dorsal parietal and prefrontal regions) that is especially sensitive to geometric regularity (i.e., features like symmetry, right angles, and parallelism). They found that in both adults and children, there was reduced activation in the ventral visual cortex for geometric shapes, and increased engagement in the fronto-parietal network in response to regular shapes. Overall, this study provided strong evidence that humans possess an early-emerging, symbolic system for encoding geometric regularities that becomes increasingly specialised and refined with age (Sablé-Meyer et al., 2024).

While previous work has provided valuable insight into how different brain regions respond to various types of stimuli, much of it has focused on older populations, leaving a significant gap in our understanding of how these mechanisms emerge and differentiate in early development. Very few studies have utilised neuroimaging methods to examine how children process different visual stimulus types, particularly during the first few years of life. Additionally, there is a lack of research directly comparing brain responses to simple shape-based stimuli, which are often used in experimental paradigms, with complex, real-world objects, which more closely resemble the stimuli encountered during everyday interactions. Understanding how the developing brain processes this range of input is crucial for bridging the gap between experimental research and real-world visual cognition.

6.1.3. The current study.

Significant gaps remain in our understanding of how toddlers process and respond to different kinds of visual input. Existing experimental research has relied on simplified stimuli such as geometric shapes and colours, which, while useful for standardisation, may not fully capture the richness and variability of toddlers' everyday visual experiences. Critically, there is a lack of research directly comparing

toddlers' visual cognition when engaging with abstract versus ecologically valid, real-world stimuli. Furthermore, few studies have examined how these differences may interact with the quality and structure of dyadic interactions, which are known to play a central role in shaping early learning. While research in infants has begun to highlight developmental shifts in attention, categorisation, and memory as a function of stimulus complexity, more work is needed. Moreover, the brain mechanisms underlying such processing differences in early childhood are still poorly understood. These gaps limit our ability to draw meaningful connections between lab-based findings and naturalistic developmental contexts. Addressing these issues is essential for building a more ecologically valid model of visual cognition in early childhood.

The over-arching objective of the current study was to examine differences in looking behaviours and brain function in toddlers in response to different experimental stimuli, and how these measures were associated with real-world dyadic interactions. To achieve this, looking behaviours and brain function were collected from toddlers in two variants of the preferential looking task – one task using coloured shapes based on the version used in Chapter 3 (referred to as 'simple' task), and another task using images of real-world objects (referred to as 'complex' task).

Concretely, the study posed five research questions. The first research question inquired whether toddler looking behaviours would differ between the simple and complex tasks. Previous findings are mixed. On the one hand, Mitsven et al. (2018) reported similar patterns of performance on variants of visual working memory tasks using simple shapes and complex real-world objects in 10-month-old infants. In contrast, other work has emphasised that older infants may show heightened engagement in real-world stimuli (Gerhard et al., 2021; Hauschild et al., 2021; Spriet et al., 2022). Given the age range of the current sample, the prediction was that toddlers would show better looking behaviours (longer looking times, less switching, and higher CP scores) during the complex task compared to the simple task.

The second question inquired whether there would be differences in brain function elicited by simple and complex tasks. Previous neuroimaging work with toddlers has shown emerging specialisation in regions associated with visual

working memory. Delgado Reyes et al. (2020) found that by two years of age, toddlers exhibit robust, localised activation in canonical regions of the visual working memory network, including bilateral anterior intraparietal sulcus, DLPFC, left ventral occipital cortex, and left temporoparietal junction during a preferential looking task with coloured shapes. Findings from adult studies suggest that complex stimuli recruit broader and more integrative processing networks. For instance, Grill-Spector & Weiner (2014) and Kriegeskorte et al. (2008) reported that real-world stimuli engage the ventral temporal cortex and inferior temporal cortex, reflecting semantic and category-level processing. Given these findings, it was expected that the complex task will exclusively recruit activation in regions of the temporal cortex in addition to activation in the fronto-parietal regions, associated with general visual working memory processing. It was predicted that the simple task would only elicit activation in the fronto-parietal network.

The third objective was whether visual cognition in the simple task would be positively associated with visual cognition in the complex task. It was expected that there would be a positive association between looking behaviours in the simple and complex tasks; however, this prediction is not based on previous experimental work. Rather, it is based on alignment in toddler object engagement between SO and MO play during toddlerhood in the same sample (Chapter 5).

The fourth and fifth objectives examined links between visual working memory and caregiver-child behaviours in dyadic interactions. Note that the focus was on MO play only, as (i) caregiver-infant behaviours during this interaction were linked to infant CP scores (Chapter 4), (ii) there was an increase in engagement during this interaction from the first to second year of life (Chapter 5), and (iii) there was greater engagement during this interaction, compared to SO play (Chapter 5). The fourth objective examined the associations between caregiver-toddler behaviours during MO play and toddler visual working memory in both tasks. Findings from Chapter 4 showed that the interaction between caregiver scaffolding and infant object engagement, and the interaction between caregiver scaffolding and infant distractibility were associated with infant CP scores at the low load in the simple version task. It is predicted that this association would still be evident in toddlerhood. Further, it was expected that associations would be stronger between caregiver-toddler behaviours during MO play and toddler visual working memory in the complex task, compared to toddler visual working memory in the simple task –

due to perceptual, semantic, and purpose-based similarity between the dyadic objects and images of real-world objects. However, due to lack of concrete evidence driving this expectation, an exploratory approach was taken. The fifth objective examined whether caregiver-infant behaviours during MO play predicted toddler visual working memory in both tasks. Based on general evidence showing predictive links between caregiver-infant dyadic interactions and later child outcomes (e.g., Gunderson et al., 2013; Meins et al., 2002; Tamis-LeMonda et al., 2001), it is expected that caregiver-infant behaviours during dyadic interactions would predict visual working memory in toddlerhood. Further, it was speculated that there would be stronger predictive associations between caregiver-infant behaviours during MO play and toddler visual working memory in the complex task, compared to toddler visual working memory in the simple task. However, again, due to lack of evidence, an exploratory approach was taken to answer this research question.

6.2. Methods.

6.2.1. Participants.

Refer to section 3.2.1. in Chapter 3 for full recruitment details. Refer to section 5.2.1. in Chapter 5 for recruitment details for additional families with children between 18 and 22 months of age.

A total of 77 toddlers (43 females, Mage = 615.3 days, SD = 25.3) participated in the study. 2 toddlers were excluded due to the presence of familial colour blindness. Thus, the final sample consisted of 75 toddlers (43 females, Mage = 615.8 days, SD = 25.4). Other demographic and socioeconomic status information, collected from the caregivers of the participating toddlers, is provided in Table 6.1. Task specific exclusions are presented in the following sections.

Table 6.1. Socioeconomic and demographic information was collected via questionnaires. Data was not available from all families (as indicated by N).

	N	Mean	SD
Child age (days)	75	615.8	25.4
Primary caregiver age (years)	75	34.1	4.3
Primary caregiver education (years)	68	16.3	2.5
Secondary caregiver education (years)	67	14.0	4.0
Primary caregiver income	62	£ 26,419	£ 12,559
Secondary caregiver income	44	£ 30,244	£ 10,777
Primary Caregiver's Ethnicity	**N**	**%**	
Asian	5	6.7	
Mixed	3	4	
Arab	1	1.3	
White British	57	76	
Other White	2	2.7	
Did not answer	7	9.3	

6.2.2. Preferential looking tasks.

Two variants of the preferential looking task were run – simple and complex. The simple preferential looking task is based on the version used for the infants in Chapter 3. Refer to section 3.2.3 for the details. The simple task used coloured shapes; the complex task used images of real-world objects.

The real-world objects were chosen from the Bank of Standardised Stimuli (BOSS; Brodeur et al., 2014) image database. A total of 137 images were initially selected from the database. Images were then modified to decrease stimuli variability in mean luminance, luminance variance, and visual-field area, following from previous object-processing research (e.g., Madan et al., 2018). Mean luminance was adjusted for images greater than 1 standard deviation from the mean by converting the image to CIE Lab* colour space, increasing/decreasing the luminance of the object mask and then converting back to RGB colour space. Within-image luminance variance was calculated and any images with greater than the modal luminance

variance value were adjusted. Finally, visual-field area was calculated as the proportion of the image that represented the object, intended to equate objects from the original database that were relatively small in pixel area (e.g., long-thin objects [e.g., candle] vs. compact objects [e.g., apple]). A criterion of 75% white space was set, with the size of the object iteratively decreased, relative to the overall image dimensions until the criterion was reached. Following these adjustments, any images that looked unusual were excluded. Additionally, any images that might be easily nameable or recognisable to the toddlers were excluded. For example, toddlers might encounter an 'apple' or a 'sippy cup' quite frequently. This list now consisted of images such as 'artichoke' and 'flashlight', which were unlikely to elicit specific preferences from toddlers. The remaining object images were then assigned into categories (e.g., animals, nature, food, transport) and colours to minimise similarity and interference effects. The final set of images consisted of 33 real world objects (e.g., candle, globe, sponge).

Similar to the simple task, in a trial, the real-world objects differed from each other, but objects could be repeated between the displays (i.e., the same object could appear on both displays). For both tasks, visual working memory load was manipulated across 2 (low load), 4 (medium load), or 6 (high load) items.

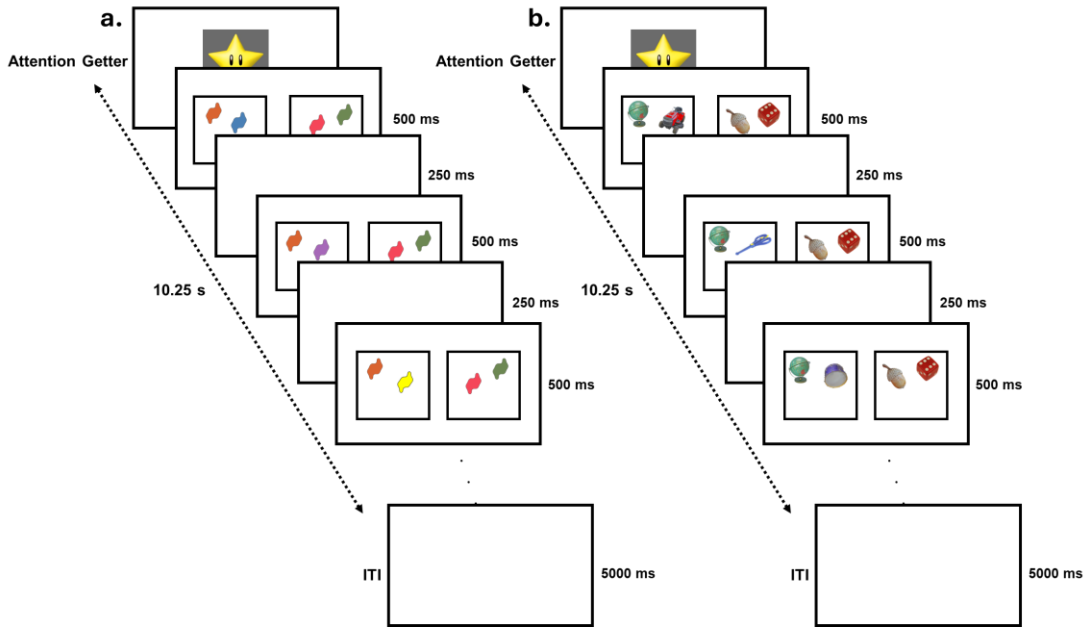


Figure 6.1. (a) Low load trial from the simple preferential looking task. Changing side showed on the left. (b) Low load trial from the complex preferential looking task. Changing side showed on the left.

Note that the background of both tasks was grey, however for improved image clarity, the figures show a white background. For clarity, it is best to view all figures in the original colour version.

6.2.3. fNIRS data acquisition.

Refer to section 3.2.4. in Chapter 3 for full details.

6.2.4. Dyadic play interactions.

Refer to section 4.2.2. in Chapter 4 for details of infant dyadic interactions. Refer to section 5.2.2. in Chapter 5 for details of toddler dyadic interactions.

6.2.5. Procedure.

Refer to section 4.2.5. in Chapter 4 for procedural details of the preferential looking task and Y1 dyadic interactions. Refer to section 5.2.3. in Chapter 5 for procedural information for Y2 dyadic interactions.

The two preferential looking tasks were administered by alternating runs of each. For example, the toddler would first be presented with a run of the complex task and then be presented with a run of the simple task. This approach was taken to avoid the toddlers becoming uninterested in the tasks. Families were renumerated with £10 for each visit to the lab.

6.2.6. Behavioural analyses.

Toddler visual working memory behaviour. Refer to section 3.2.6. in Chapter 3 for full details of how looking data was coded.

Two coders (AT, AD) manually coded 23% of the data from the simple task. Two coders (CD, BM) manually coded 21% of the data from the complex task. Kappa values from 0.81 to 0.99 indicate near perfect agreement. The mean Kappa was 0.91 for the simple task, and 0.97 for the complex task.

Refer to section 3.2.6. in Chapter 3 for full details of the four measures of visual cognition.

All behavioural data were screened for outliers. Data-points were considered outliers if they fell outside of $\pm$ 3 SDs from the mean. For the simple task, 8 outliers were identified and removed from the dataset (2 for MLD at medium load, 1 for SR at

low load, 1 for SR at medium load, 1 for SR at high load, 2 for CP at medium load, and 1 for CP at high load). For the complex task, 10 outliers were identified and removed from the dataset (1 for TLD at low load, 1 for TLD at medium load, 1 for TLD at high load, 2 for SR at low load, 1 for SR at medium load, 2 for SR at high load, 1 for CP at low load, and 1 for CP at high load). The number of toddlers contributing data to each looking measure at each load and each task is shown in Table 6.2.

Table 6.2. Number of toddlers contributing to each looking measures and each task.

Looking Measures	**Task Loads**	**Simple Task**	**Complex Task**	**Common Across Tasks**
TLD	*Low Load*	74	71	70
	Medium Load	74	69	69
	High Load	73	70	68
MLD	*Low Load*	74	72	71
	Medium Load	72	70	69
	High Load	73	71	69
SR	*Low Load*	73	70	69
	Medium Load	73	69	68
	High Load	72	69	66
CP	*Low Load*	74	71	70
	Medium Load	72	70	69
	High Load	72	70	67

Dyadic play interactions. Refer to section 4.2.6. in Chapter 4 for full details of how dyadic play interactions were coded.

Refer to section 4.2.9. in Chapter 4 for outlier details for Y1 dyadic interactions.

Refer to section 5.2.5. in Chapter 5 for outlier details for Y2 dyadic interactions.

6.2.7. fNIRS brain analyses.

Refer to section 3.2.7. in Chapter 3 for details related to fNIRS pre-processing, image reconstruction and group analyses of the fNIRS data. Only details that differ from Chapter 3 are mentioned here.

During pre-processing of the fNIRS data for the simple task, 6.19% of channels were pruned. Following pre-processing, 10.21% of trials were lost at low load, 10.22% of trials were lost at medium load, and 9.83% of trials were lost at high load. Consequently, for the simple task, 62 toddlers contributed data for the low load, 63 toddlers for medium load, and 62 toddlers for high load.

For the complex task, during pre-processing of the fNIRS data, 6.13% of the channels were pruned. Following pre-processing of the complex fNIRS data, 10.54% of trials were lost at low load, 8.24% of trials were lost at medium load, and 9.06% of trials were lost at high load. Consequently, 64 toddlers contributed data for the low load, 61 toddlers for medium load, and 64 toddlers for high load.

For image reconstruction, scalp landmarks and probe geometry were digitised using a Polhemus Patriot Motion Tracking System on a child wearing a 48 cm size cap. An 18-month-old template was used for analyses.

For group analyses, a mask was created for voxels that contributed data for the simple and complex tasks. This group mask was used in the linear mixed effects model run on the fNIRS data from both tasks. Concretely, the model was run with fixed within-subjects factors of load (low, medium, and high), task (simple and complex), and chromophore (HbO and HbR), and CP score as a quantitative variable. The model yielded an F-statistic image each for main effects of, and interactions between, load, task, chromophore, and CP score. To answer the proposed research questions, only interactions that included chromophore were considered. Thus, the effects of interest were main effect of chromophore, interaction between load and chromophore, interaction between task and chromophore, interaction between CP score and chromophore, interaction between load, CP score, and chromophore, interaction between task, CP score, and chromophore, interaction between load, task, and chromophore, and interaction between load, task, CP score, and chromophore. Family-wise corrections were applied to these F-statistic images (voxel-wise p value of 0.01 and cluster size of 280 voxels). Beta values were

averaged across voxels of each cluster and follow-up tests were ran in RStudio (RStudio Team, 2020).

6.2.8. Statistical analyses.

Statistical analyses were carried out using RStudio (RStudio Team, 2020). Two-factor ANCOVAs were run to investigate how looking behaviours differed by task and load, while controlling for toddler age in days. To test whether looking behaviours during the simple task were associated with looking behaviours during the complex task, regression models were run, controlling for toddler age. Further regression models were run to test whether brain function in the simple task was associated with brain function in the complex task. To examine whether caregiver-toddler behaviours during MO play were associated with toddler visual working memory, regression models with toddler age as a covariate were run. Finally, to examine whether caregiver-infant behaviours during MO play predicted toddler visual working memory, regression models with toddler age as a covariate were run.

6.3. Results.

To address the first research question, two-factor ANCOVAs were run to investigate how looking behaviours (TLD, MLD, SR, and CP) differed by task and load, after controlling for toddler age. The two-factor ANCOVA on TLD scores revealed a significant main effect of task ($F(1,424) = 62.936$, $p < .001$, $\eta 2 = .13$). Specifically, TLD scores for the complex task were significantly greater than TLD scores for the simple task ($p < .001$) – see Figure 6.2a. The two-factor ANCOVA on MLD scores revealed a significant main effect of task ($F(1,425) = 56.640$, $p < .001$, $\eta 2 = .12$) and a significant main effect of load ($F(2,425) = 3.950$, $p = .02$, $\eta 2 = .02$). Specifically, MLD scores for the complex task were significantly greater than MLD scores for the simple task ($p < .001$) – see Figure 6.2b. Across both tasks, MLD scores at the high load were significantly greater than MLD scores at the low load ($p = .027$). The two-factor ANCOVA on SR scores revealed only a significant main effect of task ($F(1,419) = 17.041$, $p < .001$, $\eta 2 = .04$). Specifically, SR scores for the simple task were significantly greater than SR scores for the complex task ($p < .001$) – see Figure 6.2c. Finally, the two-factor ANCOVA on CP scores revealed a significant main effect of task ($F(1,422) = 9.876$, $p = .002$, $\eta 2 = .02$) and a significant main effect of load ($F(1,422) = 6.435$, $p = .002$, $\eta 2 = .03$). Specifically,

CP scores on the simple task were significantly greater than CP scores on the complex task (p = .002) – see Figure 6.2d. Across both tasks, CP scores at low (p = .002) and medium load (p = .03) were significantly higher than those at high load. Overall, looking behaviours differed significantly by task with the complex task eliciting greater TLD and MLD scores, while the simple task was associated with higher SR and CP scores.

