Inhibitory Control Development from Infancy: Identifying Neural Correlates and Mapping Behavioural Trajectories into Early Childhood

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Abstract

This thesis aims to investigate the behavioural development and neural correlates of inhibitory control across two key transitions in the early years of life. To do so, four experimental chapters are presented that report data from a longitudinal sample of participants at three age points: infancy (10-months), the transition to toddlerhood (16-months), and the start of early childhood (3½ years). A literature review is provided in the general introduction (Chapter 1), the methodological approaches taken to measure early inhibitory control development are described in Chapter 2, and an introduction to functional near-infrared spectroscopy (fNIRS) is presented in Chapter 3. The first three experimental chapters (Chapters 4 – 6) used fNIRS alongside an age-appropriate task to investigate the behavioural development and neural correlates of response inhibition across the first four years of life. Whilst there was no response inhibition improvement from 10- to 16-months, there was substantial change in the brain regions that were more active when inhibition was required at 16-months. By early childhood, response inhibition performance had significantly improved, yet there was some commonality in the brain regions recruited when inhibition was required at both 16-months and 3½ years. Chapter 7 presents a longitudinal examination of the development of 'hot' and 'cool' inhibitory control and investigates predictive associations with pre-academic skills in early childhood. Whilst there was some consistency in inhibitory control performance between tasks in infancy and early childhood, there was no evidence of longitudinal stability across development. Significant associations were found between 'hot' inhibitory control and early academic skills at 3½ years, suggesting that early inhibitory control skills may have an important role in early numeracy and language skills in the preschool years. Finally, Chapter 8 includes a discussion of the contributions this thesis makes to the field and evaluates the strengths and limitations of this research.





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Chapter 1

General Introduction

The early years of life are abundant with developmental milestones – the first year sees the strengthening of motor skills and the ability to walk, the second year of life brings language, expression and understanding, and by the third and fourth years, this walking, talking, human is eagerly seeking independence and social connection with peers, yet is still learning to regulate and control their behaviours. Underscoring this rich developmental period is the emergence and development of executive functions (EFs); fundamental cognitive skills that serve to guide goal-directed behaviours.

Three core components of EF are commonly described within the literature (Diamond, 2013; Lehto et al., 2003; Miyake et al., 2000): *inhibitory control*, which is broadly defined as the exertion of control over thoughts, actions, and behaviours, *working memory*, referring to the ability to store and manipulate information in mind, and *cognitive flexibility* which facilitates mental agility and the ability to switch between different thoughts and actions. EFs are a set of correlated but differentiable executive processes that enable us to pay attention, resist temptation, think flexibly, and retain and manipulate mental information (Diamond, 2013; Miyake & Friedman, 2012). As such, EFs are fundamental for success in much of our everyday life and have been shown to predict a wide range of outcomes such as school readiness (Blair & Raver, 2015; Blair & Razza, 2007; Fitzpatrick & Pagani, 2012; Mann et al., 2017), academic achievement (Becker et al., 2014; Best et al., 2011; Bull & Scerif, 2001; Willoughby et al., 2011), and even physical health, criminal activity, and substance dependence (Moffitt et al., 2011).

Early EF skills emerge in infancy, can be reliably measured from the second half of the first year (Courage et al., 2006; Holmboe et al., 2018), and rapidly improve across toddlerhood and early childhood (Friedman et al., 2011; Garon et al., 2008, 2014; Hendry et al., 2016). This early developmental period also reflects an important time for the structural and functional maturation of the prefrontal cortex (PFC), an area of the brain that has been consistently associated with EFs (Diamond, 2002; Fiske & Holmboe, 2019). Yet very little is understood about how the development of the PFC (and other cortical regions) supports the rapid improvement of EFs during the first years of life.

Although working memory (and to some extent cognitive flexibility) can also be measured in infancy (Káldy & Sigala, 2004; Kovács et al., 2009; Reyes et al., 2020; Wijeakumar et al., 2019), this thesis will focus specifically on examining the behavioural development and neural correlates of early inhibitory control across the first four years of life. There are three main reasons for this specific focus. Firstly, whilst there is a foundation of knowledge about the emergence of rudimentary inhibitory skills already in infancy (e.g., Bell & Adams, 1999; Cuevas, Swingler, et al., 2012), much of this research centres around one task (the A-not-B task) and understanding is limited about *how* these skills develop longitudinally across the early years of life. Secondly, much of the existing research about the neural correlates of early inhibitory control development has come from electroencephalography (EEG) studies (e.g., Bell, 2001, 2012; Bell & Fox, 1992, 1997; Morasch & Bell, 2011) that have established important links between the PFC and inhibitory control in infancy. However, due to the limitations of EEG, these studies have been unable to identify specific regions of the PFC (and indeed other cortical regions) as neural correlates of early inhibitory control. Thirdly, from a theoretical perspective, there is evidence to suggest that, in childhood and adulthood, inhibitory control processes and their associated neural correlates are not separable from a 'common EF' (Friedman & Miyake, 2017; McKenna et al., 2017; Miyake & Friedman, 2012). However, there is limited evidence regarding the structure and organisation of inhibitory control in the first years of life. As such, this thesis aims to investigate the development and structure of inhibitory control and to identify the associated neural correlates, from infancy and across early childhood.

In this current chapter, I will review what is known and what is not yet understood about the development of EF in the early years of life and the cortical mechanisms that may underpin this development. Note that I have authored a published review on the neural substrates of early EF development (Fiske & Holmboe, 2019) which provides a broader coverage of this topic. In comparison, in this chapter, I will present a more focused review of existing literature on early inhibitory control development (specifically highlighting how inhibitory control is measured in this population) to identify key gaps in knowledge and discuss potential methodological reasons for these knowledge gaps. Following this, I will examine theories of functional brain development against the backdrop of EF development. Then, I will describe research into the neural correlates of early EF (with a focus on inhibitory control), specifically emphasising how functional near-infrared spectroscopy (fNIRS) can be employed in developmental cognitive neuroscience to answer questions about how functional brain development may be associated with early EF skills. Finally, I will close this chapter with a broad overview of the key aims of this thesis and the content of upcoming chapters.

1. Defining and Measuring Early Inhibitory Control

Inhibitory control is an EF skill that enables the exertion of control over thoughts, actions, and behaviour. Simple versions of inhibitory control emerge early in infancy and can be reliably measured in the second half of the first year (Clearfield et al., 2006; Diamond, 1985; Holmboe et al., 2008, 2018), and more sophisticated inhibitory skills continue to develop across early childhood (Cuevas & Bell, 2014; Hendry et al., 2016; Moilanen et al., 2010). Early inhibitory control is predictive of several outcomes later in life, such as self-regulation (Nigg, 2017), academic skills (Bull & Scerif, 2001; St Clair-Thompson & Gathercole, 2006), adolescent EF (Friedman et al., 2011) and health and wellbeing in adolescence and adulthood (Anzman-Frasca et al., 2015; Moffitt et al., 2011).

This section will provide an in-depth examination of inhibitory control as a multi-faceted construct, discuss methodological limitations concerning the measurement of inhibitory control in early development, and review existing literature that has provided knowledge about the emergence and development of inhibitory control from infancy and across the first four years of life.

1.1. Defining Inhibitory Control

To define inhibitory control, it first must be considered how inhibitory control may (or may not) be separable from the other EF skills. The unity and diversity theory of EF was proposed by Miyake et al. (2000) to explain how individual differences in measures of shifting, updating (working memory), and inhibition were moderately correlated (unity), yet were distinct processes (diversity). In this model, *shifting* is defined as the flexible switching between mental sets, *updating* refers to the refreshing of information in working memory, and *inhibiting* is characterised by the inhibition or stopping of prepotent responses (Miyake et al., 2000). Following a large body of research that included twin studies, this model was updated in line with the evidence, such that, a *common EF* factor represents the unity (i.e., shared variance) between each of the three EFs, and two specific factors (updating-specific, shifting-specific) that reflect the diversity (i.e., distinct components) in EF (Miyake & Friedman, 2012). Interestingly, there is no specific factor for inhibition, which according to Miyake & Friedman (2012), was virtually undistinguishable from the common EF factor.

Whilst debate still exists about the structure of EF, it is understood that inhibitory control is a multi-faceted construct, and there have been several attempts to define and conceptualise this within the literature. At a basic level, inhibitory control can be dichotomised into ‘simple’ and ‘complex’ inhibition and researchers have designed several tasks to assess these constructs. As defined by Petersen et al. (2016), simple inhibitory control tasks do not have

many working memory demands and often focus on the delay of a response (i.e., delay of gratification type tasks) or the inhibition of a prepotent response, whereas complex inhibitory control tasks involve conflict and require working memory to remember task-relevant rules (i.e., age-appropriate Stroop tasks, 'Simon Says' type tasks, Reverse Categorisation, and Spatial Conflict tasks). Evidence supports the emergence of simple forms of inhibition already in infancy. For example, research has demonstrated the ability of young infants to inhibit visual saccades to distractors (Holmboe et al., 2008; Johnson, 1995), and other studies have shown that infants can inhibit a prepotent motor response towards the end of the first year of life (Bell & Adams, 1999; Clearfield et al., 2006; Diamond, 1985; Fiske et al., 2022; Hendry et al., 2021). With development into early childhood, more complex forms of inhibitory control begin to emerge, such as interference control (i.e., preventing interference from distractors; Montgomery & Koeltzow, 2010), the ability to resolve conflict (Gerardi-Caulton, 2000) and delay of gratification (Mischel et al., 1989).