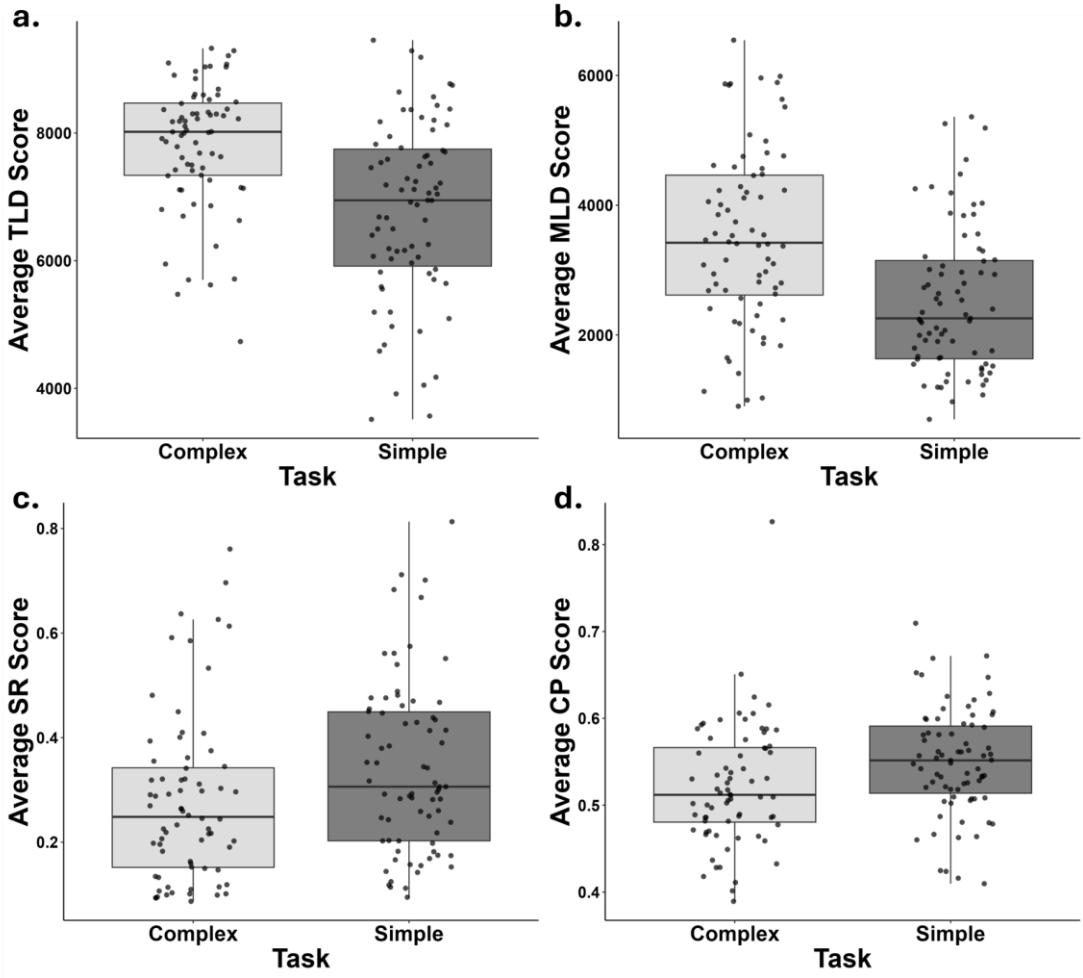


Figure 6.2. (a) Main effect of task on TLD scores. (b) Main effect of task on MLD scores. (c) Main effect of task on SR scores. (d) Main effect of task on CP scores. Each box represents the IQR, with the horizontal line indicating the median. Whiskers extend to 1.5 times the IQR, and data points outside this range are plotted as outliers.

To address the second research question, a linear mixed effects model was run on the brain data with load, task, and chromophore as within-subjects factors, and CP as a quantitative variable. This analysis revealed only a significant main effect of chromophore in six clusters – rSFG [MNI coordinates: -21.8 -18.0 58.4, 1704 voxels], right superior temporal gyrus (rSTG) [MNI coordinates: -62.8 17.3

12.4, 1153 voxels], lAG [MNI coordinates: 45.5 60.4 44.5, 866 voxels], rSPL [MNI coordinates: -35.5 61.5 55.2, 693 voxels], left precentral gyrus (lPG) [MNI coordinates: 48.0 -9.9 38.4, 461 voxels], and left superior frontal gyrus (lSFG) [MNI coordinates: 24.4 -35.7 45.1, 307 voxels] – see Table 6.3 and Figure 6.3. Follow-up tests revealed that HbO concentration was greater than HbR concentration in rSTG (rSTG: $p = .013$), lAG (lAG: $p < .001$), rSPL (rSPL: $p = .008$), and lPG (lPG: $p < .001$). In contrast, for rSFG and lSFG, HbO concentration was lesser than HbR concentration (rSFG: $p < .001$; lSFG: $p = .01$). In summary, brain activation differed significantly by chromophore across six regions, with HbO generally exceeding HbR concentrations (increased activation), except in frontal regions (rSFG and lSFG) where the reverse pattern was observed.

Following this, exploratory analyses were run to examine potential links to looking behaviours. Pearson correlations were conducted between mean HbO and HbR concentrations in each of the six significant clusters (rSFG, rSTG, lAG, rSPL, lPG, and lSFG) and overall looking behaviour scores (TLD, MLD, SR, and CP). P-values were corrected for multiple comparisons using the Benjamini–Hochberg procedure, applied separately for each brain region, across the 2 tasks and 4 behavioural measures (8 tests), and independently for HbO and HbR. This approach was chosen as the chromophores reflect different physiological processes.

There were three significant results. First, a significant negative correlation was found between HbO concentration in the rSPL and SR scores during the complex task ($r = -.27$, $p = .027$) (Figure 6.4a). Second, HbR concentration in the lSFG was negatively correlated with CP scores during the complex task ($r = -.26$, $p = .034$). Third, a significant positive correlation was observed between HbO concentration in the lPG and SR scores during the simple task ($r = .31$, $p = .015$) (Figure 6.4b). Following Benjamini Hochberg corrections, the relationships between rSPL HbO concentration and complex SR scores (adjusted $p = .031$, $Q = .25$) and lPG HbO concentration and simple SR scores (adjusted $p = .025$, $Q = .2$) survived. The relationship between lSFG HbR concentration and complex CP scores did not survive at any threshold. No other significant correlations were found.

*Table 6.3. Cluster information for significant effects in the across task brain model. * Indicates effects that yielded significant results after follow-up tests.*

Significant effects	Cluster	Size (mm^3)	MNI coordinates		
			Centre of Mass		
			x	y	z
Chromophore	Right superior frontal gyrus (rSFG) *	1704	-21.8	-18.0	58.4
	Right superior temporal gyrus (rSTG) *	1153	-62.8	17.3	12.4
	Left angular gyrus (lAG) *	866	45.5	60.4	44.5
	Right superior parietal lobule (rSPL) *	693	-35.5	61.5	55.2
	Left precentral gyrus (lPG) *	461	48.0	-9.9	38.4
	Left superior frontal gyrus (lSFG) *	307	24.4	-35.7	45.1

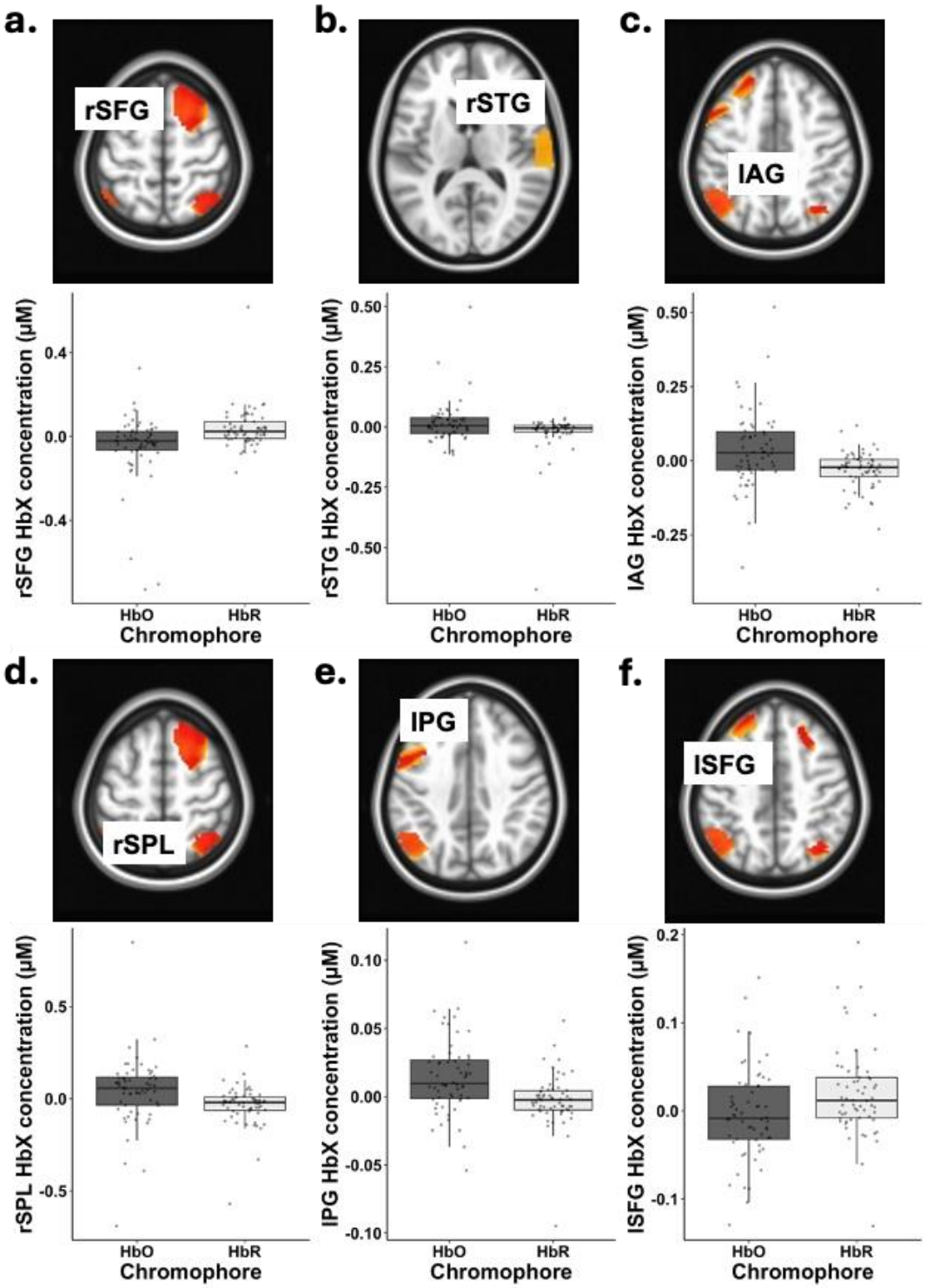


Figure 6.3. Brain images and boxplots for significant main effect of chromophore in (a) right superior frontal gyrus (rSFG) – [MNI coordinates: -21.8 -18.0 58.4], (b) right superior temporal gyrus (rSTG) – [MNI coordinates: -62.8 17.3 12.4], (c) left angular gyrus (lAG) – [MNI coordinates: 45.5 60.4 44.5], (d) right superior parietal lobule (rSPL) – [MNI coordinates: -35.5 61.5 55.2], (e) left precentral gyrus (lPG) – [MNI coordinates: 48.0 -9.9 38.4], and (f) left superior frontal gyrus (lSFG) – [MNI coordinates: 24.4 -35.7 45.1]. HbO concentration is shown in black and HbR concentration is

shown in grey. Each box represents the IQR, with the horizontal line indicating the median. Whiskers extend to 1.5 times the IQR, and data points outside this range are plotted as outliers.

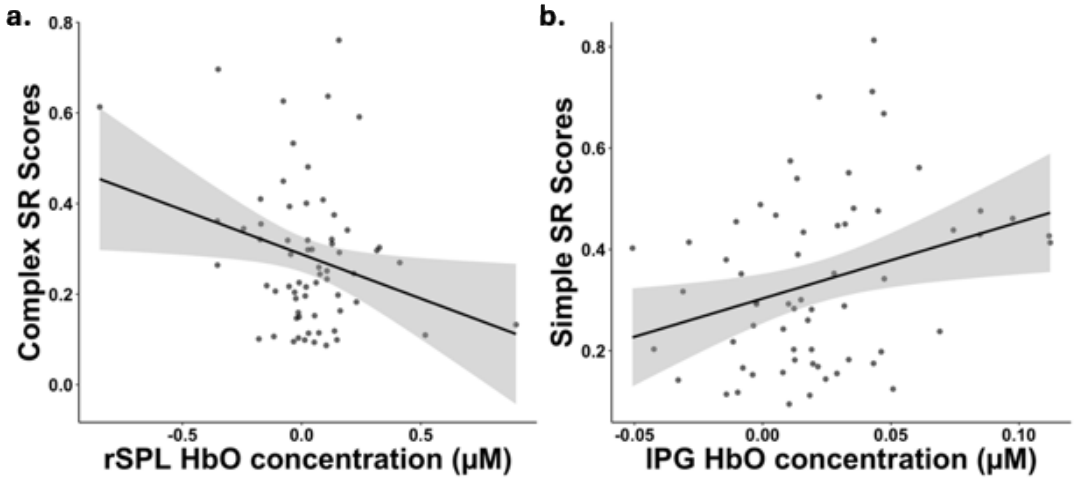


Figure 6.4. (a) Negative correlation between rSPL HbO concentration and complex SR scores. (b) Positive correlation between lPG HbO concentration and simple SR scores.

To address the third research question, four separate regression models were run to test whether looking behaviours during the simple task were associated with looking behaviours during the complex task, after controlling for toddler age. Results revealed positive associations for TLD ($\beta = 0.443$, SE = 0.07, $t = 6.621$, $p < .001$), MLD ($\beta = 0.862$, SE = 0.10, $t = 8.259$, $p < .001$), and SR ($\beta = 0.596$, SE = 0.10, $t = 6.198$, $p < .001$) – see Figure 6.5(a – c). There was no association for CP scores. Concretely, looking behaviours on the simple task were significantly associated with the same behaviours on the complex task for TLD, MLD, and SR, but not for CP. Note that initial analyses were conducted separately for each load (low, medium, and high). However, similar significant associations were found at all loads for TLD, MLD, and SR, and no associations were found for CP at any load. Therefore, to simplify the presentation and interpretation of results, only the overall associations are reported here.

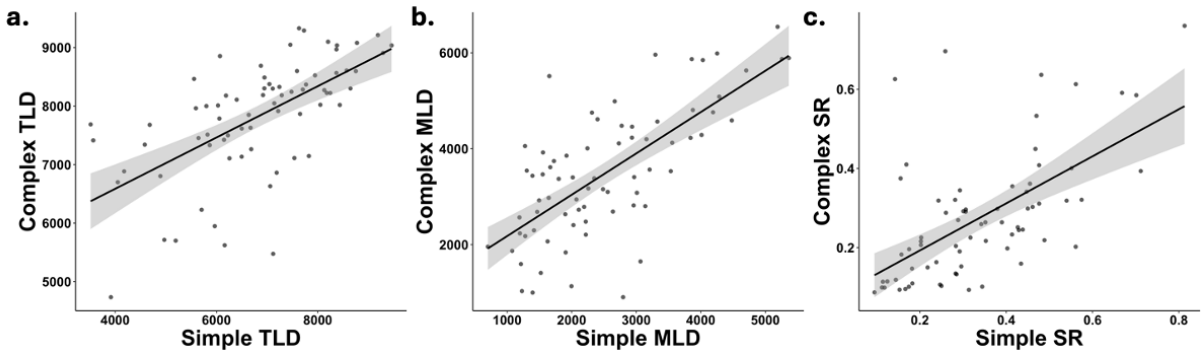


Figure 6.5. (a) Association between simple TLD and complex TLD. (b) Association between simple MLD and complex MLD. (c) Association between simple SR and complex SR.

In line with the previous objective of cross-task associations, regression models were run to test whether brain function in the simple task was associated with brain function in the complex task, while controlling for toddler age. Separate models were run for HbO and HbR. P-values were corrected for multiple comparisons using the Benjamini–Hochberg procedure, applied separately for each chromophore (6 tests). This approach was chosen as the chromophores reflect different physiological processes.

Significant results were obtained for lAG, rSPL and lSFG clusters only – see Figure 6.6(a-d). First, in lAG, HbO concentration during the simple task was negatively associated with HbO concentration during the complex task ($F(1,57) = 5.121$, $p = .027$, $\eta2 = .08$). Second, in rSPL, HbO concentration and HbR concentration during the simple task was positively associated with HbO and HbR concentration during the complex task, respectively (HbO: $F(1,57) = 8.315$, $p = .006$, $\eta2 = .13$; HbR: $F(1,57) = 10.354$, $p = .002$, $\eta2 = .15$). Finally, in lSFG, HbR concentration during the simple task was positively associated with HbR concentration during the complex task ($F(1,57) = 5.238$, $p = .026$, $\eta2 = .08$). Following Benjamini Hochberg corrections, all four relationships survived (lAG HbO: $p = .033$, $Q = .1$; rSPL HbO: $p = .017$, $Q = .1$; rSPL HbR: $p = .017$, $Q = .1$; lSFG HbR: $p = .033$, $Q = .1$). These findings suggested that there were associations in brain function between both tasks, however, these associations varied by region, indicating potentially distinct functional roles across tasks.

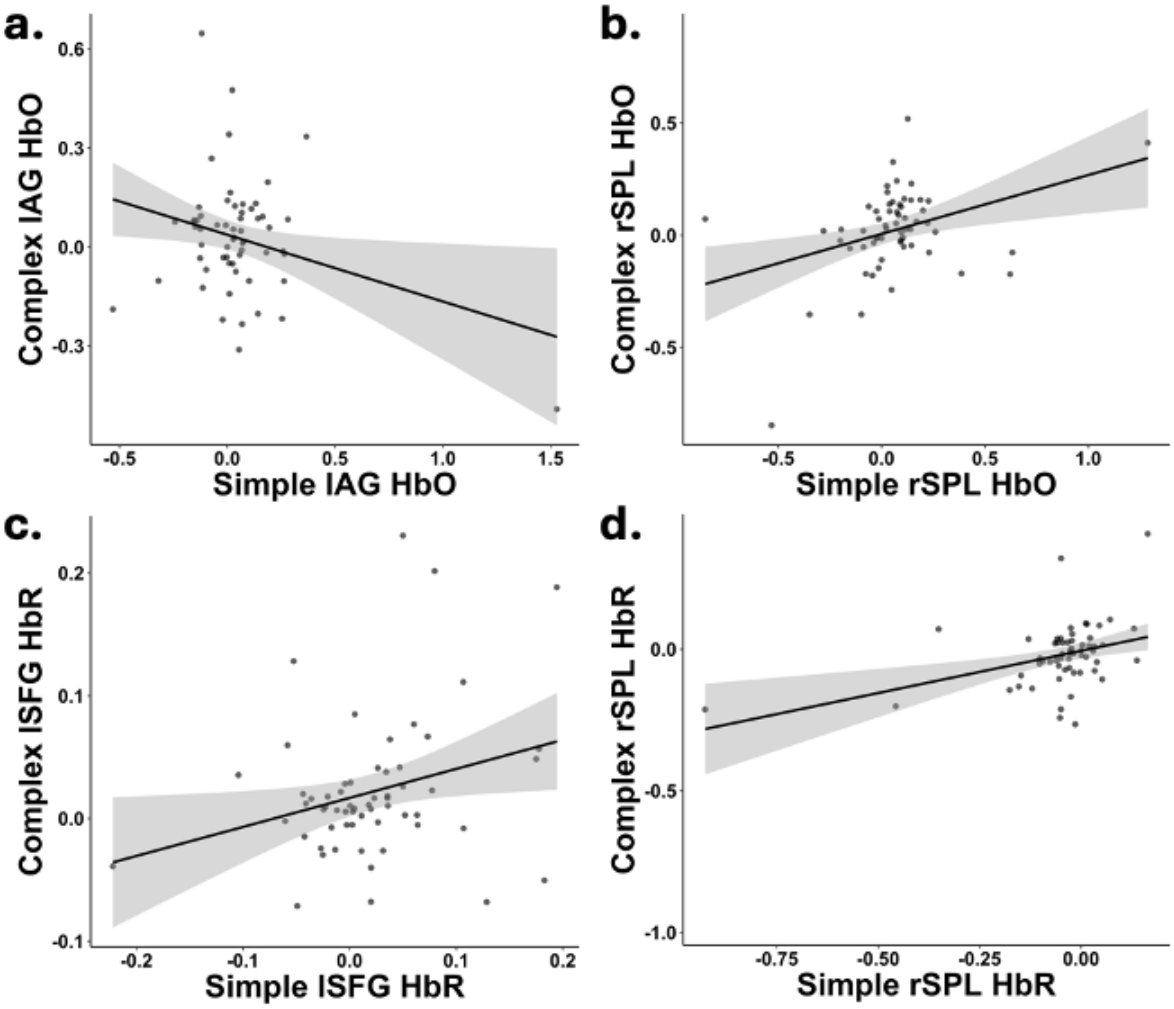


Figure 6.6. (a) Association between simple and complex tasks for left angular gyrus (lAG) HbO concentration. (b) Association between simple and complex tasks for right superior parietal lobule (rSPL) HbO concentration. (c) Association between simple and complex tasks for left superior frontal gyrus (lSFG) HbR concentration. (d) Association between simple and complex tasks for rSPL HbR concentration.