According to Nigg (2000), several inhibitory systems have been defined and studied in the fields of psychology and neuroscience. These were: interference control (prevent interference from competing stimuli), cognitive inhibition (suppressing irrelevant thoughts in service of working memory), behavioural inhibition (suppressing a prepotent or automatic/habitual response), oculomotor inhibition (suppression of reflexive saccades), and attentional inhibition. This view is echoed by Diamond (2013) who defines inhibitory control as a form of interference control at the levels of attention (i.e., selectively attending to target stimuli whilst suppressing attention to irrelevant stimuli), cognition (i.e., suppressing irrelevant thoughts) and behaviour (i.e., self-control, resisting temptation and impulses). Diamond (2013) also describes a form of inhibition that is needed to delay gratification (i.e., exerting control to resist immediate reward in favour of a greater reward later). Taking another approach to defining inhibitory control at the neural level, Munakata et al. (2011) describe two distinct inhibitory mechanisms within the PFC. Here, 'indirect competitive inhibition' refers to the suppression of one response (inhibition of some brain regions) in favour of another (excitation of goal-relevant brain regions), and 'directed global inhibition' as the suppression of action, thought or behaviour (i.e., stopping; inhibiting processing in that brain region) (Hendry et al., 2021; Munakata et al., 2011).

A further conceptualisation within the literature attempts to separate aspects of inhibitory control into 'hot' and 'cool' components – where 'hot' inhibitory control involves exerting control in affective or motivationally salient contexts (such as delay of gratification), and 'cool' inhibitory control refers to the employment of control in affectively neutral contexts (Zelazo & Carlson, 2012). Researchers have employed this taxonomy in studies with young children, finding differing contributions of hot and cool inhibition to aspects of behaviour (Di

Norcia et al., 2015; Draperi et al., 2022; Lui et al., 2021), and there is some evidence to suggest that hot and cool EFs may be processed by different areas of the cortex (Perone, Almy, et al., 2018; Salehinejad et al., 2021).

Chapter 2 of this thesis will provide an overview of the methods used to study inhibitory control in infancy and early childhood, and Chapter 3 will focus on fNIRS as an important tool for the study of the neural correlates of inhibitory control in early developmental populations. Chapters 4, 5, and 6 of this current thesis will focus specifically on the development and neural correlates of response inhibition, which is the ability to inhibit a prepotent or well-learned response (Friedman & Miyake, 2004). Although there are many forms of inhibitory control (as described above), response inhibition is commonly assessed in developmental research since it can be reliably measured from its emergence in infancy and as it develops across the first years of life (Holmboe et al., 2021). Chapter 7 of this thesis explores longitudinal and concurrent relations between different facets of 'hot' (prohibition and delay of gratification) and 'cool' inhibitory control (response inhibition) measured in both infancy and early childhood.

1.2. Measurement of Early Inhibitory Control

The assessment of early EFs in developmental populations comes with a complex set of difficulties relating to task design and other methodological factors, as well as the challenges relating to recruiting and assessing infants, toddlers, and young children (i.e., increased data attrition and lower signal to noise ratio due to fussiness, distraction, short attention span, spontaneity of behaviour; see Spit et al. (2023) for discussion of task engagement and non-completion in developmental studies). This has led to a lack of research studies that have examined early EF, compared to a large number of studies that examine mature EF in older children and adults. The current section will outline and discuss these challenges, both within the context of the broader measurement of EF and specifically regarding the measurement of inhibition in early developmental populations.

1.2.1. The Task Impurity Problem

As highlighted in their influential unity and diversity paper, Miyake et al. (2000) outlined the "task impurity problem" as a common challenge within EF research. This is where tasks designed to measure a specific component of EF may be drawing on more than one EF skill or require other higher-order resources such as attention or language (Miyake et al., 2000). One example of this from the developmental literature is the classic A-not-B task (Diamond, 1985; Diamond & Goldman-Rakic, 1985; Piaget, 1954) that has been used consistently with

infant participants, originally as a measure of object permanence (representing an object in mind even when it is out of sight). This task requires the experimenter, in view of the infant, to hide an attractive object (e.g., a toy) in one of two locations (e.g., location 'A'). Then, after a delay, the infant is allowed to search for the object. Several trials are administered where the object is hidden in location 'A' to enable the infant to establish a prepotent motor response to this location. Then, the object is hidden in location 'B' and the infant is required to exert their inhibitory control ability to overcome the prepotency and instead find the toy in the alternative location.

However, since this task also imposes a delay between the hiding and the searching event it introduces a working memory demand. As such, it could be argued that the demands of the task tax both inhibitory control and working memory skills (Diamond, 1985). This has caused problems in the literature (Smith et al., 1999), as it is not always clear whether the task that has been described by one author to measure 'inhibition' is truly measuring inhibition (i.e., Hendry et al., 2021) when it has been used by another author to measure 'working memory' (i.e., Bell, 2012). Indeed, it is often impossible to remove working memory demands from tasks that are designed to assess other EF skills. As soon as there are instructions that define the task goal (however simple or intuitive), working memory is required to maintain them. As such, the measurement of performance on EF tasks can become impossible to disentangle from general working memory ability. It also becomes challenging to examine models of EF structure as some of the shared variance between tasks that are captured in the 'common EF' factor for example (Miyake & Friedman, 2012) may be explained by "impure" tasks that assess multiple EFs. For example, research by Wiebe et al., (2008, 2011) examining the factor structure of EF in preschoolers found that a single unitary factor was the best fit for the data, however, this could be driven by the working memory demands tied into the rules of the EF tasks. When designing tasks to examine EF in infants and young children, it is important to ensure that task rules and instructions are as simple as possible to minimise the working memory demands associated with simply remembering the task instructions.

Another facet of the task impurity problem is where individual differences in task performance may reflect other non-executive abilities that are required to complete the task (i.e., motor skills) (Wiebe et al., 2011). For example, several EF tasks designed for adults require a motor response, which is still undergoing development in the first year of life and can be highly variable throughout early childhood (Malina, 2004). According to Wiebe et al. (2011), tasks that are used to measure early EFs must also consider the variability in prior experience, language, and attention of this population, and as such, recommends that tasks are simple, have minimal instructions, and draw on everyday concepts that are common and

familiar to the specific age of children. From these recommendations and methodological considerations, a task battery designed specifically to examine EF in 3-year-olds was created by Wiebe et al. (2011) and EF tasks were found to be age-appropriate and reliable in this population. This highlights another problem within the development literature, in that researchers are often forced to design new tasks or make adaptations to existing tasks (designed for adults) to ensure they are appropriate and reliable measures of EF in younger populations.

To overcome some of the methodological challenges related to the task impurity problem, developmental researchers have opted to assess early EF through a battery of age-appropriate tasks, rather than relying on one task to index EF. In this way, researchers can vary the demands of tasks within the battery (i.e., differing presentation and response modalities, task length, and language and attentional demands), and adopt a latent variable approach to the data. For example, shared variance in performance on multiple tasks thought to measure inhibitory control can be used as an indicator of a latent variable that is considered a 'purer' measure of inhibition than performance on a single task (Wiebe et al., 2011). Although, it is worth noting that this is not the only approach to measuring EFs early in development. It is also valuable and informative to conduct research using a single task or measure and to assess performance improvements on this task over time (Clearfield et al., 2006; Hendry & Holmboe, 2021; Holmboe et al., 2021; Wiebe et al., 2012). Likely, a combination of research that uses a single task and research that uses a task battery is the best way for the field to learn more about how inhibitory control functions across development.

An example of the task battery approach comes from a longitudinal study by Broomell and Bell (2022), who used a multitude of inhibitory control tasks (among other EFs) that were appropriate for the age of participants at each assessment point. In infancy (5- and 10-months), inhibitory control was measured using a looking version of the A-not-B task. In toddlerhood and early childhood (24-, 36-, and 48-months), measures covered both 'cool' and 'hot' aspects of inhibitory control. To examine the ability to inhibit a prepotent response ('cool' inhibitory control), children completed: the Day / Night task (saying the opposite; Gerstadt et al., 1994), the Yes / No task (saying the opposite; Wolfe & Bell, 2004), and the 'Simon Says' task (follow instructions given by one character and ignore the instructions of another character; Kochanska et al., 1996). At 9 years old, children also completed the 'Number Stroop' task (Ruffman et al., 2001) where they were required to inhibit the prepotent response of naming the number and instead count the number of digits. 'Hot' inhibitory control was measured in early childhood using tasks that assessed the ability of children to follow a prohibition or delay gratification, such as the 'Tongue task' (delay gratification by

holding a food item on their tongue; Kochanska et al., 2000), the 'Crayon Delay' task (prohibition/delay of gratification; Calkins, 1997) and the 'Gift Delay' task (prohibition/delay of gratification; Kochanska et al., 1998). The authors took a latent variable approach and performed confirmatory factor analyses, finding that a single latent EF factor best fits the data at all age points.

1.2.2. Task Development

Within the literature, several well-validated tasks have been used to reliably measure inhibitory control. However, it is not always possible to use these tasks (that have been designed to assess inhibitory control in adults) with developmental populations. For example, the Go / No-Go task (Drewe, 1975) is a classic measure of response inhibition. This task encourages the development of a prepotent motor response to frequent 'Go' stimuli and requires participants to inhibit this response when they see the infrequent 'No / Go' stimuli. Similarly, the Stop Signal task (Logan & Cowan, 1984) measures response inhibition by encouraging participants to make a response to the target stimuli, but when the target stimuli are accompanied by the stop signal (usually an auditory tone or a second visual stimulus), the participant must inhibit the already prepared motor response. Whilst such tasks may appear simple, the task demands are inappropriate for infants and young children. For example, these tasks rely on the participant to understand task instructions (e.g., requiring language comprehension and working memory), complete high numbers of repetitive trials (e.g., requiring sustained attention over time), and respond within a given time limit (e.g., to maintain the pace of responding / maintenance of the prepotency).