The fourth research question was to examine whether caregiver-toddler behaviours during MO play were associated with toddler visual working memory. First, Pearson's correlations were run between caregiver scaffolding and toddler object engagement, and caregiver scaffolding and toddler distractibility during MO play to check if they were significantly correlated, and therefore, must not be included in the same models. These three behaviours were selected for analysis because they were previously found to be associated with infant CP scores in Chapter 4. Results revealed a significant relationship between caregiver scaffolding and toddler object engagement ($r = .29$, $p = .02$). However, the relationship between caregiver scaffolding and toddler distractibility was not significant ($r = -.10$, $p = .416$) – see Table 6.4.

Following this, two regression models were run for each task. In all models, toddler CP score was the outcome variable and toddler age in days was a covariate. The first model used centred caregiver scaffolding and toddler distractibility as the predictor, and the second model used only centred toddler object engagement as the predictor.

For the simple task, no significant relationships were found. For the complex task, two significant relationships were found. First, toddler object engagement was associated with CP scores ($\beta = 0.001$, SE = 0.00, $t = 2.256$, $p = .028$), such that higher object engagement was linked to higher CP scores – see Figure 6.7a. Second, caregiver scaffolding was also associated with CP scores ($\beta = 0.001$, SE = 0.00, $t = 2.385$, $p = .02$), such that higher scaffolding was linked to higher CP scores – see Figure 6.7b. No interaction effects were found between caregiver scaffolding and toddler distractibility.

*Table 6.4. Correlation between caregiver/toddler behaviours for MO play. * represents significance.*

MO play			
	1	**2**	**3**
1. Caregiver scaffolding	-	.29*	-.10
2. Toddler object engagement		-	-.61*
3. Toddler distractibility			-

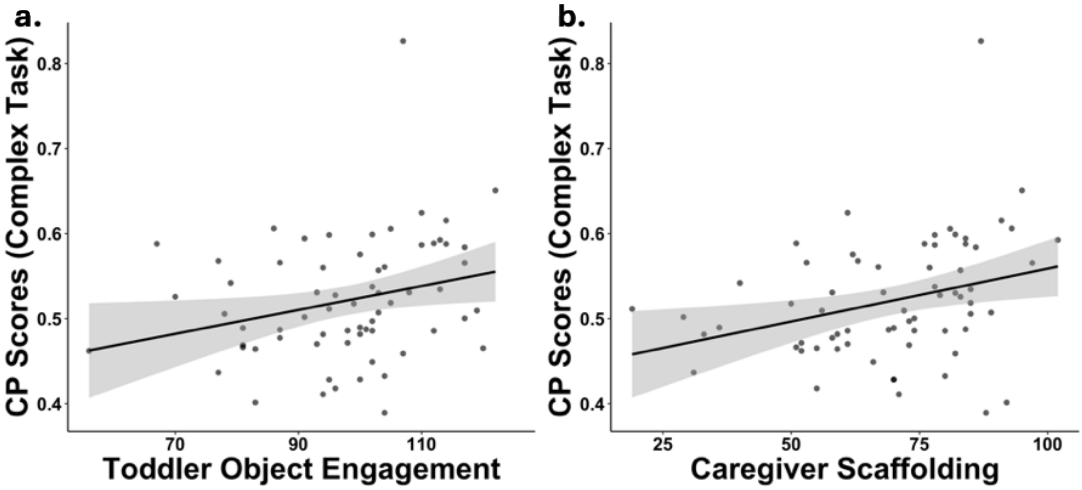


Figure 6.7. (a) Association between toddler object engagement and complex CP scores. (b) Association between caregiver scaffolding and complex CP scores.

Finally, the fifth research question was to examine whether caregiver-infant behaviours during MO play predicted toddler visual working memory in both tasks. First, Pearson's correlations were run between caregiver scaffolding and infant object engagement, and caregiver scaffolding and infant distractibility during MO play to check if they were significantly correlated, and therefore, must not be included in the same models. Results revealed no significant relationships between caregiver scaffolding and infant object engagement ($r = .08$, $p = .446$) or caregiver scaffolding and infant distractibility ($r = .00$, $p = .969$) – see Table 6.5. These findings are consistent with those reported in Chapter 4.

Following this, two regression models were run for each task. In all models, toddler CP score was the outcome variable and toddler age in days was a covariate. The first model consisted of centred caregiver scaffolding and infant distractibility as predictors, and the second model consisted of centred caregiver scaffolding and infant object engagement as predictors. No significant relationships were found for either task.

*Table 6.5. Correlation between caregiver/infant behaviours for MO play. * represents significance.*

MO play			
	1	**2**	**3**
1. Caregiver scaffolding	-	.08	.00
2. Infant object engagement		-	-.63*
3. Infant distractibility			-

6.4. Discussion.

The current study posed five research questions to understand how visual cognition was impacted by different experimental stimuli, and how it was associated with real-world dyadic interactions. The first research question inquired whether toddler looking behaviours would differ between the simple and complex tasks. There were significant task differences for all looking measures. Specifically, CP and SR were higher for the simple task and TLD and MLD were higher for the complex task. The second question inquired whether there would be differences in brain function elicited by simple and complex tasks. Six regions showed overall engagement across both tasks. Specifically, activation was observed in rSTG, lAG,

rSPL, and lPG and suppression was observed in rSFG and lSFG. However, there were no task-related differences in any regions. The third question inquired whether visual cognition in the simple task would be positively associated with visual cognition in the complex task. It was reported that TLD, MLD, and SR during the simple task were positively associated with the same measures during the complex task. However, there were no effects for CP scores. The fourth question examined the associations between caregiver-toddler behaviours during MO play and toddler visual working memory in both tasks. There were two significant associations between dyadic behaviours and toddler visual working memory in the complex task. Specifically, caregiver scaffolding and toddler object engagement were positively associated with complex CP scores. No associations were found between caregiver-toddler behaviours and toddler visual working memory in the simple task. The fifth question inquired whether caregiver-infant behaviours during MO play predicted toddler visual working memory in both tasks. There were no predictive relationships between caregiver-infant behaviours and toddler visual working memory in the complex or simple task. These findings are discussed below.

6.4.1. Toddler looking behaviours differ between simple and complex tasks.

The first objective examined whether toddler looking behaviours would differ between the two tasks. All looking behaviours significantly differed between the simple and complex tasks. The prediction was that toddlers would show better looking behaviours during the complex task compared to the simple task. However, the findings only partially supported the predictions. Specifically, toddlers exhibited higher SR and CP scores in the simple task compared to the complex task, indicating that they might have relied on comparisons between displays by switching to detect and prefer the changing side. In general, this finding is consistent with theories of attentional control, which suggest that simpler stimuli impose lower cognitive demands, thereby freeing up cognitive resources for more flexible attention allocation (Diamond, 2013; Lavie, 1995). Toddlers may have found it easier to disengage from one stimulus and reorient to another, resulting in an increased likelihood of detecting the changing side and exhibiting higher CP scores. Relatedly, toddlers demonstrated higher TLD and higher MLD scores in the complex task compared to the simple task, suggesting they might have spent more time fixating on the real-world objects in the complex task. Taken together, longer TLD and MLD,

and reduced SR culminating in reduced CP scores in the complex task might reflect difficulty in holding multiple features of individual real-world objects in working memory, and/or sticky attention due to familiarity of the items based on representations in episodic memory, and/or an inability to shift attention to another object on the same display or objects in the other display. It is not possible to disentangle these mechanisms in this design with the methods used, but it is expected that one might have preceded the other(s) or that all three mechanisms occur in different proportions in different trials, so they are discussed separately and contextualised with broader literature below.

One possible explanation for toddlers demonstrating increased looking durations and reduced switching in complex tasks is the elevated working memory demands associated with processing multiple visual features. Cognitive load theory (Sweller, 1988) proposes that working memory has a limited capacity, and that processing multiple elements can overwhelm this capacity, particularly during early development when working memory systems are still maturing (Cowan, 2016). Real-world stimuli often include greater visual detail, colour variation, texture, and spatial arrangement, compared to schematic or simplified stimuli. Holding and manipulating these features simultaneously in working memory may overwhelm toddlers' processing capabilities, leading to longer total and mean look durations (TLD, MLD) as they attempt to extract or maintain relevant information. Research has shown that infants and toddlers struggle with tasks requiring integration of multiple features, particularly when these features must be remembered over even short time intervals (Oakes et al., 2006; 2009). Thus, difficulty encoding and maintaining the complex features of real-world objects could explain the observed decrease in CP scores and reductions in SR in the complex task.

Attentional dynamics may also play a role in shaping toddlers' looking behaviour. For instance, "sticky attention", wherein toddlers persist in looking at stimuli that are salient, familiar, or emotionally engaging, could limit their ability to disengage and explore alternative visual information. Sticky attention has been observed in both typical and atypical development, with stronger effects often linked to individual differences in temperament or neurodevelopment (Kulke et al., 2015; Landry & Bryson, 2004). Familiarity plays a central role in modulating visual engagement; stimuli that resemble previously-encountered objects or categories

(e.g., toys, food items, animals) may trigger stored episodic representations, leading to prolonged fixations (Chung et al., 2024). Even though items that might be extremely familiar were removed from the list, some items or features of these items might have activated such memory traces, making them harder to disengage from. Dwyer et al. (2024) similarly found that autistic children exhibited prolonged attention to complex or emotionally salient images, suggesting that stimulus familiarity or richness in features can reduce attentional flexibility. In typical development, such effects may also emerge transiently, especially in contexts where children are still learning to manage attentional control. These findings support the idea that sticky attention driven by item familiarity could contribute to reduced SR and lower CP scores in the complex task.

Finally, toddlers may have struggled to shift attention effectively between objects or between visual arrays when viewing complex stimuli, reflecting immature attentional control mechanisms. Efficient attentional shifting requires disengaging from the current focus, orienting to a new target, and re-engaging with that target - processes that are still developing during toddlerhood (Posner & Petersen, 1990). The effort required to resolve visual competition among overlapping features may have impeded their ability to switch focus between stimuli efficiently, resulting in reduced SR and ultimately affecting CP performance. Thus, attentional inflexibility may also partially explain the observed differences in looking behaviour between tasks.

There were no task-based differences at the load level suggesting that differences in looking behaviours were consistent across all loads. Specifically, toddlers showed significantly higher MLD scores at high load compared to low load, and significantly lower CP scores at the high load relative to both low and medium loads - effects that held across both task types. Each of the three mechanisms proposed earlier may be differentially taxed as load increases, providing a framework for understanding these consistent effects. First, as visual load increases, toddlers must encode and maintain a greater number of visual features across multiple stimuli, placing escalating demands on working memory. Developmentally, working memory capacity is limited in early childhood and closely tied to attentional control (Cowan, 2016). Even in relatively simple visual tasks, increasing the number of items to be remembered affects performance (Davidson et al., 2024; Delgado

Reyes et al., 2020; Oakes et al., 2006, 2009; Ross-Sheehy et al., 2003; Wijeakumar et al., 2019, 2023). Under high-load conditions, the requirement to track more visual details, whether simple shapes or complex real-world objects, may exceed toddlers' memory capacity, resulting in prolonged looks as they attempt to process individual items more deeply, and poorer performance on change preference as they struggle to retain or compare across displays. Second, sticky attention may also become more pronounced under high-load conditions, especially when multiple items share features or categories that trigger existing representations in episodic memory. With more stimuli, the likelihood increases that at least one will be highly familiar, perceptually salient, or emotionally engaging - thus, resulting in higher MLD and lower CP scores at high loads. Third, the cognitive load imposed by more crowded or information-dense arrays likely strains toddlers' still-developing ability to shift attention efficiently. As load increases, children may not only become slower to shift, but may also develop a narrower attentional spotlight, focusing on one or two items at the expense of the rest (Johnson et al., 1991). Such a reduction in shifting and attentional breadth likely contributes to lower CP scores under high load conditions, as toddlers may fail to adequately sample and compare both sides of the display.

6.4.2. Common fronto-temporo-parietal engagement across tasks.

The second objective examined whether brain function would differ between the simple and complex tasks. Contrary to predictions, there were no task-related differences when examining brain activity. Instead, across both tasks, six regions across the fronto-temporo-parietal cortices were engaged, suggesting that toddlers rely on a shared general network for visual working memory processing regardless of stimulus complexity. Specifically, activation was observed in rSTG, lAG, rSPL, and lPG and suppression was observed in rSFG and lSFG. Among these regions, two regions showed significant associations with behaviour, suggesting a functional contribution to attentional allocation during task performance. First, a significant negative correlation was found between HbO concentration in the rSPL and SR during the complex task. The rSPL is widely implicated in the allocation of spatial attention and the dynamic control of eye movements (Corbetta & Shulman, 2002). The observed negative correlation indicates that greater activation in the rSPL was associated with fewer shifts between displays during the complex task. This pattern suggests that children who recruited this region more strongly were less likely to

alternate their attention across the competing sources of information. Prior adult work has linked rSPL to distinct roles in spatial attentional shifts and sustained attention (Vandenberghe et al., 2001). The current finding may therefore reflect individual differences in how toddlers manage competing attentional demands when task complexity increases. Second, a significant positive correlation was observed between HbO concentration in the lPG and SR scores during the simple task. The lPG is associated with visuomotor planning and the control of saccadic eye movements (Johansen-Berg & Matthews, 2002; Simon et al., 2002). The positive relationship between lPG activation and SR suggests that toddlers who engaged this region were better able to flexibly shift attention between sides. Therefore, in the simple task, greater lPG activation may reflect the involvement of visuomotor planning processes that support attentional shifting.

In contrast, the remaining regions did not show direct associations with behaviour but likely contributed to the broader network supporting task performance. For example, the rSTG, often linked to the integration of complex auditory and visual information and object recognition (Beauchamp et al., 2004), was engaged across both tasks. In this context, activation may reflect low-level perceptual processing of multi-featured stimuli, which is necessary regardless of task complexity. Similarly, activation in the lAG, a region implicated in multisensory integration and attentional reorienting (Seghier, 2013), may reflect a domain-general role in combining sensory inputs and processing spatial relationships across both tasks. Consistent engagement in this region across tasks suggests that it may support general integration processes that are not tightly linked to observable differences in behaviour at this developmental stage. Finally, both the rSFG and lSFG showed suppression across tasks. These regions are typically associated with higher-order cognitive control, sustained attention, and working memory manipulation (Boisgueheneuc et al., 2006; Nissim et al., 2017). As this pattern of suppression occurred regardless of task, it is possible that toddlers at this developmental stage do not yet heavily depend on higher-order cognitive control when processing visual stimuli. Within this network, the functional relevance of individual regions appears to shift depending on task demands, with the rSPL and lPG playing specific roles in modulating visual attention and exploration under varying task complexity.

It is important to consider why there were no task-differences in the measured regions even though there were differences in looking behaviours between the tasks. One possible explanation is that the regions that were measured, and as a result were commonly engaged/supressed represent the common visual working memory or executive control network. Importantly, it suggests that task-based differences in brain function might exist in brain regions that were not recorded from and/or sub-cortical areas. This interpretation is supported by meta-analytic evidence demonstrating that several of the cortical regions recorded in the current study form part of a domain-general network consistently engaged in executive control and working memory tasks. For example, Niendam et al. (2012) conducted a large-scale meta-analysis, synthesising data across 193 neuroimaging adult studies of executive function, spanning cognitive domains such as working memory, response inhibition, and task switching. Their analysis revealed a core, domain-general cognitive control network, alongside task-specific activations. Regions observed in the current study, STG, AG, SFG, SPL, and PG, were implicated to varying degrees in general executive function and working memory tasks. Therefore, the absence of observed task-related differences in brain activation, despite behavioural disparities, may be attributed to the limitations of the neuroimaging methods employed, which primarily capture cortical surface activity. Some previous research in adults suggests that variations in stimulus complexity and stimulus type can differentially engage deeper brain structures. For instance, Kim et al. (2010) reported that while both rural and urban scenes activated primary visual areas, differences were primarily observed in deeper brain regions: rural scenes engaged subcortical structures linked to reward and emotion (e.g., caudate, putamen), whereas urban scenes activated regions associated with arousal and memory (e.g., amygdala, hippocampus). Similarly, Balderston et al. (2011) showed that the amygdala responds selectively to novel human-related stimuli, regardless of emotional content, but not to novel neutral scenes, highlighting its sensitivity to socially-salient novelty. Additionally, Mencarelli et al. (2019), in a meta-analysis of n-back tasks using various stimulus types, found that nonverbal stimuli such as faces, objects, and images recruited subcortical areas including the insula and claustrum. Therefore, it is plausible that task-related differences in brain function might exist within these subcortical regions in children as well, which were not captured in the present study due to methodological constraints.

6.4.3. Associations between simple and complex tasks.

The third research objective explored whether visual cognition in the simple task was associated with visual cognition in the complex task. Findings revealed that TLD, MLD, and SR looking behaviours in the simple task were associated with the same looking behaviours in the complex task. In contrast, CP scores, representing toddlers' visual working memory, did not show these associations between the tasks. These findings suggest that how toddlers engage general/basic attentional behaviours might be consistent across both tasks, however, there might be differences in how they detect change/novelty and/or are able to stay fixated on the changing side. More concretely, the lack of associations in CP scores suggests that stimulus complexity might interfere with visual working memory processing in some toddlers, in that while they may be adept and show higher CP scores in the simple task, they might not demonstrate similar performance in the complex task.

The lack of associations in CP scores between the simple and complex tasks may reflect the impact of increased perceptual and cognitive demands in the complex task, which can disrupt toddlers' ability to detect change or sustain attention on the changing side. Prior work has shown that infants' attentional engagement is sensitive to stimulus complexity, with more complex stimuli often eliciting shorter looks and reduced sustained attention (Colombo, 2001). Thus, reducing the ability to notice changes. In the context of visual working memory, Oakes et al. (2006) demonstrated that infants' ability to detect changes declines as the complexity of the visual input increases. Specifically, while 6.5-month-old infants could show preferences for some types of changes, they did not exhibit preference for more complex changes involving colour-location combinations. This decline in performance for these specific combinations suggests that both perceptual load and attentional control are key constraints. These findings align with evidence from adult research. Alvarez and Cavanagh (2004) found that the capacity of visual short-term memory was significantly constrained by the amount of visual information, or complexity in each object. In this study, participants were asked to perform change detection tasks with different types of stimuli that varied in visual complexity, such as coloured squares (simple), shaded cubes, and random polygons (complex). The authors reported that as object complexity increased, participants retained fewer items in memory. These findings suggest that complex objects place a higher information load on visual

short-term memory, using more representational resources per item, and thereby reducing the total number of items that can be maintained. Similarly, Eng et al. (2005) showed that visual working memory capacity decreased as stimulus complexity increased, with simple stimuli yielding higher capacity estimates than complex stimuli. Taken together, these findings suggest that the processing and retention of complex visual information impose higher cognitive and attentional demands, which may explain why toddlers who perform well in a simple task may not show the same success in a more complex version, despite similar task structures.

When examining the neuroimaging data, there were positive associations between the tasks in the rSPL and lSFG, and a negative association between the tasks in lAG. The rSPL, a region strongly implicated in the control of spatial attention and visual working memory (Corbetta & Shulman, 2002; Vossel et al., 2014), showed a positive association between tasks, indicating that toddlers who engaged this region more during the simple task also did so during the complex task. This aligns with findings from Kastner et al. (1998) who demonstrated that superior parietal areas are recruited when attention is voluntarily directed to peripheral spatial locations in anticipation of visual input, supporting the idea that toddlers consistently engage this region across tasks to manage spatial attention. Concurrently, the previously observed negative correlation between rSPL activation and the number of attentional shifts during the complex task suggests that stronger recruitment of this region may reflect a tendency toward more sustained attention under increased cognitive demand. Together, these findings point to stable individual differences in how toddlers deploy top-down control when navigating attentional competition. The lSFG, a region associated with executive control, goal maintenance, and top-down attentional regulation (Boisgueheneuc et al., 2006; Nissim et al., 2017), also showed a positive association across tasks. Specifically, toddlers who showed suppression of lSFG in the simple task also showed suppression of this region in the complex task. This finding suggests that toddlers may begin to engage frontal control systems in a stable way across tasks of varying complexity. A different pattern was observed in the lAG, a region involved in multimodal integration, spatial reasoning, and attentional reorienting (Seghier, 2013). Here, a negative association between tasks was found, where greater activation during the simple task was associated with

reduced activation during the complex task. This finding may suggest a shift in functional role depending on task demands. In the context of the simple task, the lAG may support integration of basic spatial and visual features (Seghier, 2013), while under complex conditions, the same region may become less central as higher-order perceptual or semantic processes take precedence (Ben-Yosef & Ullman, 2018). This inverse relationship could reflect a reallocation of processing resources, with greater lAG recruitment when perceptual demands are low, but downregulated as task complexity requires broader network engagement.