To achieve a reliable measure of inhibitory control in infants and young children, novel tasks have been developed that avoid or minimise these factors (Garon et al., 2014; Holmboe et al., 2008, 2021; Howard & Melhuish, 2017; Wiebe et al., 2011). However, a meta-analysis by Petersen et al. (2016) highlighted the need for tasks and assessments that, with gradual modifications, can reliably measure inhibitory control across development. This is because many studies measuring inhibitory control demonstrated ceiling and floor effects and found that the same task could only be used on average to assess inhibitory control across three years. Describing inhibitory control development as showing "heterotypic continuity" (continuing to have the same function or purpose across development but changing the way it appears in behaviour), Petersen et al. (2016) highlighted the need for different tasks that can capture inhibitory control appropriately both within age groups and across development. However, there exists some debate in the literature, particularly in longitudinal research, regarding whether inhibitory control tasks should be gradually changed across development

to remain age-appropriate (Petersen et al., 2016), or whether tasks should be designed so that, with minor modifications to increase the difficulty, they can be used consistently across the lifespan (Holmboe et al., 2021). Both approaches have their advantages and disadvantages. For example, gradually changing tasks to be appropriate for the age and stage of participants can minimise floor and ceiling effects but it is difficult to assess change in performance with development. Whereas keeping tasks structurally similar (or the same) across development is more challenging from a task design/selection perspective (and one must be wary of ceiling and floor effects), but it allows for a more reliable picture of performance change with age (e.g., Holmboe et al., 2021).

Even when age-appropriate tasks are used to assess EF in developing populations, some studies have shown how modifications of task demands can change outcomes. For example, Simpson et al. (2012) investigated prepotency in 3- and 4-year-old children by examining performance on the Day / Night task (a verbal measure of response inhibition where children say 'day' when they see an image of the night, and vice versa) and on a child-friendly version of the Go / No-Go task. By varying task demands across conditions, Simpson et al. (2012) found that children's performance was improved by imposing a delay between stimulus and response (such that there is time for the incorrect prepotent response to decay) and was not hindered by semantically similar responses. This result supports the earlier findings of Diamond et al. (2002), who also found that imposing a delay before answering improved the performance of 4 and 4½-year-olds on the day-night task, even when children were distracted during the delay period.

However, research examining potential performance differences between the looking and reaching versions of the A-not-B task found no significant difference between task modalities in 8-month-old infants (Bell & Adams, 1999). This finding is interesting, as whilst the demands of the tasks are very different – the looking version is more passive, and requires only an eye movement, whereas the reaching version involves an active motor response – the cognitive skills required do not differ. Again, varying the task demands in the A-not-B task, Smith et al. (1999) investigated how infants' inhibitory performance changed when conditions changed and contributed important conclusions about the task dynamics that influence the A-not-B error in infancy, providing evidence that it is the action of reaching (not the knowledge of the object) that is biased by the prepotency. Overall, this evidence highlights the importance of considering methodological factors when developing or adapting existing tasks to measure EF in developmental populations.

2. The Development of Early Inhibitory Control

The following sub-sections of this chapter will review literature that follows the developmental trajectory of inhibitory control from its emergence in infancy (defined here as the first year of life), across toddlerhood (the second and third years), and to the rapid progression in inhibitory abilities observed in early childhood (3 – 6 years of age). This overview of the literature will describe what is already known and highlight what is not yet known about the development of early inhibitory control.

2.1. Infancy

Relatively few studies exist that have measured inhibitory control in infants – this is in part due to the methodological limitations described above (e.g., lack of age-appropriate tasks), the limited abilities of infants (e.g., motor and language skills still developing) as well as the general challenges that come with testing early developmental populations. As such, knowledge of inhibitory control skills in the first year of life is limited. However, there is a growing body of evidence that demonstrates the emergence of rudimentary inhibitory control skills already in infancy, such as the ability to control visual attention and motor responses (Clark et al., 2016) from as early as 6-months of age (e.g., Clearfield et al., 2006; Courage et al., 2006; Holmboe et al., 2018).

The A-not-B task (described above) (Jacobsen, 1935; Piaget, 1954) is a canonical, well-validated measure that has been used consistently to examine infant inhibitory control. Early research by Diamond and colleagues (Diamond, 1985; Diamond & Goldman-Rakic, 1989) has demonstrated that infants can engage with this task from as young as 6-months of age and can sustain increasing delays without perseveration from 6 – 12 months. Although the presence of a delay on this task introduces a working memory demand, research has shown that the task can measure inhibition through the strength of the prepotent response that is established, even on versions of this task that did not include a hiding event (i.e., just cued a location; Clearfield et al., 2006; Smith et al., 1999) and that the task is still effective at capturing a robust perseverative response where there was no delay (Hendry et al., 2021). Clearfield et al. (2006) present evidence that 5 – 6-month-old infants do not display the perseverative error on the A-not-B task, and that perseveration emerged by 7 – 8 months of age. The authors describe the developmental trajectory of perseverative reaching in that younger infants' behaviour exists in the "here and now", whereas older infants' behaviours are tied to previous responses (i.e., prepotent reaches). Further highlighting the robustness of the behavioural response pattern, research has shown that infants make perseverative

responses on both the traditional reaching version and the looking version of the A-not-B task (Bell & Adams, 1999).

Early research by Johnson (1995) demonstrated that infants as young as 4-months of age were able to inhibit automatic saccades to distractors. Whilst this could be an indication of one of the earliest forms of inhibitory control in infancy, it is worth noting that around half of the infants in the sample did not reliably orient to the cue (used to predict the target location) at the start of the experiment. Similarly, this task is not sensitive to individual differences in performance (Holmboe et al., 2008). Advancing this line of enquiry, research by Holmboe et al. (2008, 2018) used a novel eye-tracking task and found that infants aged 6 – 9 months can inhibit looks to distractors. In their 'Freeze-Frame' task, an animation is played in the centre of the screen when infants look at it and paused when infants make visual saccades to distractor stimuli. These studies found that infants look at distractors less on 'interesting' trials (children's cartoons) than on 'boring' trials (moving shape) (Holmboe et al., 2008, 2018), and demonstrated that Freeze-Frame performance at 6-months directly predicted performance at 9-months of age (Holmboe et al., 2018). This suggests that infants can selectively inhibit looks to distractors from as young as 6-months of age and that there is some stability in oculomotor inhibitory control performance across the second half of the first year (Holmboe et al., 2018). Further research by Holmboe and colleagues (Hendry et al., 2021; Holmboe et al., 2021) has used the Early Childhood Inhibitory Touchscreen Task (ECITT) to measure the inhibition of a motor response in infants as young as 10-months of age. Results from these studies demonstrate that infants are significantly more accurate at responding on prepotent trials than on trials where there is an inhibitory demand. Interestingly, performance on the ECITT does not show stability from late infancy (10-months) to early toddlerhood (Hendry et al., 2021), but is stable across toddlerhood from 18 – 21 months, and 21 – 24 months (Holmboe et al., 2021). This task will be described in full and is used as a measure of response inhibition in Chapters 4 – 7 of this thesis.

Hendry et al. (2021) presented a battery of inhibitory tasks developed for use in infancy, which included the A-not-B task and the ECITT as measures of response inhibition (described as a facet of 'competitive inhibition' in their paper; see Section 1.1. above). In addition, they employed two prohibition tasks (Toy Prohibition and Touchscreen Prohibition) designed to capture 'directed global inhibition' in infants as young as 10-months of age. Prohibition tasks are a measure of 'hot inhibitory control' and are designed to measure the ability of the infant to refrain from touching something attractive when they are instructed not to (i.e., glitter wand toy, frog cartoon on a touchscreen). Similar tasks have been used successfully in naturalistic settings with infants aged 8 – 10 months (Kochanska et al., 1998), in which an attractive everyday object was placed near the infant and mothers were

instructed to tell their child “No” when they attempted to touch it. The results of this study provided evidence for the need to use multiple indices of inhibitory control to capture important individual differences and concluded that inhibitory control was not yet stable in the infancy-toddlerhood transition (Hendry et al., 2021).

2.2. Toddlerhood

The second and third years of life mark an important period for developmental change and are characterised by improvement in a multitude of skills such as joint attention (Tomasello, 2007), self-regulation (Gago Galvagno et al., 2019; Kochanska et al., 1998), language (Gilkerson et al., 2018), and early EF skills (Miller & Marcovitch, 2015). However, despite evidence suggesting that these early years represent a distinct period for the development of early EF skills (Hendry et al., 2016; Miller & Marcovitch, 2015; Mulder et al., 2014), the challenges related to the assessment and measurement of early inhibitory control skills continue into the toddlerhood period. As a result, there is a significant lack of studies that have assessed inhibitory control (and EF more broadly) in the toddler years, specifically the second year of life. Knowledge gained from the limited literature has provided an informative foundation for our understanding of EF development in the toddlerhood period. Specific knowledge on inhibition across these toddler years is even more scarce, so the literature below will cover broader EF knowledge and focus on inhibition where possible.

Considering the transition to the second year as an important period of interest, Devine et al. (2019) studied EFs at 14-months of age and found a lack of coherence between measures of EF, although interestingly found that toddlers who performed better on the prohibition task (‘hot’ inhibitory control) also performed highly on the working memory and shifting tasks. Moving further into the first half of the second year, Miller and Marcovitch (2015) investigated the longitudinal stability of EF skills from 14 – 18 months of age. In this study, performance was assessed on a battery of EF tasks which included the A-not-B task (response inhibition / ‘cool’ inhibitory control) and a prohibition task (‘hot’ inhibitory control). Results revealed that EF performance improved from 14- to 18-months, but there was very little stability and coherence in EF measures across this developmental period. This finding is supported by Hendry et al. (2021) who similarly found a lack of longitudinal stability of performance on tasks measuring inhibition at 10- and 16-months of age (ECITT, A-not-B, and two prohibition tasks), and that associations between performance on the different inhibitory control tasks became more coherent at 16-months. Further corroborating evidence comes from important longitudinal research by Broomell & Bell (2022) who measured EFs across infancy (5-months, 10-months), toddlerhood (24-months, 36-months), early childhood (48-months), and

middle childhood (9 years). The results of this study found that from 24-months, EF performance can be predicted by performance at the previous time point. However, it is worth noting that only a single task was used to assess EF in infancy (A-not-B task), and no data was collected during the second year of life. Similarly, research by Carlson et al. (2004) observed moderate longitudinal stability in EF performance on a task battery including 'hot' inhibitory tasks (i.e., Snack Delay, Gift Delay) and 'cool' inhibitory tasks (i.e., Shape Stroop) from 24-months to 39-months. Overall, this body of evidence suggests that inhibitory control (and EFs more broadly) is not yet stable in infancy and becomes more coherent in the second year of life, but that it is not until the transition to the third year (e.g., 2 years of age) that performance becomes stable and predictive of later performance.

Contrasting findings were presented in research by Johansson et al. (2016), who conducted a longitudinal study examining individual differences in the development of sustained attention, and simple and complex EFs from infancy (12-months) and through toddlerhood (24-months, 36-months). Here a lack of stability in individual differences in EF performance was observed from 24 – 36 months (despite the use of consistent measures), and whilst it was found that infant attention and EF predicted later EFs at 36-months, this was not true at 24-months. The authors theorise that significant development of EF skills is still occurring at 24-months and is influenced by the co-development of other task-related abilities (i.e., language and motor skills) that may introduce significant variation into the task performance, whereas by 36-months, this variation has decreased and performance on EF tasks becomes more coherent (Johansson et al., 2016). However, the contradictory findings could also be related to the use of different tasks to assess EF by the different research groups. There is often very little overlap between EF batteries and task protocols are not regularly shared between groups (so even if the same tasks were administered, it cannot always be checked that they were administered in the same way).

A notable effort to overcome the lack of age-appropriate tasks to measure EFs in the toddlerhood period comes from Mulder et al. (2014) who developed and evaluated a task battery specifically for this population. This battery was tested on a large sample of 2 – 3-year-olds (N = 2437) and included measures of both 'hot EF' (snack and gift delay tasks) and a range of 'cool EF' tasks (working memory tasks; parent- and teacher-reported measure of inhibitory control). Considering the scarcity of knowledge on EF development in this population, this ground-breaking study significantly advanced the existing knowledge on EFs in 2-year-olds, including the ability of children to complete these tasks, identification of a two-factor structure of EF (labelled as 'hot' and 'cool' EF) and demonstrating the predictive association of cool EF skills on later academic skills, and of hot EF skills on behavioural problems (Mulder et al., 2014). Further, this paper demonstrated the psychometric validity of

the tasks included in the battery for the measurement of early EF skills, thus providing a battery of age-appropriate tasks that can be used in future research (Mulder et al., 2014). Similar significant efforts have been made by Hughes & Ensor (2007) who assessed 2 – 4-year-olds on a battery of EF tasks (this included age-appropriate variations of the Stroop task as a measure of inhibition). Firstly, the authors noted the suitability of measures for this age as evidenced by the high completion rates, and then highlighted the significant performance improvements from 2 – 4 years, with significant stability in individual differences across this period. Later work by these authors also highlights longitudinal associations between poor EFs at 14-months and externalising behaviour at 24-months (Hughes et al., 2020). In summary, these studies provide a battery of age-appropriate tasks that evidence the feasibility of measuring EFs in toddlerhood and again highlight the fundamental importance of early EF skills in that they are predictive of a range of academic and behavioural outcomes.

Focusing specifically on inhibitory control development in the toddler period, Gandolfi et al. (2014) investigated early inhibitory processes in two groups of children (24 – 32 months, and 36 – 48 months). The authors used a battery of inhibitory tasks that included age-appropriate behavioural measures of response inhibition and interference suppression to examine the profile of the latent structure of inhibitory control in toddlerhood. Whilst a unitary model of inhibitory control was found to best fit the data from the 24 – 32 month sample (i.e., a single inhibitory process), a two-factor model was most appropriate for the performance of children in the 36 – 48 month sample (i.e., separable response inhibition and interference suppression dimensions); although note that the two factors were strongly correlated. Gandolfi et al. (2021) interpret their results as evidence that inhibitory processes are unitary before 3 years of age, but that inhibitory processes become more distinct after the age of 3L. The authors propose a ‘sequential development of inhibitory control’ whereby early inhibitory control is centred on response inhibition (a simple inhibitory process) whereas in toddlerhood and early childhood, more complex inhibitory processes develop such as that needed to control and suppress interference (Gandolfi et al., 2021).

2.3. Early Childhood

It is well known that the preschool years represent a fundamental period for the rapid progression of EF skills (Clark et al., 2016; Garon et al., 2008, 2014). This is interesting, as this advancement in EF abilities coincides with the transition to formal schooling in many countries, and evidence has consistently supported the strong links between early EF and skills related to school readiness. For example, Kim et al. (2013) found evidence that ‘cool’

inhibitory control measured in young children (38- and 52-months) was predictive of later academic performance (aged 5 – 7 years), and that 'hot' inhibitory control was predictive of behavioural problems later in childhood. This finding is consistent with that of Willoughby et al. (2011), who also found that 'hot' EF was related to inattentive and overactive behaviours, whereas 'cool' EF was associated with academic achievement in 3- to 5-year-old children. Similarly, Morgan et al. (2019) found evidence from a large cohort study which suggested that poor inhibitory control in kindergarten (approximately 5 years old) was associated with an increased risk of academic difficulties in the first three years of primary education. There is even evidence from neuroimaging studies, such as the one from Whedon et al. (2020), which demonstrates that greater increases in electroencephalography (EEG) power in frontal regions across infancy and early childhood (10-months to 4 years) are associated with better inhibitory control skills at 4-years, and indirectly associated with better academic performance (reading, maths) at aged 6. It was found that better inhibitory control at age 4 may help to explain this indirect association (Whedon et al., 2020a).

Within the literature there is a significant disparity in the amount of research conducted on EFs in this pre-school period (i.e., 3 – 6 years) and those conducted in toddlerhood and infancy. This is largely due to the methodological limitations that have been previously highlighted, as now children are more compliant participants, can comprehend task instructions and pay attention for longer periods. As such, there is a large body of research that has demonstrated the marked age-related improvement of EF skills across this early childhood period (Clark et al., 2016). Regarding inhibitory control performance, evidence suggests that the ability to inhibit prepotent responses improves significantly across early childhood (Kochanska et al., 2000; Wiebe et al., 2012) and that children can withstand an increasing period of delay in the delay of gratification tasks over the preschool years (Carlson et al., 2004; Kochanska et al., 2000). It is argued by Clark et al. (2016) that fundamental changes in children's ability to exert control occur during this time, as is evidenced by age-related improvements in different facets of inhibition (assessed with varying task demands) that occur simultaneously in the preschool period.

Focusing specifically on the Go / No-Go task, a common measure of response inhibition used with this developmental population and with adults, Wiebe et al. (2012) examined the development of response inhibition performance from 3 – 5 years in a large sample of children. Results of this study firstly demonstrated that the most significant performance improvement was observed from 3 – 3.75 years of age, and secondly highlighted the positive relationship between working memory and general cognitive ability with more accurate response inhibition performance across this developmental period (Wiebe et al., 2012b). Finally, Wiebe et al. (2012) demonstrated an interesting interplay between the speed

of responses on the Go / No-Go task with working memory and general cognitive ability, such that higher performance was related to slower responding in younger children, but with faster responding later in this developmental period. More research is needed that carefully examines the interplay between speed, accuracy, and EFs (as well as general cognitive function) and how this dynamic changes across development. For example, many developmental researchers focus only on accuracy measures as indices of EF but may be missing important information about processing speed that can speak to individual differences in EFs (Dougherty & Haith, 1997; Hendry et al., 2016; McAuley & White, 2011).

A longitudinal study by Conejero et al. (2023) examined the predictive association of early attention (9- and 16-months) on inhibitory control in early childhood (2, 3, and 5 years). The authors examined inhibitory control using both 'hot' and 'cool' inhibitory control measures. The 'hot' measures included delay of gratification tasks such as Snack Delay (Kochanska et al., 2000) and a 'Less Is More' task (i.e., choosing between having a smaller reward now, or a larger reward later)). The 'cool' measures were the Spatial Conflict task (Gerardi-Caulton, 2000) which requires children to respond to targets in either spatially congruent or spatially incongruent locations, and the Go / No-Go task (which was administered only at 5 years). The results of this study indicated that early attention in infancy was associated with individual differences in inhibitory control in early childhood (2 and 5 years), and that inhibitory control at 2 years (but not at age 3) predicted later inhibitory control (5 years) (Conejero et al., 2023). There is evidence to suggest that different facets of inhibitory control (i.e., 'hot' and 'cool' aspects, or 'delay' and 'conflict' tasks) may have different patterns of development in early childhood (Joyce et al., 2016), and so it is possible that performance on delay and conflict tasks in toddlerhood would not be related to response inhibition performance in early childhood (i.e., Conejero et al., 2023). It is worth noting, however, that in the study by Conejero et al. (2023), only one 'hot' and one 'cool' task was used at each assessment point, and these tasks were different at each time point (although somewhat structurally similar). As such, the results may be influenced by inherent task-related factors, and so highlights again the need for increased consistency of measures that can be used across this early developmental period (Carlson et al., 2016; Hendry et al., 2016; Holmboe et al., 2021).

It is also during these years that more complex and sophisticated EF skills emerge, such as the ability to think flexibly to resolve conflict and follow rules (i.e., cognitive flexibility). Evidence for this comes from research involving the Dimensional Change Card Sort (DCCS) task (Zelazo, 2006; Zelazo et al., 1996; Zelazo & Frye, 1998), whereby children are required to sort cards by one rule (i.e., sort the cards by the shape of the object on the card) and then after sorting several cards, switch to follow a new rule (i.e., sort the cards by the colour of the

object). Research using this task has found age-related improvements across the early childhood period, whereby 2-year-olds typically sort cards randomly, most 3-year-olds can sort cards by one rule but are unable to switch to follow the new rule (Zelazo et al., 1996), and many 4- and 5-year-olds can flexibly switch (Zelazo, 2006). This has been further corroborated by Clark et al. (2013) who used the 'Shape School' task (Espy, 1997) to examine changes in inhibitory control and cognitive flexibility skills from 3 – 5 years of age. This task is presented in a storybook format with conditions that require children to inhibit prepotent verbal responses (i.e., only say the colour of 'people' with happy faces) and to use cognitive flexibility to switch between rules (i.e., saying the colour for people with happy faces, and the shape for people wearing hats). The results of this study demonstrated age-related improvements in both inhibition and cognitive flexibility (particularly between ages 3 and 4), but that improvements in inhibition happened faster than improvements in switching. The authors also reported interesting qualitative changes as children got older with regard to error detection and self-correction during the task (Clark et al., 2013).