Finally, no significant cross-task associations were observed in the remaining chromophore main-effect regions, including the rSTG and lPG. Although these regions were engaged at the group level in both tasks, the lack of significant associations suggests individual differences in how toddlers recruited them. For example, the rSTG, linked to audiovisual integration and spatial orienting (Gharabaghi et al., 2006; Himmelbach et al., 2006), may be variably engaged depending on how much attention a toddler allocates to specific features of stimuli. Similarly, while the lPG, associated with eye movement control and visuomotor planning (Johansen-Berg & Matthews, 2002; Simon et al., 2002), showed behavioural links with SR scores in the simple task, it was not consistently engaged across tasks. This variability may reflect flexible, context-dependent engagement of these regions, influenced by specific task demands or the strategies employed. To summarise, these findings indicate that while some regions show consistent patterns of recruitment across tasks, only certain brain regions might be functionally tied more directly to attentional behaviours.

6.4.4. Association between caregiver-toddler behaviours and toddler visual working memory in the complex task.

The fourth research question explored whether toddler visual working memory in both tasks would be associated with caregiver-toddler behaviours during MO play. As hypothesised, significant associations emerged only for the complex task. Specifically, caregiver scaffolding and toddler object engagement during MO play were positively associated with complex CP scores, suggesting that toddlers' engagement with objects in real-world play settings alongside caregiver support may more closely relate to how toddlers attend to and engage with visual stimuli that have richer semantic value and links to episodic memories, compared to how they engage

with coloured shapes. This interpretation aligns with theories of embodied and grounded cognition, which posit that cognition is contextually linked to action and perception in familiar, meaningful environments (Barsalou, 2008; Smith & Gasser, 2005). From this perspective, cognitive processes are not isolated functions but are intertwined with the physical and social contexts in which they occur. The significant associations observed only in the complex preferential looking task suggest that when toddlers engage with stimuli that are semantically rich and more closely resemble real-world objects, such as those encountered during caregiver-child interactions, there is a stronger link to their prior interactive experiences. To date, no prior research has directly linked caregiver-child play behaviours to visual cognition in this type of task. While these findings are novel, they can be contextualised within broader work on how toddlers perceive and attend to objects in everyday, meaningful contexts. Studies using head-mounted cameras in toddlers have shown that sustained object attention is shaped by both the toddler's own handling of objects and caregiver input (e.g., Smith et al., 2011; Yu & Smith, 2012, 2016). For example, Yu and Smith (2016) found that during play, caregivers rapidly shifted their gaze between their infant and objects, reflecting their dual attentional focus, while infants showed slower gaze shifts and longer object fixations, consistent with exploratory behaviour. These patterns highlight the complementary roles of caregiver monitoring and infant exploration in shared attention contexts. Further, the current findings suggest that toddler engagement with multi-component objects, often requiring sustained manipulation and involving multiple visual and functional features, might support the development of attention strategies that are similarly drawn upon in visual cognition tasks involving semantically rich or conceptually structured stimuli. In contrast, while coloured shapes elicit memories of colours, they likely do not engage perception, attention, and memory systems in the same manner. Further, the association may also reflect how toddlers extract regularities across experiences with meaningful objects. For example, cross-situational word learning research (e.g., Smith et al., 2011; Smith & Samuelson, 2003) has shown that toddlers can learn mappings between labels and object features across different contexts, suggesting that repeated interactions with functional objects may support the encoding of visual features that generalise to new tasks. Although the current study did not assess word learning or conceptual knowledge, such work illustrates how visual attention, semantic knowledge, and working memory can operate in similar ways across

contexts. These findings underscore the importance of considering the context and complexity of both real-world interactions and lab-based tasks when examining early cognitive development.

6.4.5. Lack of predictive associations between caregiver-infant behaviours and toddler visual working memory.

The fifth research question examined whether caregiver-infant behaviours during MO play predicted toddler visual working memory in both tasks. Despite expectations that caregiver-infant behaviours during early dyadic interactions would predict toddler visual working memory more strongly in the complex task compared to the simple task, no significant associations were found for either task. These null findings are particularly striking considering findings from Chapter 4, where caregiver and infant behaviours during MO play were associated with infant visual working memory. These set of findings suggest that while social interaction plays a key role in supporting early visual cognitive processes, the predictive value of these behaviours may not straightforwardly extend into toddlerhood.

One interpretation is that the developmental mechanisms linking dyadic interaction and visual cognition shift over time. The lack of continuity from infancy to toddlerhood, both in terms of predictive associations with visual working memory and in the behavioural stability of MO play (as shown in Chapter 5), may point to a broader developmental reorganisation. As toddlers begin to rely more on semantic, feature-based, and conceptual information to guide their engagement with objects, the types of social behaviours that supported attention and memory in infancy may no longer provide the same support. In other words, the forms of attentional guidance and regulatory support that are effective during infancy may not generalise to the more complex and internally driven memory processes that begin to develop in toddlerhood. This shift may reflect changes in the child's agency (Ridgway et al., 2016), nature of experiences that accompany refined motor abilities (Iverson, 2010), evolving caregiver support (Hughes et al., 2018), changing cognitive capacities (Garon et al., 2008), and prior knowledge (Brady et al., 2016).

6.5. Conclusion.

The current study investigated how visual cognition was impacted by different experimental stimuli, and how it was associated with real-world dyadic

interactions. To achieve this, looking behaviours and brain function were collected from toddlers between 18 and 22 months in two variants of the preferential looking task – one task using coloured shapes based on the version used in Chapter 3 ('simple' task), and another task using images of real-world objects ('complex' task). Distinct differences in toddlers' looking behaviour were found between the two tasks. Specifically, CP and SR were higher for the simple task and TLD and MLD were higher for the complex task. However, in the brain, there were no task-related differences. Rather, there was increased activation in parietal regions and increased suppression across frontal regions across both preferential looking tasks. This pattern indicates that, despite variations in stimulus complexity, toddlers engage a similar set of brain regions for visual processing, suggesting the involvement of a common brain network underlying attention and perception at this developmental stage. Regarding associations between tasks, TLD, MLD, and SR, but not CP, during the simple task were associated with the same measures during the complex task. Further, activity in the rSPL and lSFG during the simple task were positively associated with activity during the complex task, while activation in lAG in the simple task was negatively associated with activation in the same region in the complex task. Notably, activation in the rSPL was negatively correlated with SR scores in the complex task, suggesting that this region involved in visuospatial attention is activated when there is reduced switching between displays in the complex task. Next, caregiver scaffolding and toddler object engagement were positively associated with CP scores in the complex task. Here, real-world interactions may offer structured, meaningful input that supports strong memory, especially when experimental tasks use semantically-rich stimuli such as objects used in play interactions. Interestingly, there were no associations between caregiver-infant behaviours and toddler performance in either task. The absence of observed associations suggests that early and later visual working memory may depend on distinct underlying mechanisms, thereby limiting the long-term influence of early dyadic interactions. Overall, this study provides initial evidence that toddler engagement and caregiver support during naturalistic play with complex objects may support emerging visual cognition in tasks involving semantically rich stimuli. While direct evidence remains limited, converging support from studies of joint attention, object learning, and embodied cognition offers a useful framework for interpreting these findings.

Chapter 7:

General Discussion.

This thesis has investigated developmental changes in child visual neurocognition and play interactions, advancing our understanding of the intricate interplay between these domains. By addressing key gaps in the literature and utilising innovative methodologies, this research provides novel insights into how early visual cognition develops and interacts with play behaviours, ultimately influencing broader cognitive and socio-emotional outcomes. This general discussion chapter begins by reintroducing foundational concepts and evidence from the two introductory chapters. Next, summaries for each of the experimental chapters will be provided, focusing on the objectives, methods, and findings, before moving onto the implications of the experimental findings. The strengths and limitations of this work will also be discussed and recommendations for future research will be presented.

7.1. Introduction.

Understanding how visual cognition develops during childhood is essential for revealing the mechanisms underpinning early cognitive growth and laying the foundation for lifelong learning. Visual cognition, the ability to process, interpret, and interact with visual stimuli, undergoes rapid transformation in early development. In the first six months of life, infants experience significant improvements in visual acuity, moving from an initial state of low resolution to more refined perceptual capabilities (Maurer et al., 2005). These early enhancements are closely linked to the maturation of neural pathways in the visual cortex, which support depth perception, object recognition, and spatial awareness (Atkinson & Braddick, 2020). Beyond these basic perceptual developments, infants also begin to develop selective attention, allowing them to focus on relevant stimuli while filtering out distractions. Visual working memory is central to these cognitive advancements, as it facilitates the temporary storage and manipulation of visual information (Baddeley, 1992).

Developmental changes in visual working memory reflect both neural and behavioural maturation. Empirical studies reveal that infants' visual working memory is initially limited but improves significantly over the first year, with memory capacity increasing from one to four items between 4 and 10 months (Ross-Sheehy et al., 2003; Oakes et al., 2009). The ability to manipulate working memory load in experimental tasks provides insight into these developmental trajectories, though gaps remain in understanding how these abilities generalise across contexts and stimuli (Cowan, 2010). The maturation of attention systems is another critical aspect of visual cognitive development. In infancy, attention is primarily driven by salient external stimuli, but by toddlerhood, it shifts towards intrinsically-driven mechanisms. This progression reflects the interplay between structural and functional brain development, particularly in the connectivity between posterior and prefrontal regions (Posner & Raichle, 1994; Ruff & Capozzoli, 2003). Improvements in attentional flexibility and control are closely tied to broader executive functions, problem-solving, and behavioural regulation, highlighting the interconnected nature of early cognitive processes.

Advances in neuroimaging techniques, such as fNIRS, have significantly enhanced our understanding of the brain mechanisms supporting visual cognition. These tools allow researchers to map cortical activity during tasks that engage working memory and attention, providing insights into the functional specialisation of brain regions like the DLPFC and posterior temporal cortex (Baird et al., 2002; Wilcox & Biondi, 2016). Although fNIRS overcomes many limitations of other modalities, such as its ability to measure activity in naturalistic contexts, it remains restricted to cortical regions, leaving questions about subcortical contributions unanswered (Llyod-Fox et al., 2010). Despite these limitations, the evidence highlights the increasing specialisation and integration of brain networks during infancy, particularly within the fronto-parietal network, which supports higher-order cognitive functions (Buss et al., 2014).

Naturalistic play interactions provide a unique context for examining how visual cognition unfolds in everyday environments. Play allows children to engage dynamically with their surroundings, promoting the integration of visual, motor, and

social skills (Whitebread et al., 2017; McQuillan et al., 2020). Object manipulation during play fosters spatial reasoning and visual-motor integration (Needham et al., 2002), while peer and caregiver interactions enhance selective attention and joint attention (Ruff & Capozzoli, 2003). However, the specific contributions of different types of play remain underexplored, leaving important questions about how these experiences shape developmental trajectories.

Caregiver involvement during dyadic play represents a critical foundation for early developmental processes, shaping cognitive, emotional, and social trajectories. The quality of these interactions not only influence immediate developmental milestones but also establish pathways for long-term socio-cognitive competencies. Central to these interactions is caregiver scaffolding, an essential caregiving practice that exemplifies how adults guide and support children in tasks that extend beyond their independent capabilities (Mermelshtine, 2017). Effective scaffolding promotes cognitive resilience and mastery, especially during play contexts where challenges require tailored intervention (Wood et al., 1976). In contrast, intrusiveness, characterised by excessive control or over-directiveness, disrupts the balance of dyadic interactions, often hindering the child's ability to self-regulate and engage autonomously (Swingler et al., 2017). Caregiving practices also evolve longitudinally, reflecting both the child's developmental progression and the caregiver's growing understanding of their needs. Maternal responsiveness, for example, shifts from meeting basic physical needs in infancy to fostering cognitive engagement and autonomy in toddlerhood (Bornstein et al., 2008). As children develop, caregivers often reduce their direct involvement, allowing the child greater independence while maintaining a supportive presence (Wood et al., 1976). This balance between guidance and autonomy is crucial for promoting self-regulation and confidence.

Overall, the introductory chapters of this thesis outlined the fundamental processes underpinning visual cognitive development in early childhood, with a particular focus on visual working memory, attention, and the brain mechanisms supporting these abilities. In addition, the role of caregiver involvement in dyadic play interactions was explored, emphasising how scaffolding contributes to cognitive and socio-emotional development. Further, while positive caregiving practices foster

engagement and learning, intrusive behaviours and variations in caregiver executive functions were highlighted as these can also shape developmental trajectories. Despite significant progress in the field, key research gaps have remained. While much is known about the caregiver-child dynamic in older children, few studies examine this relationship during infancy, a critical period that marks the emergence of executive sub-functions. Additionally, most existing research focuses on broad measures of executive function, overlooking the nuanced impact of individual sub-functions like inhibitory control on early cognitive processes. Additionally, while dyadic interactions between caregivers and infants are crucial for cognitive and emotional growth, research often focuses on isolated interactions rather than examining multiple interaction types longitudinally. Ultimately, this thesis has sought to deepen our understanding of the mechanisms underlying caregiver contributions to early cognitive development by addressing these research gaps within the four experimental chapters.

7.2. Summary of experimental chapters.

7.2.1. Chapter 3: The association between caregiver inhibitory control and infant visual cognition.

Chapter 3 investigated whether caregiver inhibitory control was associated with infants' visual cognitive performance and brain function. The study recruited 88 caregivers and 86 infants aged between 6 and 10 months. Caregivers completed a Go-NoGo task designed to measure inhibitory control. This task involved responding to "Go" stimuli while inhibiting responses to "NoGo" stimuli. Reaction times and accuracy rates were used to calculate an inhibitory control efficiency score. Infants participated in a preferential looking task, which measured their ability to detect changes in visual arrays under varying memory loads (1 to 3 items). Behavioural looking measures included total look duration (TLD - total amount of time an infant spent looking at both displays), mean look duration (MLD - average length of time an infant spent looking towards one display), switch rate (SR - how often an infant switched from one display to the other), and change preference (CP - whether an infant showed preference for the changing display). fNIRS was used to record brain activation in both caregivers and infant during their respective tasks.

The main findings revealed two associations between caregiver inhibitory control and infant brain function. First, better caregiver efficiency was associated with reduced lMFG activation in infants. Critically, caregiver inhibitory efficiency was linked to infant activation patterns in the lIPL, a region involved in attentional regulation and working memory. Infants of caregivers with higher inhibitory efficiency exhibited less pronounced activation changes in the lIPL, suggesting more efficient processing. In contrast, infants of caregivers with lower inhibitory efficiency showed load-dependent modulation in the same region, indicating compensatory mechanisms in response to increased cognitive demands. This finding highlighted the role of caregiver inhibitory control in shaping pathways critical for attentional regulation and working memory in infants. Interestingly, no direct behavioural links were observed between caregiver inhibitory control and infant visual working memory performance. While results show that caregiver inhibitory control influences infant brain function, these effects may not yet manifest as measurable differences in behaviour during the first year of life. Overall, this chapter emphasises the role of caregiver inhibitory control in shaping brain function related to early visual cognition. The findings suggest that caregiver regulatory capacities influence infants' cognitive development by modulating brain function, rather than through direct effects on observable behaviour. These results contribute to a growing body of research highlighting the interplay between caregiver executive functions and infant cognitive processes. By examining specific components of executive function, namely caregiver inhibitory control, rather than relying on global executive function measures, the study demonstrates that this subcomponent can play a distinct role in early cognitive development. This approach reveals more nuanced brain–behaviour relationships and offers a clearer foundation for understanding how caregivers can shape emerging cognition in their infants.

7.2.2. Chapter 4: Caregiver-infant interactions and infant visual working memory.

Chapter 4 investigated how caregiver and infant behaviours differed between two types of play interactions (single object [SO] and multi-component object [MO] play). It further examined whether these dyadic behaviours were related to infant visual working memory, as assessed by the preferential looking task in Chapter 3. This study involved 91 caregivers and their 6- to 10-month-old infants. Dyads engaged in two types of play interactions: SO play with five objects (i.e., car, cup,

pop-it butterfly, gears, and rattle) that the caregiver could use to engage in specific activities related to the object (e.g., racing car on table, drinking from cup etc.), and MO play with three objects (i.e., shape sorter, rainbow stacker, and hide 'n' squeak eggs) that the caregiver could use for the intended purpose (e.g., sorting into box by shape, stacking according to colour and size etc.). Each play interaction lasted 7 minutes and was video recorded for later behavioural coding. Caregiver intrusiveness and scaffolding, as well as infant object engagement and distractibility, were coded during 30-second epochs. Infant visual working memory was assessed using the preferential looking task and CP scores were used to indicate visual working memory performance.

The findings revealed that caregiver scaffolding was higher during MO play compared to SO play, likely reflecting the increased complexity of MO objects, which elicited more frequent use of strategies like labelling, questioning, and demonstrations to support infant engagement. Caregiver intrusiveness showed no significant difference between play contexts, possibly due to the influence of caregivers' broader interaction styles rather than the play materials themselves. Infants demonstrated greater object engagement during MO play compared to SO play, with more frequent self-initiated actions such as bringing objects closer, suggesting that the MO objects better aligned with infants' emerging sensorimotor abilities. Infant distractibility did not vary significantly between interaction types, as distractibility appeared to manifest differently across contexts and may be more strongly shaped by individual temperament and external environmental factors than by the play interaction itself. Further, caregiver intrusiveness, caregiver scaffolding, and infant object engagement during SO play were associated with the same behaviours during MO play. The study also found significant links between dyadic behaviours and infant visual working memory. Specifically, during MO play, better caregiver scaffolding in accompaniment with increased infant object engagement and reduced distractibility was associated with better infant working memory performance. Specifically, for infants with higher CP scores, higher object engagement and lower distractibility was associated with greater caregiver scaffolding. This finding highlights the importance of caregiver responsiveness in supporting infants' early cognitive skills, particularly in contexts requiring sustained attention and task engagement. Finally, from Chapter 3, better caregiver efficiency

was associated with reduced lMFG activation in infants when engaging with the preferential looking task. In the current chapter, it was reported that caregiver behaviours during SO and MO play were uniquely associated with this previous Chapter 3 result. Specifically, higher caregiver intrusiveness during SO play was linked to increased lMFG activation and higher caregiver scaffolding during MO play was linked to reduced activation. Intrusive caregiving during SO play may increase infants' cognitive effort to maintain attention, while supportive scaffolding during MO may facilitate more efficient engagement, reducing the need for top-down attentional control. These context-specific associations suggest that the affordances of each play type shape caregiver-infant dynamics, with MO play offering more opportunities for responsive scaffolding, while SO play may limit infant involvement and rely more on caregiver direction. Overall, this chapter offers foundational insight into caregiver-infant play behaviours during early development.

7.2.3. Chapter 5: Longitudinal caregiver-child dyadic interactions.

Chapter 5 examined longitudinal changes in caregiver-child dyadic interactions from infancy to toddlerhood. The study examined how caregiver and child behaviours varied across different types of play interactions in toddlerhood, and whether these behaviours were associated across play contexts. It also assessed developmental changes in caregiver-child interactions from infancy to toddlerhood, evaluated the stability of specific behaviours over time, and investigated whether early caregiver behaviours predicted their child's behaviours one year later. By addressing these questions, this chapter shed light on the developmental significance of dyadic play contexts for cognitive and social growth. The study followed 91 caregiver-child dyads initially recruited when infants were between 6 and 10 months old (Y1), for a year and assessed them when the children were between 18 and 22 months of age (Y2). Of these, 67 dyads returned for the second assessment in Y2, and an additional 5 families with toddlers were recruited, resulting in a final sample of 72 dyads. Caregivers and toddlers engaged in two types of play interactions during both years (SO and MO play). Caregiver scaffolding and intrusiveness were coded alongside child object engagement and distractibility.