Overall, these studies provide evidence for the development of more sophisticated and integrated EF skills across the early childhood period (Howard et al., 2015) and begin to evidence the emergence of monitoring and strategy use as children become more able to exert control over their attention to monitor goal-relevant environmental cues. It has been argued that this represents a shift in modes of control employed by young children, from a reactive to a more proactive exertion of control such that control is exerted in anticipation instead of in response to events (Chatham et al., 2009; Chevalier et al., 2015; Clark et al., 2016; Waxer & Morton, 2011).

3. Early Executive Functions and the Developing Brain

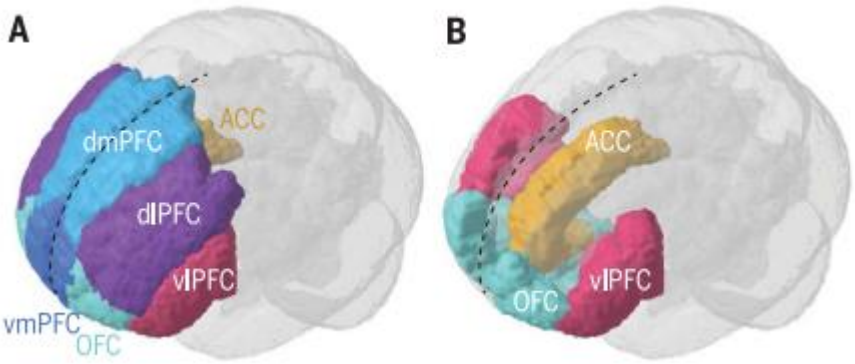
Underpinning the substantial EF development in the early years of life is the structural and functional maturation of the prefrontal cortex (PFC), an area of the brain that has been consistently associated with higher-order executive processes (Diamond, 2002; Fiske & Holmboe, 2019). Similarly, there is increasing evidence to support the role of the parietal cortex (Cai et al., 2016; Kolodny et al., 2017; Tamnes et al., 2013), as well as a frontoparietal network (Aron et al., 2007; Klingberg et al., 2002; Niendam et al., 2012), as key neural substrates of EF. Over the last two decades, developmental cognitive neuroscience researchers have become increasingly interested in the role of the PFC and the parietal cortex, as well as broader networks between these regions and other brain areas (e.g., Reyes et al., 2020), in facilitating the development of EF in infants and young children. This research serves to better understand the mechanisms through which neural processes

and cognition interact as EF skills emerge and develop early in life. However, until relatively recently, it has been difficult to examine the neural correlates of EF in developmental populations. As such, there are fundamental gaps in the literature whereby very little is known about the neural correlates of early EFs in infancy and toddlerhood (for review, see Fiske & Holmboe, 2019). The current section of the chapter will review knowledge about the development of the prefrontal and parietal cortices in the first years of life and examine neuroscientific theories of EF development. An overview of research that has investigated the neural correlates of early EF will also be provided.

3.1. Brain Development and Executive Function in the First Years of Life

The cerebral cortex of the human brain is divided into four lobes: the frontal lobe, the temporal lobe, the parietal lobe, and the occipital lobe. Broadly, the frontal lobe is responsible for higher-order processes such as EFs, attention, learning, language and speech, social behaviour, and voluntary movement. The PFC is located within the frontal lobe and accounts for almost one-third of the cerebral cortex (Carlén, 2017). There are several regions within the PFC that each have different functions in relation to complex behaviour. Although anatomic labels differ, these are commonly referred to in terms of their organisation within the PFC (see **Figure 1**). The PFC is one of the last brain regions to reach maturity, following a protracted developmental trajectory and taking over two decades to reach full structural and functional maturity (Diamond, 2002; Fiske & Holmboe, 2019). Of particular interest is the commonly observed parallels between the development of the PFC and improvements in cognitive abilities observed in childhood and adolescence (Bathelt et al., 2017, 2018; Fiske & Holmboe, 2019; Gibson, 1991; Gogtay et al., 2004; Goldman-Rakic, 1987; Romine & Reynolds, 2005). As well as this, the functional connections within the PFC and between the PFC and other brain regions (e.g., the parietal lobe in the context of EF) are rich and abundant, and evidence has suggested that it is the functional connectivity between the frontal and parietal cortices, or frontal regions and sub-cortical areas that support the development of EF (Aron et al., 2007; Buss & Spencer, 2014, 2018; Durston et al., 2002).

Figure 1. Chapter 1. Functional Division of the Human Prefrontal Cortex.



Note. Figure, figure caption and figure title are from Carlén, M. (2017). What constitutes the prefrontal cortex? *Science, 358*(6362), 478-482 (Figure 3). Reprinted with permission from AAAS. OFC (orbital frontal cortex), vmPFC (ventromedial prefrontal cortex), dmPFC (dorsomedial prefrontal cortex), dlPFC (dorsolateral prefrontal cortex), vlPFC (ventrolateral PFC), ACC (anterior cingulate cortex). Note that the ACC is considered by some to be a structure within the PFC.

Indeed, a fundamental component of the developing brain is the formation of functional connections both within the PFC and between the PFC and other cortical and subcortical regions. A body of research has evidenced the association between the PFC and other regions, particularly the parietal cortex, in the involvement of early EF abilities (Buss & Spencer, 2014, 2018). For example, Buss et al. (2014) highlighted that functional connectivity within a fronto-parietal network supported the development of visual working memory in 3- and 4-year-old children and that older children showed greater recruitment of parietal regions than younger children. Similarly, research by Mehnert et al. (2013) also found that short-range functional connectivity between right frontal and right parietal regions was stronger in children aged 4 – 6 years, whereas long-range connections between the bilateral PFC and parietal cortex were stronger in adult participants. This suggests that the strengthening of connections between the frontal cortex and other regions with development supports the age-related improvement of EF skills (for review, see Fiske & Holmboe, 2019).

Several theories of functional brain development have been proposed that are important for the consideration of how the maturation of the brain may support early EF development. For example, Johnson (2001) outlines three theories that may explain the link between brain maturation and cognitive advances. The ‘maturational perspective’ proposes that cognitive improvements are related to the anatomic maturation of specific cortical regions. The ‘skill-learning hypothesis’ argues that the neural basis of cognition changes depending on

whether the skill is being learned (through new experiences) or has been learned (expertise). The 'interactive specialisation approach' proposes two key processes through which the brain develops – first, that cortical regions become more specialised with development and second, that an organisational process occurs whereby brain regions interact and form networks that support cognitive development. The 'interactive specialisation' account has been further explored by Johnson (2011), who proposed that cognitive advancements in early development are associated with changes in neural networks, rather than in isolated brain regions.

A review of functional magnetic resonance imaging (fMRI) research by Durston & Casey (2006) described a shift from more global to local activation in the PFC during EF tasks across development, which may reflect the increased efficiency and specific functionality of prefrontal regions for executive processes (see also, Fiske & Holmboe, 2019). Based on a wealth of existing fMRI research, the 'adaptive neural coding framework' has been applied as a model that explains the structure of EF (Duncan & Miller, 2002; Duncan & Owen, 2000). This theory is described by Duncan & Miller (2002), who present evidence that functional neural activation within the PFC is not fixed for a specific purpose but rather is flexible or adaptive in response to the behavioural context. From the perspective of the structure of EF, Duncan & Owen (2000) highlight that the same, specific frontal network is recruited to support a range of cognitive executive problems. This common pathway includes the mid-dorsolateral prefrontal cortex (DLPFC), the mid-ventrolateral prefrontal cortex (VLPFC) and the anterior cingulate cortex (ACC); regions of the frontal cortex which are all recruited in response to varying cognitive demands (response conflict, novelty, working memory, and perception; Duncan & Owen, 2000). More recent neuroscientific evidence from Duncan (2010) emphasises the 'multiple demand system', whereby specific regions of the frontal and parietal cortex are recruited for a diverse range of executive demands. As such, the 'adaptive neural coding' model (when applied to the examination of EF structure) proposes that EF is a unitary, domain-general construct that is supported by a specialised prefrontal network that serves to facilitate an array of varied, executive processes.

A meta-analysis of functional neuroimaging data across childhood and adolescence (aged 6 – 18 years) has provided informative insights into EFs in the developing functional brain (McKenna et al., 2017). Studies included in the meta-analysis involved EF tasks that were designed to measure inhibition, switching, and working memory/updating. The results demonstrate that there is common neural activation across all tasks that were overlapping with, but distinct from, neural activation that was specific to each EF. Evidence suggested that this 'common' network involved bilateral regions of the prefrontal and parietal cortex, which aligns with the common frontal pathway highlighted in the 'adaptive neural coding'

framework discussed above. As well as the common network shared across all tasks, distinct neural correlates of updating and shifting (but not inhibition) were found, offering support for the unity and diversity model of EF (Miyake et al., 2000; Miyake & Friedman, 2012).

Using neural network models, Morton and Munakata (2002) also demonstrate how perseveration occurs in young children by describing the interaction between two memory systems. In their theory, perseveration occurs when memory systems are biased towards latent memory (based on experience; posterior regions), and new memories (active memory; PFC) are insufficient to overcome this bias (Morton & Munakata, 2002). Focusing specifically on inhibitory control and its relation to the PFC, Munakata et al. (2011) have proposed a 'unified framework' which highlights the unity and diversity principles even within a single facet of EF. It is argued that the PFC serves to support executive processes such as inhibition (unity) but that there are at least two distinct neural pathways that facilitate the inhibition (or excitation) of different brain regions (diversity). The authors highlight that the PFC initiates 'targeted global inhibition' over brain regions associated with memory processing and motor skills, whereas 'indirect competitive inhibition' is facilitated by the PFC to excite goal-relevant brain areas or representations (Munakata et al., 2011).

Recently, Kievit & Simpson-Kent (2019) outlined the value of longitudinal research for the examination of dynamic interactions between cognitive and neural development over time. They propose three theories that may explain these interactions. First, the 'structural scaffolding' theory argues that the change in cognitive performance is determined by the current neural architecture. Second, the 'cognitive plasticity' explanation is where the reorganisation of neural structures and functions is driven by advances in cognitive performance. The third theory proposes that changes in cognitive performance and neural architecture may be correlated (Kievit & Simpson-Kent, 2019). Finally, Astle et al. (2023) proposed a theory of 'computational neuroconstructivism' as part of a developmental systems neuroscience framework, which theorises that advances in cognitive processes create the opportunity for increased interactions between neuronal populations which results in the formation of neural networks. This work highlights how this novel computational modelling approach could be used to shape the future of developmental cognitive neuroscience. Specifically, by reducing the existing gap between neural and cognitive models of development.

3.2. The Neural Correlates of Early Executive Function Development

Within the field of developmental cognitive neuroscience there exists a “data desert” (Kerr-German et al., 2023) in that there is very little knowledge about the neural correlates of early attention and EF development in infancy and toddlerhood. This is in part due to a lack of age appropriate tasks suitable for measuring early EF in very young children, as well as limitations surrounding the availability of child-friendly neuroimaging techniques that enable brain activation to be localised to specific regions of the cortex. Yet, to have a picture of the developmental trajectory of EF from its emergence in infancy and across the life span, as well as an understanding of the change in the functional neural substrates that underpin this development, would have significant implications for the field.

For example, it is of great importance to understand the mechanisms by which the frontal cortex matures early in infancy, and how it supports the rapid development of cognitive skills observed in the first four years of life. There are also important implications for many individuals, educators, practitioners, and parents in that it might be possible to identify early in life those who may have poorer EF skills and thus need additional support ahead of key transition points (i.e., young children about to start school, adolescents taking examinations, young adults making decisions about their future, and older adults who may be at risk of cognitive decline or illness). Specifically, neuroimaging research can provide a window into mechanisms (beyond what can be achieved through observations of behaviour) that relate to individual differences in performance (Dubois & Adolphs, 2016; Garavan et al., 2006), and even neurodiversity (Liddle et al., 2011). Therefore, by examining neural development in early life it may be possible to identify and understand potential mechanisms that relate to cognitive development at an earlier age than is possible with behavioural studies.

Much of what is already known about the neural substrates of early EF development comes from a substantial and significant body of research from the electroencephalography (EEG) literature (e.g., Bell, 2001; Bell et al., 2007; Bell & Fox, 1992, 1997; Bell & Wolfe, 2007; Cuevas, Bell, et al., 2012; Fox & Bell, 1990; Morasch & Bell, 2011; Wolfe & Bell, 2007). This literature provides evidence that EEG can be used as an index of cognition across infancy and childhood and suggests that there is an important role of frontal and parietal regions, as well as connections between the frontal cortex and other regions (e.g., occipital and temporal lobes), in inhibitory demanding tasks. Overall, the knowledge provided from this research effort has provided a strong foundation on which to build our understanding of the functional mechanisms through which the PFC and parietal cortex matures, and early EF develops.

However, many of these studies, particularly with infant participants, employ resting state or passive tasks such as the looking version of the A-not-B task so no active, motor response is required from the participant. This differs significantly from the response modality and demands of the tasks used to assess inhibitory control in older children and adults, which often require a motor response. Thus, it is very difficult to compare knowledge of the neural correlates of inhibition in infancy with those found in older populations. Additionally, whilst EEG evidence gives us broad indices of activation (e.g., frontal regions), the limited spatial resolution of the technology has meant that it is not possible to localise functional activation to specific regions of the cortex, and so knowledge is lacking compared to that which can be achieved with fMRI in older populations. Indeed, much more is understood about the neural substrates of EF in adulthood (Aron, 2007; Aron et al., 2004; 2014; Collette et al., 2006), but without research into the earliest emergence of executive skills, it is not possible to understand how the maturation of the PFC and other cortical regions facilitates or supports the advancement of EF.

Although there has recently been an increase in the number of studies using neuroimaging techniques alongside EF tasks with developmental populations, there is still a large discrepancy between what is known about the neural substrates of 'mature' EF and what is known about 'immature' EF during development. However, with the introduction of functional near-infrared spectroscopy (fNIRS) to the developmental cognitive neuroscientist's toolbox approximately two decades ago, researchers have begun to elucidate the functional neural substrates of many facets of early development (Aslin & Mehler, 2005; Gervain et al., 2023; Lloyd-Fox et al., 2010; Wilcox & Biondi, 2015). Whilst knowledge from these fNIRS studies has provided a wealth of information about the functional neural correlates of inhibitory control in development, there is no previous research that has investigated this in children younger than 2 years of age. As previously discussed, there is evidence from EEG studies that have confirmed the involvement of broad indices of frontal cortex activation in inhibitory processes in infancy, however, due to the limitations of EEG, it has not previously been possible to localise activation to specific regions. As such, there is a fundamental gap in the literature whereby little is known about the emergence of inhibitory control and the associated functional brain mechanisms in infancy.

This section of the chapter will review what we already know about the functional brain mechanisms that underpin early EF development and highlight gaps where further research is needed. Since the current thesis centres on early inhibitory control development from infancy to early childhood, much of the research reviewed will be focused on this.

3.2.1. Spatial Organisation of Executive Functions in the Cortex

When compiling knowledge on the neural substrates of early EF development, it is important to consider contributions from neuroimaging studies with older children and adults. In this way, it can be identified whether the cortical regions associated with mature EF are also recruited during executively demanding tasks in early development. Specific regions of the frontal and parietal cortices have been consistently implicated in neuroimaging studies that have examined the neural substrates of inhibitory control processes. For example, a large body of evidence exists that supports the significant role of the right inferior frontal gyrus (IFG) for response inhibition in adults (for reviews, see Aron et al., 2004; 2014). It is worth noting that there have been contradictory results where the left or bilateral IFG activation has been associated with inhibitory control (Durston et al., 2002; Rubia et al., 2007; Tamm et al., 2002). Similarly, there is evidence to suggest that the involvement of the IFG may occur later in development and so may be a sign of more mature inhibitory control (Durston et al., 2006; Rubia et al., 2007; Schroeter et al., 2004). Additionally, evidence points to the involvement of the right DLPFC (Casey et al., 1997; Cope et al., 2020; Durston et al., 2006) and the orbital frontal cortex (Casey et al., 1997; Cope et al., 2020; Rubia et al., 2006; Tamm et al., 2002) when inhibition is required. There is also increasing evidence for the involvement of parietal regions in inhibitory tasks (Bunge et al., 2002; Chikazoe et al., 2009; Cope et al., 2020; Durston et al., 2002, 2006; Gonzalez Alam et al., 2018; Mehnert et al., 2013a; Osada et al., 2019). As such, it may be reasonably expected that these brain regions may also underpin response inhibition earlier in development.

It is important to note that knowledge gained from fMRI studies with older children and adults provides a starting point for which brain regions may be involved in facilitating the emergence and development of rudimentary executive function skills in early developmental populations. Whilst fMRI studies achieve excellent spatial localisation of activation, there are of course several challenges to using fMRI with awake infants and young children. As such, techniques such as EEG and fNIRS have been used to probe the spatial organisation of EF in childhood and infancy.

There is a growing body of evidence that highlights, as in adulthood, the involvement of prefrontal and parietal regions in facilitating executive processes also in childhood (Smith et al., 2017), across the pre-school years (Kerr-German & Buss, 2020; Moriguchi et al., 2018; Yanaoka et al., 2020), and already in infancy (Baird et al., 2002; Reyes et al., 2020). A seminal study by Baird et al. (2002) demonstrated the utility of fNIRS for the measurement of functional cortical activation in awake infants (5 – 12 months) engaging in an active task designed to examine object permanence. The results of this study highlighted links between increases in frontal haemoglobin concentrations and the development of object permanence

skills (i.e., representation; a precursor to working memory; Káldy & Sigala, 2004) in infancy. Using fNIRS to examine visual working memory in the first two years of life, Reyes et al. (2020) found evidence for a distributed network that included regions of the bilateral parietal cortex, the left temporoparietal junction and the left ventral occipital complex. Moving into early childhood, Kerr-German & Buss (2020) used fNIRS to investigate the behavioural development and neural underpinnings of flexible and selective attentional processes (thought to underpin executive processes) in 3.5- and 4.5-year-old children. This study found that regions of the bilateral frontal cortex were associated with flexible attention, whereas only the right frontal cortex was involved with selective attention processes.

With specific focus on the neural substrates of inhibitory control development, evidence also supports the involvement of prefrontal and parietal regions in facilitating inhibitory processes in early childhood (i.e., 3 – 6 years). A longitudinal study by McKay et al. (2022) investigated children's (4.5 – 5.5 years) performance on the Go / No-Go task whilst fNIRS measurement was collected and evidenced the involvement of the right middle frontal gyrus, right IFG and the bilateral supramarginal gyrus when inhibitory control was required. Research by Yanaoka et al. (2020) used fNIRS to investigate the maintenance of goal representations (a key process in both working memory and inhibitory tasks) and found that the right lateral PFC was activated when children were required to maintain goal representations and resolve conflicts in an executive task (a version of the DCCS). In a similar sample of preschool-aged children, Moriguchi et al. (2018) investigated the neural correlates of delay of gratification ('hot' inhibitory control) and highlighted the involvement of the right inferior PFC when children failed to delay gratification. Finally, Cuevas, Swingler, et al. (2012) examined the performance of 10-month-old infants on the looking A-not-B task and found increased frontal coherence when inhibition was required, although there was no increase in EEG power.

In summary, research has highlighted the role of the PFC, and its functional associations with the parietal cortex and other cortical regions, in processes related to or involving EFs in infancy, across childhood and in adulthood.

3.2.2. Developmental Changes in the Neural Correlates of Early Executive Function

Whilst research has started to pinpoint key neural substrates of early EF in the cortex of the brain, little is understood about the neural changes that may occur in the developing brain on the trajectory towards full 'maturity'. However, it is important to gain knowledge about these

developmental trajectories in order to understand more about how cortical brain regions may support improvements in cognitive skills, such as EFs.