The findings revealed that toddlers displayed greater object engagement in MO play and displayed greater distractibility in SO play. The difference in toddler

engagement may be because multi-component objects provide richer sensory input and afford more opportunities for purposeful interaction, helping to anchor toddlers' attention, whereas single objects offer less stimulation, making children more prone to distraction. However, no significant differences in scaffolding or intrusiveness were observed between the two play contexts. Longitudinal comparisons highlighted significant changes in dyadic behaviours from Y1 to Y2. Both caregiver scaffolding and child object engagement increased over time, reflecting the developmental progression of children becoming more autonomous and caregivers adapting their support to match their children's growing abilities. Conversely, caregiver intrusiveness and child distractibility decreased from infancy to toddlerhood, suggesting that toddlers were better able to focus on play tasks and caregivers were less likely to impose unnecessary control. These developmental changes underscore the dynamic nature of caregiver-child interactions, with caregivers adjusting their behaviours in response to their child's evolving needs and capacities. Caregiver-infant behaviours during SO play in Y1 were predictive of caregiver-toddler behaviours in Y2. These findings suggested that SO play fostered more stable interaction patterns over time, due to the constrained nature of these interactions. Further, caregiver behaviours in infancy were found to significantly predict toddler behaviours in Y2, specifically within SO play contexts. Higher caregiver scaffolding in Y1 was associated with greater toddler object engagement and lower distractibility in SO play during Y2. Caregiver scaffolding during SO play (such as verbalising with physical demonstrations, labelling actions, and expressing positive affect) likely helped infants learn to interact with objects in focused, purposeful ways, laying a foundation for sustained attention and reduced distractibility in toddlerhood. The lack of findings for MO play may reflect shifting dynamics as toddlers become more autonomous in managing the complex demands of multi-component objects. While caregiver scaffolding may be crucial in infancy, developmental gains in working memory, motor skills, and spatial reasoning by toddlerhood likely reduce reliance on caregiver support, weakening the continuity of early influences. Overall, this chapter highlights the critical role of early caregiver scaffolding in supporting cognitive and attentional development, while also illustrating how caregiver-child play behaviours evolve across the transition from infancy to toddlerhood.

7.2.4. Chapter 6: Impact of stimulus type on toddler visual cognition and associations with dyadic interactions.

Chapter 6 investigated how looking behaviours and brain function differed in toddlers in response to different experimental stimuli in a visual cognition task, and how visual working memory was associated with real-world dyadic interactions. Visual cognition was assessed in 75 toddlers, aged between 18 and 22 months. Two variants of the preferential looking task were presented – one task used coloured shapes (simple task), and the other task used images of real-world objects (complex task). Both tasks manipulated load by varying the number of items (low: 2 items; medium: 4 items; high: 6 items). TLD, MLD, SR, and CP scores were calculated from toddler looking behaviours. Brain activity was recorded using fNIRS to identify brain function associated with task engagement. Caregiver-child behaviours during MO play from Chapters 4 and 5 were also used. The focus on MO play was driven by its links to infant visual working memory in Chapter 4 and increased behavioural engagement across developmental timepoints in Chapter 5.

When comparing behaviours between the simple and complex tasks, clear differences emerged. The simple task elicited higher SR and CP scores, compared to the complex task, reflecting increased gaze shifts and a stronger preference for the changing display. In contrast, there was higher TLD and MLD during the complex task compared to the simple task, indicating more time spent fixating on the real-world objects. These results suggest that toddlers allocated their attention differently depending on stimulus complexity, with simpler stimuli encouraging exploration and complex stimuli requiring prolonged focus. Despite behavioural differences, brain activation patterns were consistent across tasks. Commonly activated regions included the rSTG, lAG, rSPL, and lPG, while suppression was noted in the rSFG and lSFG, suggesting the involvement of a shared network underlying attention and perception across different stimulus types. When examining associations between tasks, TLD, MLD, and SR scores in the simple task were significantly associated with the same measures in the complex task. However, CP scores did not show an association, indicating greater variability in toddlers' preference for novel stimuli across tasks. These findings suggest that while toddlers may show consistent basic attentional behaviours across tasks, the ability to detect novelty or maintain fixation

on changing stimuli may be more sensitive to task complexity and cognitive demands. Within the brain, there were positive associations between the simple and complex tasks in the rSPL and lSFG, and a negative association between the tasks in lAG. The rSPL was consistently recruited across both simple and complex tasks, suggesting it supports a shared attentional orienting mechanism in toddlers. However, greater activation of the rSPL during the complex task was linked to fewer attentional shifts, indicating that while stable engagement of this region reflects consistent attentional strategies, it may also signal reduced flexibility under higher visual demands. The lSFG showed consistent engagement across tasks, suggesting emerging stability in toddlers' use of frontal attentional control systems. In contrast, the lAG showed an inverse activation pattern across tasks, indicating a potential shift in its functional role based on task complexity, with greater involvement in simpler perceptual integration and downregulation under more demanding conditions. When examining associations between toddler visual working memory and caregiver-toddler behaviours, caregiver scaffolding and toddler object engagement during MO play were positively associated with CP scores in the complex task. These findings point to the importance of ecological relevance, suggesting that toddlers' engagement with complex stimuli may be shaped by their everyday experiences with similarly complex objects. Finally, when examining whether caregiver-infant behaviours were associated with toddler visual working memory, no associations were found for either task. While social interaction is crucial for early visual cognitive development, the lack of findings here suggests that any predictive influences do not carry over into toddlerhood in a simple or direct manner. In summary, the findings from this chapter highlight the nuanced effects of stimulus complexity on toddler visual cognition.

7.3. Implications of experimental chapters.

7.3.1. Use of neuroimaging for detecting early developmental patterns.

The findings presented in this thesis demonstrate the potential of neuroimaging for uncovering early developmental patterns in cognitive functioning. By examining brain activation during visual working memory tasks in infants (Chapter 3) and toddlers (Chapter 6), this research contributes to a growing body of evidence that neuroimaging can detect both emerging and evolving patterns of brain activity that underlie core cognitive processes. Crucially, this work highlights how

early brain activity, particularly in fronto-parietal networks, not only reflects foundational capacities like attention and memory but also reveals age-related shifts in how the brain responds to increasing task complexity (D'Esposito & Postle, 1999; Geier et al., 2009; Todd & Marois, 2004). This supports a shift away from purely behavioural indicators toward multimodal assessment strategies, especially in early developmental windows where behaviour alone may not capture the full picture (Gilmore et al., 2018). A review by Marsh and colleagues (2008) outlined how brain maturation follows a structured trajectory and any deviation from normative patterns may underlie various neurodevelopmental disorders. Together, the current thesis and prior work emphasises that understanding typical brain trajectories provides a crucial baseline for detecting and interpreting atypical development, ultimately supporting earlier diagnosis and intervention for developmental disorders in children.

One area of developmental research that could benefit from the addition of neuroimaging is work on "sticky attention". "Sticky attention" has commonly been associated with autism spectrum disorder (ASD) (Keehn et al., 2019; Landry & Bryson, 2004; Sacrey et al., 2014). For instance, Sacrey et al. (2014) reported that infants who were later diagnosed with ASD showed prolonged latency to disengage attention beginning by 12 months of age. This attentional pattern persisted through 15, 18, and 24 months, distinguishing them from their non-ASD peers. These findings suggested that sticky attention may emerge early in development and could influence later cognitive outcomes in children with ASD. However, work by Fischer and colleagues (2016) found no differences in disengagement performance between toddlers with ASD and typically developing peers, contrary to the sticky attention hypothesis. Their results suggested that attentional disengagement was intact even at the age when ASD symptoms begin to emerge. Therefore, sticky attention was unlikely to be a fundamental or causal feature of ASD development. More recent findings by Dwyer et al. (2024) support this as they also found that ASD children did not show greater "sticky attention" compared to non-ASD peers. Neuroimaging could help mitigate these discrepancies by providing insight into the brain mechanisms underlying attentional disengagement. Behavioral measures alone may not capture the full complexity of attentional processes, particularly when surface-level behaviours appear similar but are driven by different pathways. For example, in Chapter 6 of this thesis, greater activation in the rSPL was associated with fewer

shifts between visual displays during the task featuring complex real-world stimuli. This pattern suggested that children who recruited this region more strongly were less likely to alternate their attention across the competing sources of information. Importantly, when looking at behavioural looking measures in isolation, it was found that toddlers' switch rate in the simple task was associated with their switch rate in the complex task. Therefore, the use of neuroimaging could reveal whether children with ASD engage different brain networks during attentional shifts, even when their behavioural performance mirrors that of typically developing peers. This would allow researchers to determine whether "sticky attention" reflects a compensatory process, a distinct developmental pathway, or a true deficit. Additionally, longitudinal neuroimaging could help clarify whether differences in attentional control are stable features, emerge only at certain developmental stages, or are secondary to other neurocognitive processes. As such, integrating neuroimaging into studies of attentional disengagement could critically inform whether "sticky attention" is a fundamental feature of ASD or a transient, non-specific marker of developmental variability. Taken together, this thesis demonstrates that neuroimaging is not only a powerful research tool but also a promising avenue for translational applications. Its ability to detect early and dynamic changes in brain function opens new opportunities for advancing our understanding and practical approaches to supporting children's developmental trajectories.

7.3.2. Early caregiving interventions.

The findings of this thesis offer important implications for the design and refinement of early caregiving interventions. Specifically, Chapters 3, 4, and 5 reveal that caregiver regulatory capacities, specifically inhibitory control and scaffolding behaviours, play a key role in shaping children's attentional engagement, visual working memory performance, and underlying brain function. The current findings suggest that the quality of caregiver regulatory function may influence the development of similar capacities in their children, likely through both structured interaction and modelling of regulation strategies.

The results from Chapter 3 underscore a key neurocognitive pathway through which caregiver self-regulation may influence infant development. Caregivers with higher inhibitory efficiency had infants who showed more efficient patterns of

fronto-parietal activation, particularly in the lIPL, a region implicated in attentional control and working memory maintenance (Corbetta et al., 2000; Culham & Kanwisher, 2001). Conversely, infants of caregivers with lower inhibitory control exhibited greater modulation of this region in response to task demands, potentially reflecting less efficient processing or compensatory effort. This current work aligns well with a two-generation approach to early intervention, which emphasises supporting both the child and their caregiver to promote optimal developmental outcomes (Shonkoff & Fisher, 2013). Unlike one-generation interventions, where programs target the child directly through classroom-based executive function training (e.g., Tools of the Mind; Bodrova & Leong, 2007), two-generation interventions recognise that children's development is embedded within broader caregiving contexts. As such, interventions have since adopted this integrated approach, combining classroom-based executive function activities and caregiving training (e.g., Mind in the Making; Galinsky et al., 2017). Overall, the results from Chapter 3 are consistent with intervention approaches that incorporate executive function training for caregivers and generally include them as a contributor for reinforcing executive function development.

Chapters 4 and 5 highlighted the value of scaffolded play within dyadic play interactions as an active ingredient in cognitive development. In Chapter 4, caregiver scaffolding was shown to interact with infants' levels of object engagement and distractibility, and these combined behaviours were associated with infants' visual working memory. These results suggest that regulatory-sensitive caregiving, particularly in moments of shared attention and guided interaction, may scaffold early cognitive development by helping infants sustain focus, filter distraction, and organise visual input. Additional findings reported that caregiver scaffolding was associated with optimal engagement of lMFG when infants engaged in a visual working memory task. Further, Chapter 5 underscored that effective scaffolding evolves in response to the changing cognitive needs of the child. Together, these findings emphasise the need for longitudinal, adaptive caregiving interventions. As such, intervention models must move beyond one-off or time-limited approaches and instead support caregivers over time, equipping them to adjust their strategies as their child develops. Programs that offer sustained support and caregiver education, especially those that prioritise responsive caregiving and scaffolding techniques, are

well positioned to meet this need (Cologon et al., 2017; Magnuson & Schindler, 2019; Salomone et al., 2019). For instance, the Caregiver Skills Training program demonstrates how structured guidance in behaviour management, communication, and emotional connection can improve both child outcomes and caregiver confidence (Salomone et al., 2019). The present research adds weight to such programs by offering evidence that caregiver cognitive and behavioural strategies are associated with measurable changes in child attention and working memory. Overall, the integration of behavioural and neuroimaging data in this thesis supports the case for developmentally informed, neurobiologically grounded interventions. By demonstrating links between caregiver behaviour and infant brain function, the research bridges gaps between developmental neuroscience and applied early childhood practice. It advocates for a multidimensional understanding of caregiving, one that recognises the cognitive demands placed on caregivers and the long-term implications of their regulatory abilities for children's developmental trajectories.

7.3.3. The importance of individual differences in children.

Recognising and understanding individual differences in children is essential for fostering development. Children are a unique blend of genetic, environmental, and experiential factors that shape their personality, learning style, interests, and pace of development (Plomin & Daniels, 2011). Acknowledging these differences allows parents, educators, and caregivers to support children more effectively. Individual differences manifest in various domains, including cognitive abilities, emotional regulation, temperament, and social interaction (Bates et al., 2008; Campos-Moinier et al., 2023; Dunn & Cutting, 1999; McKay et al., 2021). For instance, some children may grasp concepts quickly, while others may need more time and alternative methods of instruction. Similarly, a child who is naturally introverted may engage differently in social settings compared to an extroverted peer. Understanding these variations helps avoid unfair comparisons and unrealistic expectations.

The findings from this thesis underscore the importance of individual differences in shaping early attentional and cognitive processes from infancy to toddlerhood. While group-level trends provide valuable insight into typical developmental trajectories, variability observed across participants can highlight how behaviour and brain function are shaped by a complex interplay of individual

characteristics and environmental contexts. For example, the absence of interaction-based differences in infant distractibility (Chapter 4) suggests that attentional control in infancy may be more heavily influenced by stable temperament traits and broader environmental factors than by variations in play (Hill-Soderlund & Braungart-Rieker, 2008). The association between caregiver inhibitory control and infant brain function (Chapter 3) further emphasises the significance of individual differences in shaping early cognitive development. Infants of caregivers with higher inhibitory efficiency demonstrated more efficient fronto-parietal engagement, suggesting that caregiver self-regulation may serve as a scaffold for the development of attentional systems in infancy. In contrast, greater engagement in infants of caregivers with lower inhibitory control reflected compensatory strategies and/or less efficient processing, highlighting that individual variability in caregiver traits can have meaningful neurodevelopmental consequences. Moreover, the lack of consistent cross-task associations in toddlers' recruitment of the rSTG and lPG (Chapter 6) highlights the flexible and context-dependent nature of brain function in early development. Despite being active at the group level in both simple and complex tasks, individual children appeared to engage these regions differently, possibly due to variability in attention allocation, task strategies, or underlying efficiency.

Together, these findings highlight the need for frameworks that account for individual differences. Respecting individual differences serves to promote inclusive practices, ensuring that every child feels valued and understood (Florian & Black-Hawkins, 2011). It encourages the development of tailored educational approaches and support systems that cater to diverse needs, such as differentiated instruction or personalised learning plans (Santangelo & Tomlinson, 2009; Tomlinson, 2001; Tomlinson & Imbeau, 2014). Ultimately, future research should aim to characterise the sources and trajectories of individual differences more comprehensively, potentially through multimodal, longitudinal studies that integrate neuroimaging, behavioural assessments, and contextual measures across development.

7.4. Strengths and limitations.

7.4.1. Strengths.

There are several notable strengths in the research presented throughout the thesis. A key strength lies in the exploration of early links between caregiver

cognitive traits and infant brain function. Chapter 3 investigated whether caregiver inhibitory control was associated with infants' visual cognitive processing. Importantly, this study moved beyond behavioural observation alone by integrating fNIRS to examine brain activity in both caregivers and infants. The key results demonstrated that caregivers with higher inhibitory control efficiency had infants who exhibited less pronounced activation in regions implicated in attentional control and working memory, suggesting more efficient processing under cognitive load. This integration of both behavioural and brain-based measures, contributes to a growing body of research by specifying how specific caregiver traits may shape early development, offering a more comprehensive understanding of the caregiver-infant relationship.

Chapters 4 and 5 of this thesis offer additional strengths through their exploration of SO and MO play across infancy and toddlerhood. Chapter 4 examined dyadic interactions during SO and MO play, identifying differences in how caregivers scaffold and how infants engage with materials depending on the play context. MO play, which afforded greater complexity and goal-directed manipulation, elicited higher levels of caregiver scaffolding and infant object engagement, underscoring how material affordances shape interaction dynamics. This context-sensitive approach adds nuance to the study of early behaviour by demonstrating that the quality of play is not uniform across tasks but instead varies with the cognitive and sensorimotor demands embedded in the activity. Notably, this study is among the first to examine naturalistic caregiver–infant behaviours within play interactions alongside infant performance in the preferential looking task, providing an ecologically valid bridge between everyday social interactions and lab-based cognitive measures. Building on this, Chapter 5 extended the investigation longitudinally across two timepoints, spanning the transition from infancy to toddlerhood. This broader developmental window enabled a more comprehensive understanding of how different play contexts influence cognitive development over time. The study revealed patterns of both stability and growth: caregiver scaffolding and child object engagement increased over time, while caregiver intrusiveness and child distractibility decreased. Such changes reflect an adaptive progression in which caregivers adjust their support to align with children's increasing autonomy, and children in turn develop more focused, sustained engagement.

Finally, a distinctive strength of this thesis is its investigation of how stimulus complexity influences toddler visual cognition, with a particular focus on behavioural and brain responses to simple versus complex stimuli. By incorporating real-world objects alongside coloured shapes, Chapter 6 bridged the gap between laboratory-based experimental tasks and everyday experiences, providing a more realistic understanding of how toddlers engage with and process visual information. This approach allows for a more nuanced investigation into how toddlers' cognitive abilities respond to different levels of visual complexity, which is crucial for understanding the development of visual working memory in naturalistic contexts.

7.4.2. Limitations.

There are also several limitations of this thesis that are important to consider. The first limitation is the exclusive focus on primary caregivers, the majority of whom were female. While this decision was informed by prior research indicating that mothers typically exert a stronger influence on their child's early cognitive development, this focus does not account for the contributions of secondary caregivers. Previous studies have demonstrated that secondary caregivers can positively impact a child's cognitive and socio-emotional development, albeit often to a lesser extent than primary caregivers. Future investigations should strive for a more inclusive approach by incorporating secondary caregivers and exploring the unique roles they play in early cognitive development. Such work could provide a more comprehensive understanding of the broader caregiving environment, including the interplay between primary and secondary caregivers and how their joint contributions shape developmental outcomes.

Another limitation of this study was the use of a single representative template head model for both children and caregivers, based on digitised scalp landmarks obtained using one cap size for children and another for caregivers. This approach does not account for individual variations in head shape, size, and anatomy, which can lead to inconsistencies in how the probe is positioned and how it corresponds to underlying cortical regions. As a result, the spatial accuracy of the recorded signals may be compromised, limiting the precision of anatomical interpretations. Future studies could address this issue by employing individualised

digitisation for each participant, capturing person-specific scalp landmarks and adapting the head model accordingly. This would improve the anatomical accuracy of channel locations and enhance the interpretability and generalisability of fNIRS findings.

Another limitation was the lack of ethnic diversity among participating families. While there was a good representation of families across different socioeconomic strata, the sample did not sufficiently capture the breadth of ethnic and cultural diversity. This is a notable limitation, as research has shown cultural differences in caregiving practices, such as communication styles, approaches to play, and emphasis on independence versus interdependence, can shape the nature and quality of dyadic interactions. Moreover, the value placed on specific cognitive skills, such as problem-solving, attention, or memory, can vary across cultures, potentially leading to differences in developmental outcomes. These variations highlight the importance of investigating how caregiver executive functions and dyadic play interactions may operate within different cultural contexts. Future work should prioritise recruiting families from a wider range of ethnic and cultural backgrounds to provide a more inclusive representation. Such research would not only broaden the generalisability of findings but also offer critical insights into how diverse caregiving practices influence early cognitive development. This could ultimately inform more culturally sensitive interventions and support systems tailored to the needs of families from diverse communities.

There are also some more chapter-specific limitations worth highlighting. In both Chapters 3 and 6, a key limitation arose from the neuroimaging methodology. To prioritise participant comfort and ensure successful data collection with young children, only 20 fNIRS channels were used. Future studies could benefit from the use of more lightweight and higher-density fNIRS systems, which would maintain comfort while allowing for more comprehensive and detailed measurement of brain activity. In Chapter 5, participant attrition posed a challenge to the longitudinal design. Some families who participated in the first year did not return for follow-up in the second year, resulting in incomplete developmental trajectories for a portion of the sample. These gaps may have constrained the ability to fully interpret changes over time in behavioural measures. Addressing this limitation in future research

through enhanced retention strategies would help preserve data continuity and strengthen longitudinal inferences. In Chapter 6, the complex preferential looking task incorporated images of real-world objects selected to be unfamiliar and non-nameable, with the aim of minimising inherent preferences. However, the results indicate that toddlers may have exhibited "sticky attention" toward certain stimuli, potentially biasing looking behaviour. To reduce this risk in future research, a small pilot study could be conducted in which children view stimuli in randomised pairings, and their looking times measured to identify any items that consistently attract disproportionate attention. Stimuli found to elicit unusually high or low looking times could then be revised or replaced to ensure a more balanced set. Together, these chapter-specific limitations highlight key methodological considerations and point to concrete areas for refinement in future developmental studies.

7.5. Future directions.

7.5.1. Understanding developmental changes in caregiver-child brain function.

A key aspect of this thesis was the investigation of caregiver-child play interactions. The chosen set-up for these dyadic sessions was influenced by the need to record brain activity simultaneously from both caregivers and children using fNIRS. Although the hyperscanning data itself was not analysed within the current thesis, it represents an important avenue for future research. Hyperscanning allows for the simultaneous recording of brain activity from interacting individuals, offering a powerful tool for examining how brain function unfolds during real-time social engagement. Leveraging this data in future work could help uncover how brain activity in both caregivers and children evolves during interactions and how these relate to observed behaviours, such as scaffolding and engagement. This is particularly pertinent considering recent work by Nguyen et al. (2024) who investigated whether interpersonal neural and behavioural synchrony during parent-child interactions were associated with attachment representations. Critically, they reported that individual differences in attachment representations were not linked to behavioural synchrony but were linked to neural synchrony. These findings underscore the unique contribution of neural synchrony in capturing relational dynamics that may not be evident through behavioural observations alone. Therefore, utilising the hyperscanning data could provide a neurophysiological

foundation for interpreting behavioural patterns identified in the current thesis, and more broadly, contribute to our understanding of how brain function supports early cognitive development within social contexts.

7.5.2. Caregiver executive functions.

A key strength of this thesis was its focus on caregiver inhibitory control, an important executive function sub-function. This focus addressed one of the major research gaps in which the majority of studies examining caregiver executive function utilise an overall composite score rather than exploring the individual sub-functions. Future research should thoroughly explore the remaining sub-functions of working memory and cognitive flexibility, investigating how these skills impact early cognitive development. Work has previously explored the influence of maternal working memory on reactive negativity in parenting (Deater-Deckard et al., 2010). They found that mothers with lower working memory capacity were more likely to exhibit reactive negativity in response to their children's challenging behaviours, such as opposition and distractibility. Whereas mothers with stronger working memory could better regulate their emotional responses, showing less reactive negativity (Deater-Deckard et al., 2010). From this, future work could explore how maternal working memory directly influences early visual cognition and how it interacts with specific child behaviours during play interactions. Additionally, cognitive flexibility enables caregivers to adjust their strategies and behaviours in response to their child's changing needs and interests (Dajani & Uddin, 2015). This adaptability will be critical for maintaining child engagement in dyadic interactions, such as play or problem-solving activities. Therefore, exploring this relationship directly by examining caregiver-child interactions could be another interesting avenue for future research.

7.5.3. Caregiver stress and mental health.

Caregiver internalising problems and stress are significant factors influencing parenting behaviours. Maternal depression has been identified as a risk factor for reduced parenting effectiveness (Turney, 2011), increased negative parenting practices (Lovejoy et al., 2000; Zimmer-Gembeck & Thomas, 2010), and diminished scaffolding behaviours (Hoffman et al., 2006). Furthermore, higher levels of maternal depressive symptoms have been linked to reduced accuracy in recognising

infant positive emotions (Broth et al., 2004) and more frequent intrusive parenting behaviours (Cornish et al., 2008). In addition to depression, parenting stress related to perceived competence can negatively impact parenting practices (Webster-Stratton, 1998). Similarly, research suggests that parenting-related stress contributes to greater negativity in children during parent–child interactions (Crnic et al., 2005), highlighting the potential influence of parenting stress on children's emotional expressions in certain contexts. Due to these established links, the role of caregiver mental health and stress in shaping dyadic play interactions and their influence on child cognitive outcomes should be further explored. For instance, caregivers experiencing heightened stress or mental health difficulties may exhibit reduced responsiveness or engage in less enriching play activities, which could hinder opportunities for joint attention and scaffolding (Ward & Lee, 2020). Future research should examine how caregiver stress and mental health intersect with executive functioning to influence dyadic play interactions and child outcomes. Furthermore, the bidirectional nature of stress in the caregiver-child relationship warrants further investigation. Children's behaviours and developmental challenges can contribute to caregiver stress, creating a feedback loop that may intensify negative parenting behaviours or reduce engagement during interactions (Baker et al., 2003; Neece et al., 2012). Examining these reciprocal dynamics could offer valuable insights into how stress is both a cause and consequence of caregiving challenges. Ultimately, understanding the nuanced impact of caregiver stress and mental health could inform the development of interventions aimed at reducing stress and promoting mental well-being in caregivers. Such interventions could enhance the quality of caregiver-child interactions and, in turn, support optimal developmental outcomes for children. Exploring these pathways is essential for creating support systems that address the needs of both caregivers and children.

7.5.4. Examining the home environment.

The home environment has previously been studied due to its critical role in neurocognitive development, particularly in young children who rely solely on their caregivers. For example, Davidson et al. (2023) investigated whether home enrichment was associated with preschoolers' visual working memory function. Home enrichment was assessed using an adapted version of the Home Observation Measurement of the Environment Interview (Caldwell & Bradley, 2003). The

interview included questions that probed the availability and utilisation of resources and/or activities that supported children's literacy and mathematics development. Parent responses were examined using inductive content analysis (Elo & Kyngäs, 2008). Results revealed that home enrichment was associated with right-lateralised fronto-parietal engagement. Specifically, greater home enrichment was linked to increased suppression in the right inferior frontal gyrus, important for re-orienting attention. Critically, this home enrichment-related suppression was linked to better visual working memory performance (Davidson, Caes et al., 2023). This work shed light on potential mechanisms through which enrichment in homes might be involved with cognitive development and could also inspire future directions for this thesis. Examining the specific types of objects and play materials available within the home could provide additional insights into the quality of daily play opportunities. The objects children have access to may reflect whether they have the tools necessary for engaging in meaningful play interactions that support cognitive, social, and emotional development. For example, open-ended objects such as building blocks or art supplies may encourage creativity, problem-solving, and collaboration during caregiver-child interactions (Yazgin, 2021). In contrast, objects with limited functionality may provide fewer opportunities for such meaningful engagements. Moreover, the types of objects children engage with can reveal underlying differences in family priorities and socioeconomic constraints. For instance, children from resource-limited households may have fewer objects overall or objects that are primarily designed for solitary rather than interactive play. This could limit opportunities for joint attention, scaffolding, and other critical aspects of dyadic play interactions that support early learning. For example, Chang and colleagues (2024) reported that limited access to books was linked to children's developmental delay. Investigating these dynamics could shed light on how the home environment and the availability of objects shapes how children learn through everyday play experiences. Studies could also explore how caregiver involvement and executive functions interact with the availability and use of objects to influence child developmental outcomes. Additionally, longitudinal designs could help clarify how access to diverse and enriching play materials contributes to cognitive and socio-emotional development over time. Finally, identifying disparities in access to enriching play materials could inform targeted interventions aimed at reducing inequalities. For example, community programs that provide low-cost or free play

materials designed to encourage caregiver-child interaction could help bridge gaps and promote equitable developmental opportunities for children from diverse backgrounds.

7.5.5. Further longitudinal work.

Another strength of this thesis is rooted in the longitudinal examination of child visual cognition and multiple dyadic play interactions. Specifically, this thesis included two timepoints of data, one where infants were between 6 and 10 months, and one where toddlers were between 18 and 22 months. These timepoints spanned a crucial developmental period however future work should endeavour to follow families for longer periods, perhaps until preschool and school enrolment. Executive functions are supported by exposure to structured learning environments (Brod et al., 2017). Here, children rely on working memory to follow directions, interact with peers, and keep track of routines (Diamond, 2013; Finch, 2019), all of which are important for early school success (Zhang et al., 2019). Previous work has reported that exposure to one year of formal schooling resulted in improvements in working memory performance and greater engagement of a left-lateralised fronto-parietal network (Davidson, Shing et al., 2023). This exposure to primary school was also associated with improvements in vocabulary and numeracy (Davidson, Shing et al., 2023). Therefore, longitudinal work that spans from infancy to 5-years would be crucial for understanding how early experiences impact factors such as school readiness and academic achievement.

7.6. Conclusion.

This thesis investigated developmental changes in child visual neurocognition and play interactions. Understanding the intricate interplay between visual neurocognition and play interactions is essential for advancing developmental science. Early childhood is marked by rapid changes in both visual cognitive abilities and social engagement, with each domain influencing and shaping the other. This thesis explored these developmental trajectories, integrating findings from both visual cognition and dyadic play research to provide a comprehensive framework for understanding how children process and interact with their environments. In doing so, it has not only built upon existing literature but has also addressed key research gaps that have limited our understanding of these interconnected domains.

Additionally, the novel research presented in this thesis has demonstrated the potential for cognitive neuroscience to be applied in early development to identify individual differences, before these are evident in behaviour.

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Appendices

Appendix A:

Published results section from Chapter 3 – excluding infant age covariate.

AA.1. Association between caregiver efficiency and infant visual working memory (VWM) behaviour.

The one-factor ANOVA on infant CP scores revealed a main effect of load ($F(2,164) = 12.107$, $p = 0.0001$, $\eta 2 = 0.10$; low load = 0.59 ± 0.08; medium load = 0.55 ± 0.07; high load = 0.54 ± 0.07) – see Figure 2. Specifically, CP score at the low load was significantly greater than CP score at the medium ($p = 0.002$) and high loads ($p = 0.0001$). CP score at the medium load did not differ from CP score at the high load.

Linear effects modelling was used to investigate whether caregiver efficiency and load predicted infant CP scores. Neither the main effect of caregiver efficiency nor the interaction between caregiver efficiency and load were significant predictors of infant CP scores.

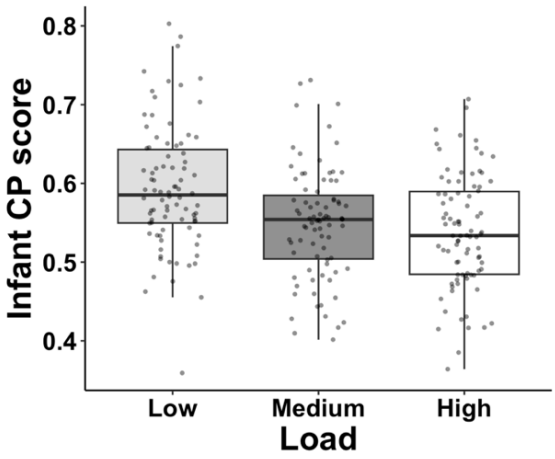


Figure 2. Main effect of load on infant CP scores.

AA.2. Caregiver brain function.

The linear mixed effects model of the caregivers' brain data revealed only a significant main effect of chromophore in four clusters – left inferior frontal gyrus (lIFG) [MNI coordinates: 58.7 -7.9 16.4, 430 voxels, $F(1,255)=10.76$, $p<0.01$], right angular gyrus (rAG) [MNI coordinates: -57.3 56.5 36.4, 186 voxels, $F(1,255)=20.80$,

p<0.01], right middle frontal gyrus (rMFG) [MNI coordinates: -43.9 -26.9 39.9, 180 voxels, F(1,255)=7.93, p<0.01] and left inferior parietal lobule (lIPL) [MNI coordinates: 57.4 54.0 39.2, 130 voxels, F(1,255)=12.88, p<0.01] – see Table 2 and Figure 3(a-d). Follow-up tests revealed that HbO concentration was greater than HbR concentration in lIFG (lIFG: p = 0.0008, Cohen's *d* = 0.37). Only a similar trend was observed in rMFG. In contrast, in rAG and lIPL, HbO concentration was lesser than HbR concentration (rAG: p = 0.0003, Cohen's *d* = -0.40; lIPL: p = 0.002, Cohen's *d* = -0.33).

Significant effects	**Cluster**	**Size (mm^3)**	**MNI coordinates**		
			Centre of Mass		
			x	**y**	**z**
Chromophore	Left inferior frontal gyrus (lIFG)*	430	58.7	-7.9	16.4
	Right angular gyrus (rAG)*	186	-57.3	56.5	36.4
	Right middle frontal gyrus (rMFG)	180	-43.9	-26.9	39.9
	Left inferior parietal lobule (lIPL)*	130	57.4	54	39.2

*Table 2. Cluster information for significant effects in the caregiver brain model. * Indicates effects that yielded significant results after follow-up tests.*

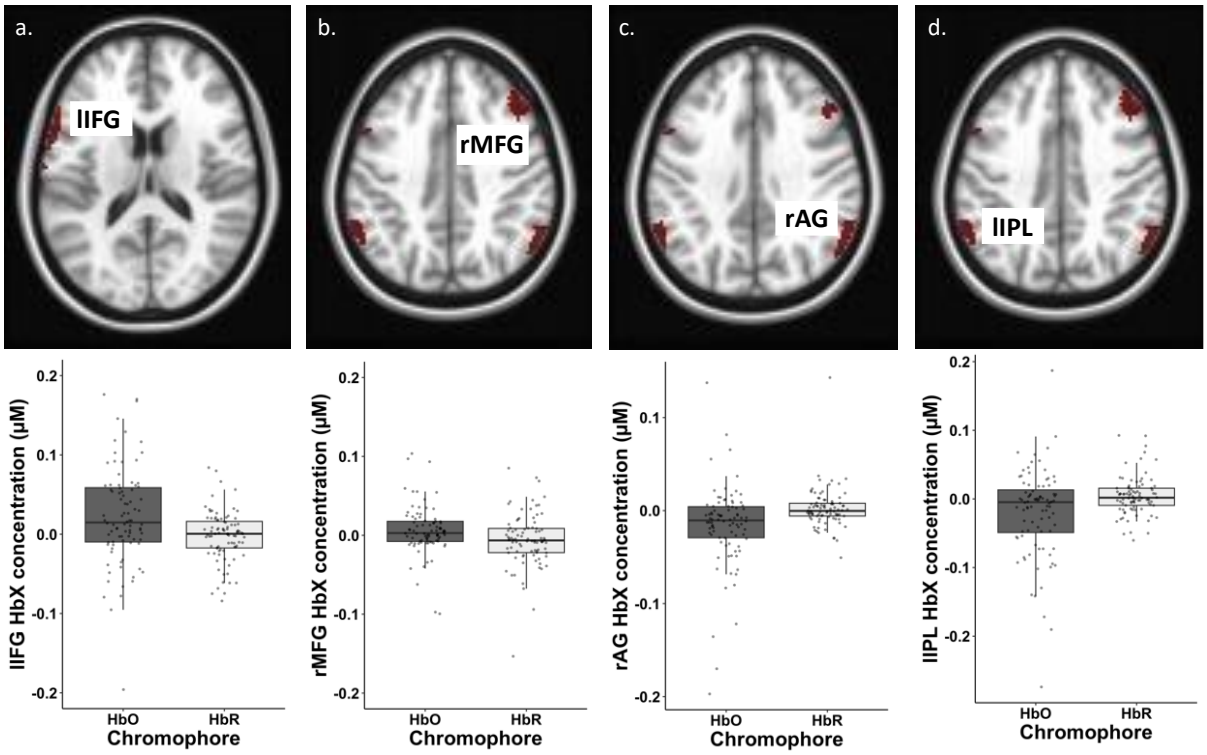


Figure 3. Brain images and boxplots for significant main effect of chromophore in (a) left inferior frontal gyrus (lIFG), (b) right middle frontal gyrus (rMFG), (c) right angular gyrus (rAG), and (d) left inferior parietal lobule (lIPL). HbO concentration is shown in black and HbR concentration is shown in grey.

AA.3. Infant brain function.

The linear mixed effects model of the infants' brain data revealed significant main effects and interactions (Table 3).

A main effect of chromophore was observed in lIFG [MNI coordinates: 40.6 -37 26.8, 774 voxels, $F(1,397)=16.94$, $p<0.01$], right superior parietal lobule (rSPL) [MNI coordinates: -23.9 63.9 60.4, 360 voxels, $F(1,397)=25.20$, $p<0.01$] and left middle temporal gyrus (lMTG) [MNI coordinates: 62.2 33.6 8.2, 333 voxels, $F(1,397)=17.50$, $p<0.01$]. In all three clusters, HbO concentration was greater than HbR concentration (lIFG: $p = 0.01$, Cohen's $d = 0.28$; rSPL: $p = 0.0003$, Cohen's $d = 0.40$; lMTG: $p = 0.02$, Cohen's $d = 0.25$) - see Figure 4(a-c).

A significant two-way interaction between infant CP score and chromophore was observed in a cluster in the left middle frontal gyrus (lMFG) [MNI coordinates: 37.8 -41.1 24.9, 318 voxels, $F(1,397)=9.52$, $p<0.01$] – see Figure 4(d). Follow-up tests

were run for each chromophore separately. Here, greater infant CP score was associated with greater HbO concentration ($p = 0.02$, $\eta_p^2 = 0.06$), but not HbR concentration in lMFG.

Significant effects	Cluster	Size (mm^3)	MNI coordinates		
			Centre of Mass		
			x	y	z
Chromophore	Left inferior frontal gyrus (lIFG)*	774	40.6	-37	26.8
	Right superior parietal lobule (rSPL)*	360	-23.9	63.9	60.4
	Left middle temporal gyrus (lMTG)*	333	62.2	33.6	8.2
Infant CP Score x Chromophore	Left middle frontal gyrus (lMFG)*	318	37.8	-41.1	24.9
Caregiver Efficiency x Chromophore	Left inferior parietal lobule (lIPL)	897	40.4	53.7	56.6

	Left middle frontal gyrus (lMFG)*	226	27.9	-48.6	29.8
Caregiver Efficiency x Load x Infant CP Score x Chromophore	Left inferior parietal lobule (lIPL)*	732	40.5	53.9	55.9

*Table 3. Cluster information for significant effects in the infant brain model. * Indicates effects that yielded significant results after follow-up tests. Note that there is no spatial overlap between the lMFG cluster showing an interaction between infant CP score and chromophore and the lMFG cluster showing an interaction between caregiver efficiency and chromophore.*

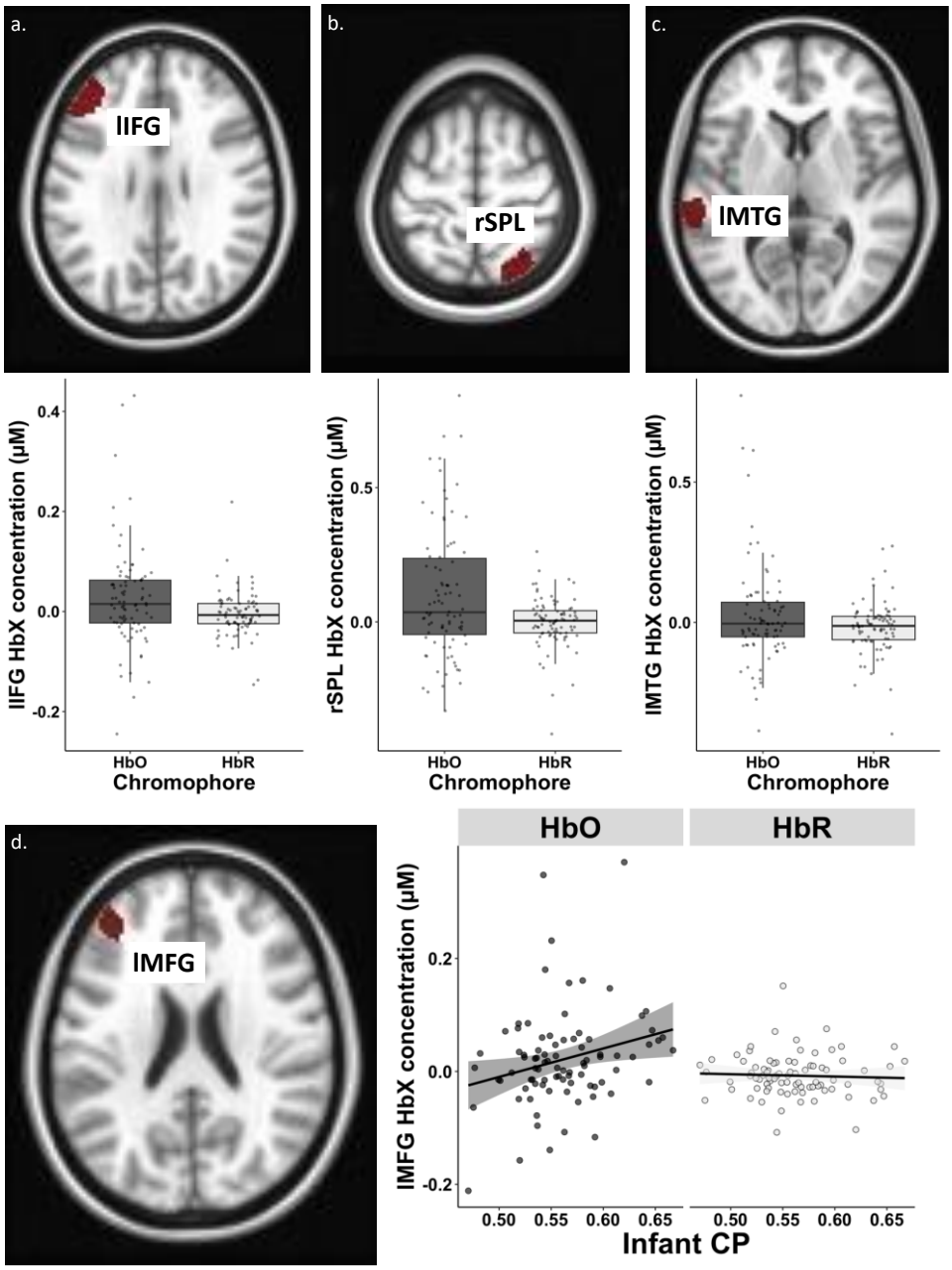


Figure 4. Brain images and boxplots for significant main effect of chromophore in (a) left inferior frontal gyrus (lIFG), (b) right superior parietal lobule (rSPL), and (c) left middle temporal gyrus (lMTG). (d) Brain image and scatterplot for significant interaction between infant CP score and chromophore in left middle frontal gyrus (lMFG). HbO concentration is shown in black and HbR concentration is shown in grey.