Significant early fMRI work by Bunge et al. (2002) demonstrated that children (8 – 12 years) recruited different regions of the PFC and parietal cortex than adults during response inhibition and interference suppression tasks, suggesting that children show an immature recruitment of cortical regions when inhibition is required. Similarly, research by Durston et al. (2002) with adults and children aged 6 – 10 years found that children activated prefrontal and parietal regions more strongly than adults when response inhibition was successful. In a later study, Durston et al. (2006) found that when inhibition was required, children showed a reduction in activation in the DLPFC and an increase in activation of the VLPFC with age (from 9 – 11 years), and that activation in the VLPFC was associated with successful task performance. In an fMRI study with participants aged 8 – 20 years of age, Tamm et al. (2002) examined performance on the Go / No-Go task and found an increase in activation in regions of the left hemisphere (left IFG, insula, and orbital frontal gyrus) with age and a decrease in activation in the left middle frontal gyrus with age. More recently, a large longitudinal fMRI study investigated the development of response inhibition from childhood (7 – 13 years) into adulthood and found an age-related increase in activation in the bilateral orbital frontal cortex, bilateral IFG, and bilateral occipital regions (Cope et al., 2020). Overall, evidence from these studies highlights the involvement of regions of the PFC and parietal cortex in maturing inhibitory control and demonstrates that activation may become more localised with age.

Longitudinal research that follows the same participants over time is an informative way to examine age-related performance improvements and to compare neural correlates at different time points. An example of this comes from Bell & Wolfe (2007), who examined longitudinal associations of EEG power and coherence from infancy (8-months) to early childhood (4½ years) during inhibitory control tasks. Brain activity was measured during a looking version of the A-not-B task in infancy, and the Day / Night and Yes / No tasks in early childhood. The results of this study indicated that task performance in infancy was associated with changes (from baseline) in EEG power and coherence across the entire scalp, whereas in early childhood task performance was associated with changes in EEG power in medial frontal regions, and in EEG coherence in medial frontal regions and posterior temporal and occipital electrode pairs. Similarly, longitudinal research by Cuevas, Bell, et al. (2012) investigated infants' performance on the looking A-not-B task from 5- to 10-months of age and found that, when inhibition was required, infants at both ages showed increases in EEG power across the whole head. Additionally, EEG coherence between medial frontal and occipital regions was found at both time points but was more localised at

10-months of age. Overall, these studies demonstrate that electrical activity during infancy is widespread and becomes more localised to specific frontal regions during early childhood. This mirrors a body of evidence that suggests that brain activation during cognitive tasks is more widespread and global during infancy but becomes more refined and localised with development (see Fiske & Holmboe, 2019).

Focusing specifically on the development of inhibitory control and the associated neural substrates, research by Mehnert et al. (2013) used fNIRS with 4 – 6-year-old children and adults to investigate the neural correlates of response inhibition (Go / No-Go). It was found that activation in the right frontal and parietal regions was important for response inhibition, but that children showed reduced activity in the right frontal and parietal regions compared to adults. Similarly, an fNIRS study with children (aged 4 – 10 years) by Smith et al. (2017) demonstrated that activation in the frontal cortex during tasks requiring inhibition and working memory processes increased with both age and task performance improvements. Finally, research by Zhou et al. (2022) with children aged 4 – 10 years examined performance on the Go / No-Go task using fNIRS and on a standardised cognitive assessment. Their results found that activation in the right PFC was associated with inhibitory control performance but independent of age, and that activation in the left orbital frontal cortex was associated with age. This could suggest that different regions of the PFC may have different roles in supporting the development of inhibitory control across childhood. Again, knowledge about the development of neural substrates that underpin inhibitory control as it emerges in infancy and develops across the first years of life is limited. This proves to be an important area for future research.

3.2.3. Brain-Behaviour Associations in Early Executive Function

As well as identifying specific cortical regions that are active during EF tasks, it is also important to understand how the activation of these regions may underpin or support performance on these tasks. A key question to probe is how these brain-behaviour associations may change across development and also to elucidate at what point these brain-behaviour associations emerge in the early developmental period. In fact, a body of research exists that suggests that there may be associations between individual differences in neural activation of the frontal cortex and performance on EF tasks, already in infancy.

Early EEG research by Fox & Bell (1990) highlighted the relationship between individual differences in the maturation of frontal regions and improved performance on tasks thought to recruit the frontal cortex (such as the A-not-B task). Investigating this further, Bell & Fox (1992) used EEG with infants aged 7 – 12 months whilst they completed a reaching version

of the A-not-B task. The behavioural results of this study found age-related improvements in inhibition (i.e., older infants were successful across longer delays), and the neural results indicated that, with age, there were changes in EEG power across frontal regions (i.e., amount of activity) and an increase in EEG coherence in anterior/posterior regions of the cortex (i.e., connections within and between brain regions). Similarly, Bell & Fox (1997) found that successful performance on the A-not-B task was associated with greater EEG power in frontal and occipital regions in 8-month-old infants. Using fNIRS, Kerr-German et al. (2022) examined functional connectivity in frontal and parietal cortices whilst 2½-year-old toddlers completed the 'snack delay' task. The results of this study were the first to identify an association between the strength of functional connectivity between frontal and parietal regions and successful delay of gratification in toddlers.

Recent longitudinal research has examined relations between EEG measurements in infancy and later indices of performance. This provides important insights into how neural maturation may be related to cognitive development across childhood. Research by Broomell et al. (2021) demonstrated that EEG coherence between frontal and temporal regions at 10-months of age was predictive of inhibitory control performance in early childhood (4 years of age), as well as social cognition later in childhood (9 years). Similar longitudinal research from Whedon et al. (2020) indicated that greater EEG alpha power over frontal regions in infancy (10-months) was associated with better inhibitory control performance at age 4, and that better inhibitory control performance was related to later academic outcomes (age 6). In their research with slightly older children, Lo et al. (2013) demonstrated that age-related performance improvements on a response inhibition task from 5- to 6 years of age were associated with an increase in EEG beta power (a possible index of inhibition) in right frontal regions. Similarly, Perone, Palanisamy, et al. (2018) examined resting state EEG power over frontal and posterior regions to investigate associations with the performance of 3 – 9-year-olds on EF tasks. Their results showed that individual differences in the theta/beta ratio (an index of cognitive processing) in the frontal and parietal regions were associated with children's EF performance, regardless of age and verbal ability.

Overall, these studies suggest that individual differences in neural development may relate to the development of early inhibitory control abilities and even other abilities later in childhood.

4. Summary of Thesis

This thesis aims to investigate the emergence and development of inhibitory control across the first four years of life. Using functional near-infrared spectroscopy (fNIRS), an optical imaging technique suitable for use with infants and young children, this thesis examines the functional neural correlates of response inhibition from infancy and across key transitions into toddlerhood and early childhood. With longitudinal data from the same sample of participants at 10-months of age, 16-months of age, and 3½ years of age, this thesis will examine developmental change in inhibitory control performance and the associated neural substrates across infancy and early childhood and will identify links with early academic outcomes.

The current chapter has introduced the topic of early inhibitory control development and the associated neural substrates through a review of the literature that has highlighted existing knowledge and areas for future investigation. Chapter 2 of this thesis will provide a detailed overview of the methodological approaches and techniques that have been used in the studies presented in this thesis to investigate early inhibitory control in infants, toddlers, and young children. Additionally, as the data presented in this thesis were collected from a cohort of participants enrolled in the Oxford Early Executive Functions (OEEF) longitudinal study, Chapter 2 will also present information about the participant demographics, study assessment points, and protocols. Chapter 3 will introduce fNIRS as a tool for use in developmental cognitive neuroscience by evaluating the strengths and limitations of this technique and highlighting how fNIRS was used in the empirical studies presented in this thesis.

Chapters 4, 5, and 6 form a trio of fNIRS studies that use the same methodological paradigm to examine the behavioural and neural correlates of response inhibition in the same sample of 10-month-old infants (Chapter 4), 16-month-old infants (Chapter 5), and 3½-year-old children (Chapter 6), and their longitudinal development across the first four years of life. Chapter 7 of this thesis aims to examine concurrent and longitudinal associations between ‘hot’ and ‘cool’ indices of inhibitory control, and to investigate potential predictive associations between infant inhibitory control and later inhibitory control measured in early childhood, and with early academic skills.

Finally, Chapter 8 provides an in-depth general discussion of the key findings presented in this thesis and highlights the novel contributions of this research to the field. This includes a discussion of the implications of the findings of this thesis for the field of early EF development, an evaluation of the limitations of this research, and an outline of suggested directions for future research.

Chapter 2

Methodological Approach to the Study of Early Executive Function Development

This chapter provides a detailed overview of the methodological approaches and techniques that have been used in the research that will be presented in this thesis to study early executive function (EF) development. The chapter begins with an overview of the participants, phases, and protocols of the longitudinal study that underpins the research studies included in this thesis. This overview is followed by an outline of the range of behavioural methods used in this thesis to measure inhibitory control in the first four years of life.

1. Study Overview

The data presented in this thesis were collected as part of the Oxford Early Executive Functions (OEEF) study, a longitudinal study conducted by Dr Karla Holmboe at the University of Oxford. Due to the collaborative nature of this study, many researchers and students were involved in collecting, processing, and analysing data collected during the OEEF study. My involvement in each of these processes will be explicitly stated where relevant throughout the thesis, and collaborators will be appreciatively acknowledged.