Lastly, there were two significant effects related to caregiver efficiency. A significant two-way interaction between caregiver efficiency and chromophore was observed in a cluster in lMFG [MNI coordinates: 27.9 -48.6 29.8, 226 voxels, $F(1,397)=8.88$, $p<0.01$] and lIPL [MNI coordinates: 40.4 53.7 56.6, 897 voxels, $F(1,397)=16.22$, $p<0.01$]. Follow-up tests were run for each chromophore and for each

cluster. Our findings revealed that in lMFG, greater caregiver efficiency was associated with lesser HbO concentration ($p = 0.03$, $\eta_p^2 = 0.05$), but not HbR concentration – see Figure 5. Note that this cluster did not spatially overlap with the lMFG cluster showing an interaction between infant CP score and chromophore (discussed in the previous paragraph). In lIPL, follow-up analyses did not reveal significant findings for either HbO or HbR concentration. Note, however, that this two-way interaction effect in lIPL was subsumed by a significant four-way interaction in the same region. We discuss this below.

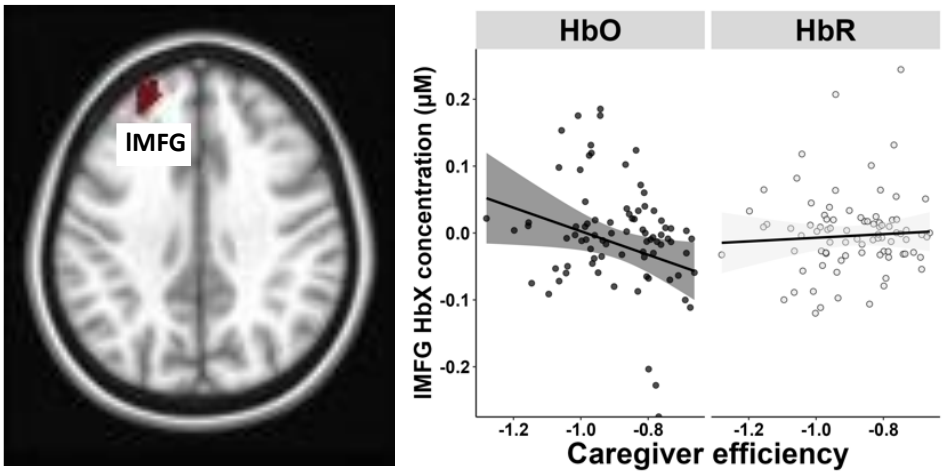


Figure 5. Significant two-way interaction between caregiver efficiency and chromophore in left middle frontal gyrus (lMFG) in infant brain data. HbO concentration is shown in black and HbR concentration is shown in grey in scatter plots.

There was also a significant four-way interaction between load, infant CP score, caregiver efficiency, and chromophore in lIPL [MNI coordinates: 40.5 53.9 55.9, 732 voxels, $F(2,397)=7.61$, $p<0.01$]. We first ran follow-up tests for each chromophore and load separately. There was a significant interaction between infant CP score and caregiver efficiency on lIPL HbR concentration at the medium load ($p = 0.003$, $\eta_p^2 = 0.10$) and lIPL HbO concentration at the high load ($p = 0.04$, $\eta_p^2 = 0.05$). For ease of understanding the association between our three continuous variables (infant CP score, caregiver CP score and lIPL activation), we median-split caregiver efficiency into low efficiency and high efficiency groups and ran a further follow-up test on each group separately. Our results revealed that both interaction effects were driven by low efficiency caregivers only (lIPL HbR at medium load: $p = 0.02$, $\eta_p^2 = 0.14$; lIPL HbO at high load: $p = 0.00001$, $\eta_p^2 = 0.45$). Specifically, at the medium

load, infants of low efficiency caregivers showed increasing lIPL HbR concentration (interpreted as decreasing lIPL activation since directionality is reversed with HbR) with increasing CP scores. Similarly, at the high load, infants of low efficiency caregivers showed decreasing lIPL HbO concentration (interpreted as decreasing lIPL activation since directionality is preserved with HbO) with increasing CP scores. Thus, at the medium and high loads, infants with low efficiency caregivers showed decreasing lIPL activation with increasing CP scores, compared to infants with high efficiency caregivers, who did not demonstrate any CP score-dependent lIPL modulation.

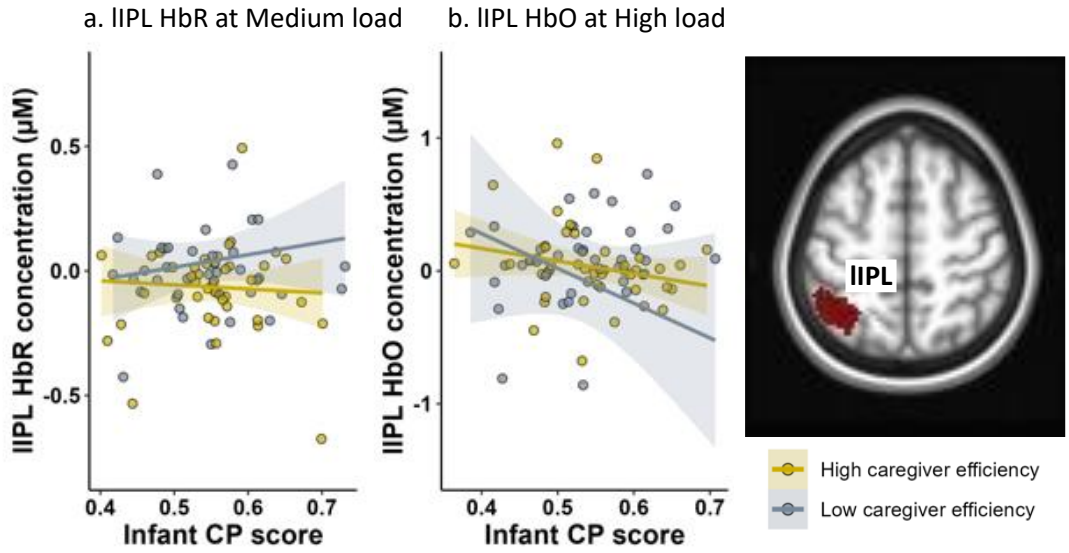


Figure 6. Significant interaction between infant CP score and caregiver efficiency on (a) lIPL HbR concentration at the medium load and (b) lIPL HbO concentration at the high load. Low efficiency caregivers are shown in grey and high efficiency caregivers are shown in yellow.

Finally, we examined whether there was any spatial overlap between significant clusters in the caregiver brain data and infant brain data. There was no spatial overlap between the clusters in both models.

Appendix B:

Articles identified for coding schemes.

Table AB.1. Papers used for extracting codes related to caregiver intrusiveness.

No.	Paper Citation
1	Lahtela, H., Nolvi, S., Flykt, M., Kataja, E. L., Eskola, E., Pelto, J., Bridgett, D. J., Karlsson, H., Karlsson, L., & Korja, R. (2023). Mother–infant interaction and maternal postnatal psychological distress are associated with negative emotional reactivity among infants and toddlers— A FinnBrain Birth Cohort study. *Infant Behavior and Development*, *72*(May), 101843. https://doi.org/10.1016/j.infbeh.2023.101843
2	Perea-Velasco, L. P., Martínez-Fuentes, M. T., & Pérez-López, J. (2023). Changes in patterns of Early Mother-Child Interaction: A longitudinal study of the first 18 months of life. *Infant Behavior and Development*, *72*(March). https://doi.org/10.1016/j.infbeh.2023.101858
3	Bozicevic, L., Ponti, L., Smorti, M., Pravettoni, G., Peccatori, F. A., Cassani, C., Nastasi, G., Sarchi, V., & Bonassi, L. (2022). Psychological Well-Being, Prenatal Attachment, and Quality of Early Mother-Infant Interaction: A Pilot Study With a Sample of Mothers With or Without Cancer History. *Frontiers in Psychology*, *13*(June). https://doi.org/10.3389/fpsyg.2022.913482
4	Endevelt-Shapira, Y., & Feldman, R. (2023). Mother–Infant Brain-to-Brain Synchrony Patterns Reflect Caregiving Profiles. *Biology*, *12*(2), 284. https://doi.org/10.3390/biology12020284
5	Goodman, S. H., Muzik, M., Simeonova, D. I., Kidd, S. A., Owen, M. T., Cooper, B., Kim, C. Y., Rosenblum, K. L., & Weiss, S. J. (2022). Maternal Interaction With Infants Among Women at Elevated Risk for Postpartum Depression. *Frontiers in Psychology*, *13*(March). https://doi.org/10.3389/fpsyg.2022.737513

6	Nicolson, S., Carron, S. P., & Paul, C. (2022). Supporting early infant relationships and reducing maternal distress with the Newborn Behavioral Observations: A randomized controlled effectiveness trial. *Infant Mental Health Journal*, *43*(3), 455–473. https://doi.org/10.1002/imhj.21987
7	Ahrnberg, H., Korja, R., Scheinin, N. M., Nolvi, S., Kataja, E. L., Kajanoja, J., Hakanen, H., Karlsson, L., Karlsson, H., & Karukivi, M. (2021). Maternal Alexithymic Traits Are Related to Lower Maternal Sensitivity and Higher Hostility in Maternal Caregiving Behavior—The FinnBrain Birth Cohort Study. *Frontiers in Psychology*, *12*(July). https://doi.org/10.3389/fpsyg.2021.704036
8	Hunter, H., Allen, K. B., Liu, R., Jaekel, J., & Bell, M. A. (2021). Examining the bidirectional relationships between maternal intrusiveness and child internalizing symptoms in a community sample: A longitudinal study from infancy to middle childhood. *Depression and Anxiety*, *38*(12), 1245–1255. https://doi.org/10.1002/da.23207
9	Vaccaro, S. M., Tofighi, D., Moss, N., Rieger, R., Lowe, J. R., Phillips, J., & Erickson, S. J. (2021). The association of infant temperament and maternal sensitivity in preterm and full-term infants. *Infant Mental Health Journal*, *42*(3), 374–385. https://doi.org/10.1002/imhj.21915
10	Broomell, A. P. R., Smith, C. L., Calkins, S. D., & Bell, M. A. (2020). Context of Maternal Intrusiveness During Infancy and Associations with Preschool Executive Function. *Infant and Child Development*, *29*(1). https://doi.org/10.1002/icd.2162
11	Huffmeijer, R., Bakermans-Kranenburg, M. J., & Gervain, J. (2020). Maternal intrusiveness predicts infants' event-related potential responses to angry and happy prosody independent of infant frontal asymmetry. *Infancy*, *25*(3), 246–263. https://doi.org/10.1111/infa.12327
12	Wu, Q., & Feng, X. (2020). Infant emotion regulation and cortisol response during the first 2 years of life: Association with maternal

	parenting profiles. *Developmental Psychobiology*, *62*(8), 1076–1091. https://doi.org/10.1002/dev.21965
13	Diaz, A., Swingler, M. M., Tan, L., Smith, C. L., Calkins, S. D., & Bell, M. A. (2019). Infant frontal EEG asymmetry moderates the association between maternal behavior and toddler negative affectivity. *Infant Behavior and Development*, *55*(March), 88–99. https://doi.org/10.1016/j.infbeh.2019.03.002
14	Hakanen, H., Flykt, M., Sinervä, E., Nolvi, S., Kataja, E. L., Pelto, J., Karlsson, H., Karlsson, L., & Korja, R. (2019). How maternal pre- and postnatal symptoms of depression and anxiety affect early mother-infant interaction? *Journal of Affective Disorders*, *257*(April), 83–90. https://doi.org/10.1016/j.jad.2019.06.048
15	Miller, N. V., Hane, A. A., Degnan, K. A., Fox, N. A., & Chronis-Tuscano, A. (2019). Investigation of a developmental pathway from infant anger reactivity to childhood inhibitory control and ADHD symptoms: interactive effects of early maternal caregiving. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *60*(7), 762–772. https://doi.org/10.1111/jcpp.13047
16	Toepfer, P., O'Donnell, K. J., Entringer, S., Garg, E., Heim, C. M., Lin, D. T. S., MacIsaac, J. L., Kobor, M. S., Meaney, M. J., Provençal, N., Binder, E. B., Wadhwa, P. D., & Buss, C. (2019). Dynamic DNA methylation changes in the maternal oxytocin gene locus (OXT) during pregnancy predict postpartum maternal intrusiveness. *Psychoneuroendocrinology*, *103*(January), 156–162. https://doi.org/10.1016/j.psyneuen.2019.01.013
17	Wagner, N. J., Mills-Koonce, W. R., Willoughby, M. T., Cox, M. J., Vernon-Feagans, L., Blair, C., Burchinal, M. R., Crnic, K., Crouter, A., Garrett-Peters, P., Greenberg, M. T., Frank, J. L., Stifter, C., Werner, E., & Lanza, S. (2019). Parenting and Cortisol in Infancy Interactively Predict Conduct Problems and Callous–Unemotional Behaviors in Childhood. *Child Development*, *90*(1), 279–297. https://doi.org/10.1111/cdev.12900

18	Zvara, B. J., Altenburger, L. E., Lang, S. N., & Schoppe-Sullivan, S. J. (2019). The role of coparenting in the association between parental neuroticism and harsh intrusive parenting. *Journal of Family Psychology*, *33*(8), 945–953. https://doi.org/10.1037/fam0000555
19	Caron, E. B., Bernard, K., & Dozier, M. (2018). In Vivo Feedback Predicts Parent Behavior Change in the Attachment and Biobehavioral Catch-up Intervention. *Journal of Clinical Child and Adolescent Psychology*, *47*(sup1), S35–S46. https://doi.org/10.1080/15374416.2016.1141359
20	Dáu, A. L. B. T., Callinan, L. S., Mayes, L. C., & Smith, M. V. (2017). Postpartum depressive symptoms and maternal sensitivity: an exploration of possible social media-based measures. *Archives of Women's Mental Health*, *20*(1), 221–224. https://doi.org/10.1007/s00737-016-0650-4
21	Lakes, K. D., Guo, Y., Lucas, C. T., & Cooper, D. (2017). Measuring maternal behaviors in the neonatal intensive care unit. *Infants and Young Children*, *30*(2), 124–132. https://doi.org/10.1097/IYC.0000000000000091
22	Smaling, H. J. A., Huijbregts, S. C. J., van der Heijden, K. B., Hay, D. F., van Goozen, S. H. M., & Swaab, H. (2017). Prenatal Reflective Functioning and Development of Aggression in Infancy: the Roles of Maternal Intrusiveness and Sensitivity. *Journal of Abnormal Child Psychology*, *45*(2), 237–248. https://doi.org/10.1007/s10802-016-0177-1
23	Swingler, M. M., Perry, N. B., Calkins, S. D., & Bell, M. A. (2017). Maternal behavior predicts infant neurophysiological and behavioral attention processes in the first year. *Developmental Psychology*, *53*(1), 13–27. https://doi.org/10.1037/dev0000187
24	Tarullo, A. R., St. John, A. M., & Meyer, J. S. (2017). Chronic stress in the mother-infant dyad: Maternal hair cortisol, infant salivary cortisol and interactional synchrony. *Infant Behavior and Development*, *47*, 92–102. https://doi.org/10.1016/j.infbeh.2017.03.007

25	Laurent, H. K., Harold, G. T., Leve, L., Shelton, K. H., & Van Goozen, S. H. M. (2016). Understanding the unfolding of stress regulation in infants. *Development and Psychopathology*, *28*(4), 1431–1440. https://doi.org/10.1017/S0954579416000171
26	Neri, E., Agostini, F., Salvatori, P., Biasini, A., & Monti, F. (2015). Mother-preterm infant interactions at 3 months of corrected age: Influence of maternal depression, anxiety and neonatal birth weight. *Frontiers in Psychology*, *6*(September), 1–12. https://doi.org/10.3389/fpsyg.2015.01234
27	Poehlmann, J., Burnson, C., & Weymouth, L. A. (2014). Early parenting, represented family relationships, and externalizing behavior problems in children born preterm. *Attachment and Human Development*, *16*(3), 271–291. https://doi.org/10.1080/14616734.2014.884610
28	Clincy, A. R., & Mills-Koonce, W. R. (2013). Trajectories of intrusive parenting during infancy and toddlerhood as predictors of rural, low-income African American boys' school-related outcomes. *American Journal of Orthopsychiatry*, *83*(2 PART 3), 194–206. https://doi.org/10.1111/ajop.12028
29	Maas, A. J. B. M., Vreeswijk, C. M. J. M., & Van Bakel, H. J. A. (2013). Effect of situation on mother-infant interaction. *Infant Behavior and Development*, *36*(1), 42–49. https://doi.org/10.1016/j.infbeh.2012.10.006
30	Sipos, L., Mengel Pers, B., Kalmár, M., Tóth, I., Krishna, S., Jensen, M. H., & Semsey, S. (2013). Comparative Network Analysis of Preterm vs. Full-Term Infant-Mother Interactions. *PLoS ONE*, *8*(6), 1–10. https://doi.org/10.1371/journal.pone.0067183
31	Bruce, M., McFayden, T. C., Ollendick, T. H., & Bell, M. A. (2022). Expressive language in infancy and toddlerhood: The roles of child temperament and maternal parenting behaviors. *Developmental Psychobiology*, *64*(6), 1–12. https://doi.org/10.1002/dev.22287
32	Hatzinikolaou, K., & Murray, L. (2010). Infant sensitivity to negative maternal emotional shifts: Effects of infant sex, maternal postnatal

	depression, and interactive style. *Infant Mental Health Journal*, *31*(5), 591–610. https://doi.org/10.1002/imhj.20265
33	Dollberg, D., Feldman, R., & Keren, M. (2010). Maternal representations, infant psychiatric status, and mother-child relationship in clinic-referred and non-referred infants. *European Child and Adolescent Psychiatry*, *19*(1), 25–36. https://doi.org/10.1007/s00787-009-0036-5
34	Diego, M. A., Field, T., Jones, N. A., & Hernandez-Reif, M. (2006). Withdrawn and intrusive maternal interaction style and infant frontal EEG asymmetry shifts in infants of depressed and non-depressed mothers. *Infant Behavior and Development*, *29*(2), 220–229. https://doi.org/10.1016/j.infbeh.2005.12.002

Table AB.2. Papers used for extracting codes related to caregiver scaffolding.

No.	**Paper Citation**
1	Mendive, S., Bornstein, M. H., & Sebastián, C. (2013). The role of maternal attention-directing strategies in 9-month-old infants attaining joint engagement. *Infant Behavior and Development*, *36*(1), 115–123. https://doi.org/10.1016/j.infbeh.2012.10.002
2	Vaughan, A., Mundy, P., Block, J., Burnette, C., Delgado, C., Gomez, Y., Meyer, J., Neal, A. R., & Pomares, Y. (2003). Child, caregiver, and temperament contributions to infant joint attention. *Infancy*, *4*(4), 603–616. https://doi.org/10.1207/S15327078IN0404_11
3	Coe, J. L., Huffhines, L., Contente, C. A., Seifer, R., & Parade, S. H. (2020). *Maternal Parenting and Infant Developmental Progress*. *41*(8), 619–627.
4	Bigelow, A. E., MacLean, K., & Proctor, J. (2004). The role of joint attention in the development of infants' play with objects. *Developmental Science*, *7*(5), 518–526. https://doi.org/10.1111/J.1467-7687.2004.00375.X
5	Dieterich, S. E., Assel, M. A., Swank, P., Smith, K. E., & Landry, S. H. (2006). The impact of early maternal verbal scaffolding and child language abilities on later decoding and reading comprehension skills.

	Journal of School Psychology, *43*(6), 481–494. https://doi.org/10.1016/j.jsp.2005.10.003
6	Conradt, E., Ostlund, B., Guerin, D., Armstrong, D. A., Marsit, C. J., Tronick, E., LaGasse, L., & Lester, B. M. (2019). DNA methylation of NR3c1 in infancy: Associations between maternal caregiving and infant sex. *Infant Mental Health Journal*, *40*(4), 513□522. https://doi.org/10.1002/imhj.21789
7	Guttentag, C. L., Landry, S. H., Williams, J. M., Baggett, K. M., Noria, C. W., Borkowski, J. G., Swank, P. R., Farris, J. R., Crawford, A., Lanzi, R. G., Carta, J. J., Warren, S. F., & Ramey, S. L. (2014). "My baby & me": Effects of an early, comprehensive parenting intervention on at-risk mothers and their children. *Developmental Psychology*, *50*(5), 1482–1496. https://doi.org/10.1037/a0035682
8	Landry, S. H., Smith, K. E., & Swank, P. R. (2006). *Responsive Parenting: Establishing Early Foundations for Social, Communication, and Independent Problem-Solving Skills*. https://doi.org/10.1037/0012
9	Lowe, J., Erickson, S. J., MacLean, P., Duvall, S. W., Ohls, R. K., & Duncan, A. F. (2014). Associations between maternal scaffolding and executive functioning in 3 and 4year olds born very low birth weight and normal birth weight. *Early Human Development*, *90*(10), 587–593. https://doi.org/10.1016/j.earlhumdev.2014.07.009
10	Landry, S. H., Miller-Loncar, C. L., Smith, K. E., & Swank, P. R. (2002). The Role of Early Parenting in Children's Development of Executive Processes. *Developmental Neuropsychology*, *21*(1), 15–41. https://doi.org/10.1207/S15326942DN2101_2
11	Lowe, J. R., Hund, L., Rodriguez, D. E., Qamruddin, A., Leeman, L., Stephen, J. M., & Bakhireva, L. N. (2021). Maternal verbal scaffolding: association with higher language skills for 20-month-old children with prenatal polysubstance exposure. *Early Human Development*, *160*, 105423. https://doi.org/10.1016/j.earlhumdev.2021.105423

12	Lowe, J. R., Erickson, S. J., MacLean, P., Schrader, R., & Fuller, J. (2013). Association of maternal scaffolding to maternal education and cognition in toddlers born preterm and full term. *Acta Paediatrica, International Journal of Paediatrics*, *102*(1), 72–77. https://doi.org/10.1111/apa.12037
13	Erickson, S. J., Duvall, S. W., Fuller, J., Schrader, R., MacLean, P., & Lowe, J. R. (2013). Differential associations between maternal scaffolding and toddler emotion regulation in toddlers born preterm and full term. *Early Human Development*, *89*(9), 699–704. https://doi.org/10.1016/j.earlhumdev.2013.05.003
14	Dilworth-Bart, J. E., Poehlmann, J. A., Miller, K. E., & Hilgendorf, A. E. (2011). Do mothers' play behaviors moderate the associations between socioeconomic status and 24-month neurocognitive outcomes of toddlers born preterm or with low birth weight? *Journal of Pediatric Psychology*, *36*(3), 289–300. https://doi.org/10.1093/jpepsy/jsq064
15	Dilworth-Bart, J., Poehlmann, J., Hilgendorf, A. E., Miller, K., & Lambert, H. (2010). Maternal scaffolding and preterm toddlers' visual-spatial processing and emerging working memory. *Journal of Pediatric Psychology*, *35*(2), 209–220. https://doi.org/10.1093/jpepsy/jsp048
16	Zampini, L., Ferrante, C., Silibello, G., DallAra, F., Rigamonti, C., Zanchi, P., Vizziello, P. G., Lalatta, F., & Costantino, M. A. (2020). Maternal input to children with sex chromosome trisomies. *International Journal of Language & Communication Disorders*, *55*(5), 724733. https://doi.org/10.1111/1460-6984.12557
17	Austin, M. P., Christl, B., McMahon, C., Kildea, S., Reilly, N., Yin, C., Simcock, G., Elgbeili, G., Laplante, D. P., & King, S. (2017). Moderating effects of maternal emotional availability on language and cognitive development in toddlers of mothers exposed to a natural disaster in pregnancy: The QF2011 Queensland Flood Study. *Infant Behavior and Development*, *49*(July), 296–309. https://doi.org/10.1016/j.infbeh.2017.10.005

18	Bigelow, A. E., MacLean, K., Proctor, J., Myatt, T., Gillis, R., & Power, M. (2010). Maternal sensitivity throughout infancy: Continuity and relation to attachment security. *Infant Behavior and Development*, *33*(1), 50–60. https://doi.org/10.1016/j.infbeh.2009.10.009
19	Wheeler, A., Hatton, D., Reichardt, A., & Bailey, D. (2007). Correlates of maternal behaviours in mothers of children with fragile X syndrome. *Journal of Intellectual Disability Research*, *51*(6), 447–462. https://doi.org/10.1111/j.1365-2788.2006.00896.x
20	Wachtel, K., & Carter, A. S. (2008). Reaction to diagnosis and parenting styles among mothers of young children with ASDs. *Autism*, *12*(5), 575–594. https://doi.org/10.1177/1362361308094505
21	O'Neill, M., Bard, K. A., Linnell, M., & Fluck, M. (2005). Maternal gestures with 20-month-old infants in two contexts. *Developmental Science*, *8*(4), 352–359. https://doi.org/10.1111/j.1467-7687.2005.00423.x
22	Waxman, R. P., & Spencer, P. E. (1997). What Mothers Do to Support Infant Visual Attention: Sensitivities to Age and Hearing Status. *Journal of Deaf Studies and Deaf Education*, *2*(2), 104–114. https://doi.org/10.1093/oxfordjournals.deafed.a014311
23	Gogate, L. J., Maganti, M., & Laing, K. B. (2013). Maternal naming of object wholes versus parts to preverbal infants: A fine-grained analysis of scaffolding at 6-8 months. *Infant Behavior and Development*, *36*(3), 470–479. https://doi.org/10.1016/j.infbeh.2013.03.012

Table AB.3. Papers used for extracting codes related to infant object engagement.

No.	**Paper Citation**
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2	de l'Etoile, S. K. (2006). Infant behavioral responses to infant-directed singing and other maternal interactions. *Infant Behavior and*

	Development, *29*(3), 456–470. https://doi.org/10.1016/j.infbeh.2006.03.002
3	Auerbach, J. G., Benjamin, J., Faroy, M., Geller, V., & Ebstein, R. (2001). DRD4 related to infant attention and information processing: A developmental link to ADHD? *Psychiatric Genetics*, *11*(1), 31–35. https://doi.org/10.1097/00041444-200103000-00006
4	Yu, C., Suanda, S. H., & Smith, L. B. (2019). Infant sustained attention but not joint attention to objects at 9 months predicts vocabulary at 12 and 15 months. *Developmental Science*, *22*(1), 1–12. https://doi.org/10.1111/desc.12735
5	Wass, S. V., Noreika, V., Georgieva, S., Clackson, K., Brightman, L., Nutbrown, R., Covarrubias, L. S., & Leong, V. (2018). Parental neural responsivity to infants' visual attention: How mature brains influence immature brains during social interaction. *PLoS Biology*, *16*(12). https://doi.org/10.1371/journal.pbio.2006328
6	Sun, L., & Yoshida, H. (2022). Why the parent's gaze is so powerful in organizing the infant's gaze: The relationship between parental referential cues and infant object looking. *Infancy*, *27*(4), 780–808. https://doi.org/10.1111/infa.12475
7	Pridham, K., Becker, P., & Brown, R. (2000). Effects of infant and caregiving conditions on an infant's focused exploration of toys. *Journal of Advanced Nursing*, *31*(6), 1439–1448. https://doi.org/10.1046/j.1365-2648.2000.01448.x
8	Heiman, C. M., Cole, W. G., Lee, D. K., & Adolph, K. E. (2019). Object Interaction and Walking: Integration of Old and New Skills in Infant Development. *Infancy*, *24*(4), 547–569. https://doi.org/10.1111/infa.12289
9	Chang, L. M., & Deák, G. O. (2019). Maternal discourse continuity and infants' actions organize 12-month-olds' language exposure during object play. *Developmental Science*, *22*(3), 1–14. https://doi.org/10.1111/desc.12770
10	Colombo, J., Zavaleta, N., Kannass, K. N., Lazarte, F., Albornoz, C., Kapa, L. L., & Caulfield, L. E. (2014). Zinc supplementation

	sustained normative neurodevelopment in a randomized, Controlled trial of peruvian infants aged 6-18 months. *Journal of Nutrition*, *144*(8), 1298–1305. https://doi.org/10.3945/jn.113.189365
11	Brigham, N. B., Yoder, P. J., Jarzynka, M. A., & Tapp, J. (2010). The sequential relationship between parent attentional cues and sustained attention to objects in young children with autism. *Journal of Autism and Developmental Disorders*, *40*(2), 200–208. https://doi.org/10.1007/s10803-009-0848-7
12	Koşkulu, S., Küntay, A. C., Liszkowski, U., & Uzundag, B. A. (2021). Number and type of toys affect joint attention of mothers and infants. *Infant Behavior and Development*, *64*(August 2020). https://doi.org/10.1016/j.infbeh.2021.101589
13	Masek, L. R., Edgar, E. V., McMillan, B. T. M., Todd, J. T., Golinkoff, R. M., Bahrick, L. E., & Hirsh-Pasek, K. (2024). Building language learning: Relations between infant attention and social contingency in the first year of life. *Infant Behavior and Development*, *75*(July 2023), 101933. https://doi.org/10.1016/j.infbeh.2024.101933
14	Rat-Fischer, L., Plunkett, K., von Bayern, A. M. P., & Kacelnik, A. (2024). Object play and problem solving in infancy: Insights into tool use. *Journal of Experimental Child Psychology*, *244*, 105957. https://doi.org/10.1016/j.jecp.2024.105957
15	Salley, B., Brady, N. C., Hoffman, L., & Fleming, K. (2020). Preverbal communication complexity in infants. *Infancy*, *25*(1), 4–21. https://doi.org/10.1111/infa.12318
16	Yu, C., Suanda, S. H., & Smith, L. B. (2019). Infant sustained attention but not joint attention to objects at 9 months predicts vocabulary at 12 and 15 months. *Developmental Science*, *22*(1), 139–148. https://doi.org/10.1111/desc.12735
17	Bradshaw, J., Fu, X., & Richards, J. E. (2024). Infant sustained attention differs by context and social content in the first 2 years of life. *Developmental Science*, *27*(4). https://doi.org/10.1111/desc.13500
18	Wass, S. V., Clackson, K., Georgieva, S. D., Brightman, L., Nutbrown, R., & Leong, V. (2018). Infants' visual sustained attention

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19	Schatz, J. L., Suarez-Rivera, C., Kaplan, B. E., & Tamis-LeMonda, C. S. (2022). Infants' object interactions are long and complex during everyday joint engagement. *Developmental Science*, *25*(4). https://doi.org/10.1111/desc.13239
20	Lasch, C., Carlson, S. M., & Elison, J. T. (2023). Responding to joint attention as a developmental catalyst: Longitudinal associations with language and social responsiveness. *Infancy*, *28*(2), 339–366. https://doi.org/10.1111/infa.12515
21	Suarez-Rivera, C., Schatz, J. L., Herzberg, O., & Tamis-LeMonda, C. S. (2022). Joint engagement in the home environment is frequent, multimodal, timely, and structured. *Infancy*, *27*(2), 232–254. https://doi.org/10.1111/infa.12446
22	Karasik, L. B., Schneider, J. L., Kuchirko, Y. A., & Dodojonova, R. (2024). Object play in Tajikistan: Infants engage with objects despite bounds on play. *Infancy*, 1–18. https://doi.org/10.1111/infa.12627
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24	Heymann, P., Northrup, J. B., West, K. L., Parladé, M. V., Leezenbaum, N. B., & Iverson, J. M. (2018). Coordination is key: Joint attention and vocalisation in infant siblings of children with Autism Spectrum Disorder. *International Journal of Language and Communication Disorders*, *53*(5), 1007–1020. https://doi.org/10.1111/1460-6984.12418
25	Urqueta Alfaro, A., Morash, V. S., Lei, D., & Orel-Bixler, D. (2018). Joint engagement in infants and its relationship to their visual impairment measurements. *Infant Behavior and Development*, *50*(June 2017), 311–323. https://doi.org/10.1016/j.infbeh.2017.05.010
26	Sun, L., Francis, D. J., Nagai, Y., & Yoshida, H. (2024). Early development of saliency-driven attention through object

	manipulation. *Acta Psychologica*, *243*(December 2023), 104124. https://doi.org/10.1016/j.actpsy.2024.104124
27	Testa, K., McNew, M. E., Todd, J. T., Eschman, B., & Bahrick, L. E. (2023). Infant distractibility from social events mediates the relation between maternal responsiveness and infant language outcomes. *Infant Behavior and Development*, *71*(May), 101840. https://doi.org/10.1016/j.infbeh.2023.101840
28	Mateus, V., Cruz, S., Ferreira-Santos, F., Osório, A., Sampaio, A., & Martins, C. (2018). Contributions of infant vagal regulation at 1 month to subsequent joint attention abilities. *Developmental Psychobiology*, *60*(1), 111–117. https://doi.org/10.1002/dev.21582
29	Ataman-Devrim, M., Quigley, J., & Nixon, E. (2024). Preterm toddlers' joint attention characteristics during dyadic interactions with their mothers and fathers compared to full-term toddlers at age 2 years. *Infant Behavior and Development*, *74*(May 2023), 101915. https://doi.org/10.1016/j.infbeh.2023.101915
30	Chen, C. hsin, Houston, D. M., & Yu, C. (2021). Parent–Child Joint Behaviors in Novel Object Play Create High-Quality Data for Word Learning. *Child Development*, *92*(5), 1889–1905. https://doi.org/10.1111/cdev.13620
31	Harris, M., & Chasin, J. (2005). Visual attention in deaf and hearing infants: The role of auditory cues. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *46*(10), 1116–1123. https://doi.org/10.1111/j.1469-7610.2005.00405.x
32	Koulomzin, M., Beebe, B., Anderson, S., Jaffe, J., Feldstein, S., & Crown, C. (2002). Infant gaze, head, face and self-touch at 4 months differentiate secure vs. avoidant attachment at 1 year: A microanalytic approach. *Attachment and Human Development*, *4*(1), 3–24. https://doi.org/10.1080/14616730210123120
33	Peláez-Nogueras, M., Field, T. M., Hossain, Z., & Pickens, J. (1996). Depressed Mothers' Touching Increases Infants' Positive Affect and Attention in Still-Face Interactions. *Child Development*, *67*(4), 1780–1792. https://doi.org/10.1111/j.1467-8624.1996.tb01827.x

Table AB.4. Papers used for extracting codes related to infant distractibility.

No.	Paper Citation
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2	Doolittle, E. J., & Ruff, H. A. (1998). Distractibility during infants' examining and repetitive rhythmic activity. *Developmental Psychobiology*, *32*(4), 275–283. https://doi.org/10.1002/(SICI)1098-2302(199805)32:4<275::AID-DEV2>3.0.CO;2-K
3	Ruff, H. A., Capozzoli, M., & Saltarelli, L. M. (1996). Focused visual attention and distractibility in 10-month-old infants. *Infant Behavior and Development*, *19*(3), 281–293. https://doi.org/10.1016/S0163-6383(96)90029-6
4	Ruff, H. A., & Capozzoli, M. C. (2003). Development of Attention and Distractibility in the First 4 Years of Life. *Developmental Psychology*, *39*(5), 877–890. https://doi.org/10.1037/0012-1649.39.5.877
5	Kannass, K. N., Oakes, L. M., & Shaddy, D. J. (2006). A longitudinal investigation of the development of attention and distractibility. *Journal of Cognition and Development*, *7*(3), 381–409. https://doi.org/10.1207/s15327647jcd0703_8
6	Oakes, L. M., Tellinghuisen, D. J., & Tjebkes, T. L. (2000). Competition for Infants' Attention: The Interactive Influence of Attentional State and Stimulus Characteristics. *Infancy*, *1*(3), 347–361. https://doi.org/10.1207/S15327078IN0103_4
7	Testa, K., McNew, M. E., Todd, J. T., Eschman, B., & Bahrick, L. E. (2023). Infant distractibility from social events mediates the relation between maternal responsiveness and infant language outcomes. *Infant Behavior and Development*, *71*(May), 101840. https://doi.org/10.1016/j.infbeh.2023.101840

8	Swingler, M. M., Perry, N. B., Calkins, S. D., & Bell, M. A. (2014). Maternal sensitivity and infant response to frustration: The moderating role of EEG asymmetry. *Infant Behavior and Development*, *37*(4), 523–535. https://doi.org/10.1016/j.infbeh.2014.06.010
9	Courage, M. L., Murphy, A. N., Goulding, S., & Setliff, A. E. (2010). When the television is on: The impact of infant-directed video on 6- and 18-month-olds' attention during toy play and on parent-infant interaction. *Infant Behavior and Development*, *33*(2), 176–188. https://doi.org/10.1016/j.infbeh.2009.12.012
10	Atkinson, N. H., Jean, A. D. L., & Stack, D. M. (2021). Emotion regulation from infancy to toddlerhood: Individual and group trajectories of full-term and very-low-birthweight preterm infants. *Infancy*, *26*(4), 570–595. https://doi.org/10.1111/infa.12405
11	Blum, N. J., Taubman, B., Tretina, L., & Heyward, R. Y. (2002). Maternal ratings of infant intensity and distractibility: Relationship with crying duration in the second month of life. *Archives of Pediatrics and Adolescent Medicine*, *156*(3), 286–290. https://doi.org/10.1001/archpedi.156.3.286
12	Kelmanson, I. (1999). Use of a pacifier and behavioural features in 2–4-month-old infants. *Acta Paediatrica*, *88*(11), 1258–1261. https://doi.org/10.1111/j.1651-2227.1999.tb01028.x
13	Loi, E. C., Marchman, V. A., Fernald, A., & Feldman, H. M. (2017). Using Eye Movements to Assess Language Comprehension in Toddlers Born Preterm and Full Term. *Journal of Pediatrics*, *180*, 124–129. https://doi.org/10.1016/j.jpeds.2016.10.004
14	Chong, S. Y., Chittleborough, C. R., Gregory, T., Lynch, J. W., & Smithers, L. G. (2015). How many infants are temperamentally difficult? Comparing norms from the Revised Infant Temperament Questionnaire to a population sample of UK infants. *Infant Behavior and Development*, *40*, 20–28. https://doi.org/10.1016/j.infbeh.2015.04.001

15	Dixon, W. E., Salley, B. J., & Clements, A. D. (2006). Temperament, distraction, and learning in toddlerhood. *Infant Behavior and Development*, *29*(3), 342–357. https://doi.org/10.1016/j.infbeh.2006.01.002
16	Lansink, J. M., & Richards, J. E. (1997). Heart Rate and Behavioral Measures of Attention in Six-, Nine-, and Twelve-Month-Old Infants during Object Exploration. *Child Development*, *68*(4), 610–620. https://doi.org/10.1111/j.1467-8624.1997.tb04224.x
17	Sun, J., Mohay, H., & O'Callaghan, M. (2009). A comparison of executive function in very preterm and term infants at 8 months corrected age. *Early Human Development*, *85*(4), 225–230. https://doi.org/10.1016/j.earlhumdev.2008.10.005
18	Diaz, A., & Bell, M. A. (2011). Information processing efficiency and regulation at five months. *Infant Behavior and Development*, *34*(2), 239–247. https://doi.org/10.1016/j.infbeh.2010.12.011