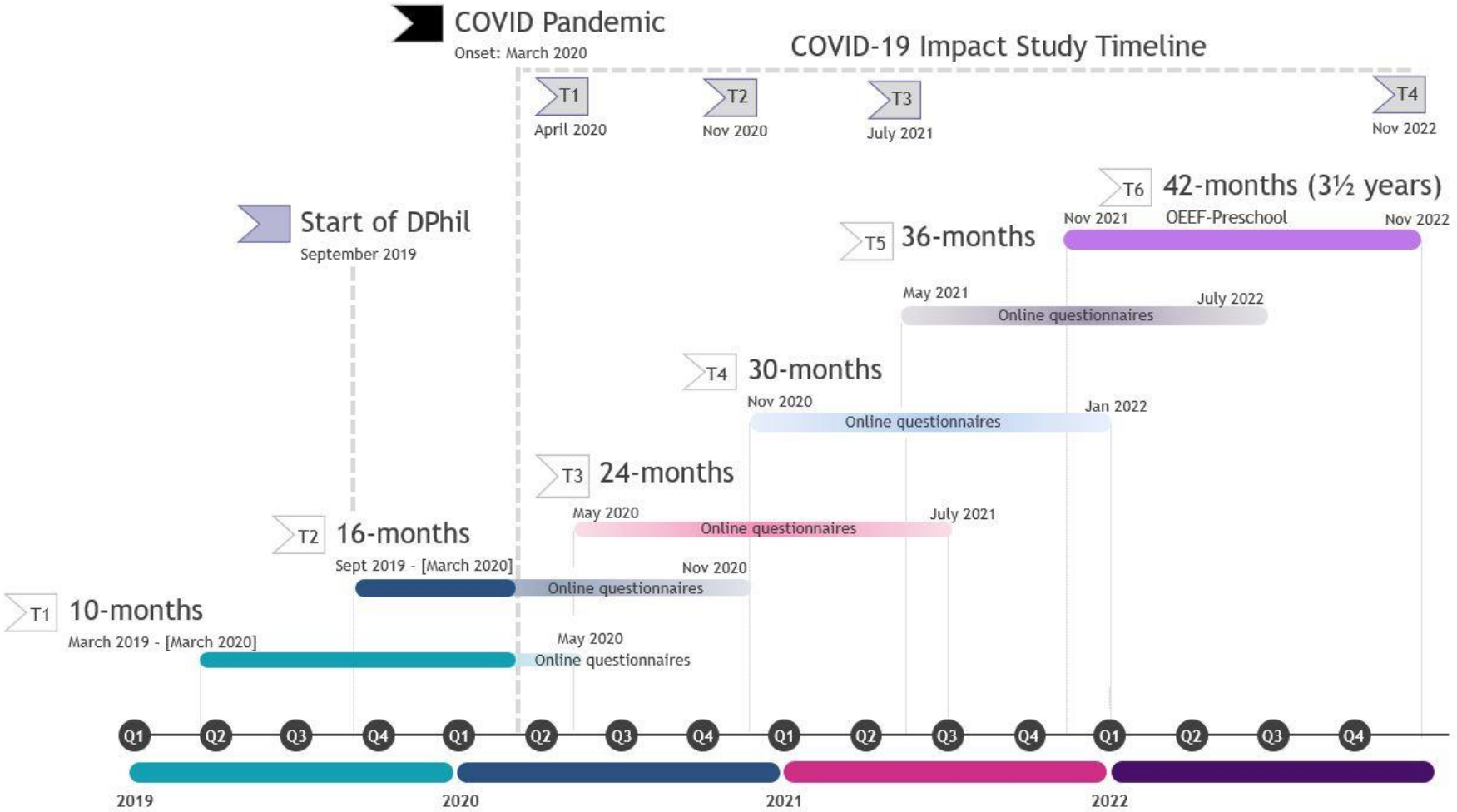
The overarching aim of the OEEF study was to assess the longitudinal development of early EFs across the first three years of life using a range of behavioural, physiological, and neuroimaging techniques. Four assessment points were planned to span this period (10-, 16-, 24-, and 30-months of age) whereby participants would be invited to the Oxford University Babylab to attend in-person testing sessions, starting in March 2019. However, the onset of the COVID-19 pandemic in March 2020 significantly disrupted these plans and all in-person testing sessions were cancelled. As a result, the 24- and 30-month assessment points continued only in the form of online questionnaires. Additional assessment points were later added because of the pandemic disruption, such that online questionnaires were completed by parents when their child was 36-months of age and, following the removal of pandemic-related restrictions, participants were invited to attend in-person testing sessions when their child was 42-months/3½ years of age (the OEEF preschool study).

Figure 1 illustrates the timeline of the OEEF study from its onset in March 2019 to its close in November 2022. While the broader longitudinal study involved an extended team of researchers, I specifically led in planning, piloting, and refining the protocol for the OEEF preschool study and collected most of the data (see Section 4.1. below for more details).

As an unplanned addition to the OEEF study, a secondary longitudinal study was conducted in response to the onset of the COVID-19 pandemic. This study aimed to examine the impact of the pandemic on families with infants and young children (already taking part in the OEEF study), with a specific focus on parental mental health and child temperament. As such, families were asked to complete online questionnaires (via Qualtrics) at four time points across the pandemic: April 2020, November 2020, July 2021, and November 2022 (see **Figure 2**). My role in this study was to prepare and distribute the questionnaires (including the development of a novel COVID-19 impact questionnaire), monitor responses, and collate and analyse the data. The data collected as part of this secondary study are not included in this thesis. See the **'**COVID-19 Impact Statement' in the Appendix for more information.

The OEEF study and additional COVID-19 impact study received full ethical approval from the Medical Sciences Inter-Divisional Research Ethics Committee at the University of Oxford (Ref. No. R57972/RE012).

Figure 1. Chapter 2. Overview of OEEF and OEEF Preschool Assessment Points.



Note. Solid bars = in-person data collection (including questionnaires), transparent bars = online data collection (questionnaires only). Square brackets = end date of data collection period due to pandemic onset). This thesis only includes data collected at T1 (10-months), T2 (16-months), and T6 (42-months). Q1 etc. = first quarter of the year (e.g., January - March).

2. Participants

2.1. Recruitment

Participants (and their parents/guardians) were recruited via the Oxford University Babylab database. Most participants on the database were recruited from the maternity ward of the John Radcliffe Hospital by a recruitment assistant who worked for the Oxford University Babylab. A small number of participants were recruited via social media platforms, community groups, or word-of-mouth. Most families lived in Oxford or the surrounding local area. Families who had registered with the Oxford University Babylab database and had an infant aged between 6- and 10-months were sent an email inviting them to participate in the OEEF study when their child was 10 months old. The email contained the participant information sheet, which was in accordance with the university's ethical guidelines. The information sheet informed parents about the purpose of the study, what participation would involve and the reimbursement, a reminder that participation would be voluntary and that they could withdraw at any time, examples of the benefits and risks of participating, information about how their personal data would be stored, and instructions on how to make a formal complaint.

Parents who were interested in participating were then invited to book two in-person testing sessions (usually spaced about one week apart) that took place at the Oxford University Babylab. Testing sessions were scheduled (where possible) within a window of one week before or two weeks after the infant's 10-month "birthday" and each session would last for no longer than 90 minutes. Parents were asked to complete online questionnaires (Qualtrics link sent via email) about their child approximately a week before and then a few days after their first testing session. Additional questionnaires were completed by parents during their visit. After the second visit, infants were given a Babylab branded gift and parents were sent a £20 digital Amazon voucher to thank them for their participation. Families who were unable to visit the laboratory but still wanted to participate in the study were invited to fill in the online questionnaires and received a £5 digital Amazon voucher upon completion. This same process was followed for the second assessment period when the child was 16-months of age.

During the COVID-19 pandemic when no in-person test sessions could take place, data collection continued in the form of online questionnaires (Qualtrics link sent via email). Approximately a week before the child's "birthday" (at each assessment point), parents were invited to complete online questionnaires about their child. Parents received a £5 digital Amazon voucher upon completion of the questionnaires at each stage.

As part of the OEEF preschool study, parents were invited to attend in-person test sessions at the Oxford University Babylab when their child was 42-months (3½ years) of age. Testing sessions were scheduled (where possible) within a window of two weeks before or two weeks after the child's 3½ year "birthday", although this was extended to 3 weeks before to three weeks after where necessary to ensure the session could be scheduled. Parents were asked to complete online questionnaires (Qualtrics link sent via email) about their child approximately a week before and a few days after their first testing session. Shorter questionnaires were also completed by parents during each testing session. After each visit, children were given a Babylab branded gift or a small toy, and parents were sent a £10 digital Amazon voucher to thank them for their participation. Families who were unable to visit the laboratory but still wanted to participate in the study were invited to complete the online questionnaires and received a £5 digital Amazon voucher upon completion.

2.2. Sample Demographics

2.2.1. 10-month Assessment Point

A total of 173 participants (*N* = 92 male infants) contributed at least some data (online questionnaire or in-person sessions) to the 10-month assessment point of the OEEF study. Of these participants, 144 infants (*N* = 74 male) visited the Oxford University Babylab for their first test session, and 138 participants (*N* = 70 male) returned for their second test session approximately one week later. Please see **Table 1** below for demographic information of the full sample. The OEEF study inclusion criteria required that infants must have been born at 36 weeks gestation or later, or with a birthweight of at least 5.5 lbs (2.5kg) and that there were no complications at birth that led to potentially serious health issues. Three male infants were excluded from the study due to birth complications leading to health-related concerns.

10-months was chosen as the first assessment point in the longitudinal study since this is the earliest age within the second half of the first year at which almost all typically developing infants have sufficient motor control that they can respond appropriately to tasks (either on a touchscreen or by manipulating physical objects on a table).

Table 1. Chapter 2. Demographic Information for the 10-month Sample.

	N	Mean	SD	Min	Max
Infant's age at Session 1 (days)	144	305	5.96	294	319
Infant's age at Session 2 (days)	138	313	6.23	301	336
Mother's age (years)	172	33.87	4.46	19	47
Father's age (years)	165	35.56	5.37	22	53
Maternal education (years)	166	17.88	3.14	10	28
Paternal education (years)	152	17.18	3.25	9	30
Infant Ethnicity	*N*	%			
Asian	3	1.73			
British Indian and White British	1	0.58			
Chinese	1	0.58			
Did not answer	1	0.58			
Mixed – Other	3	1.73			
Other White	27	15.61			
Prefer not to say	1	0.58			
White and Arabic	1	0.58			
White and Asian	7	4.05			
White and Black African	1	0.58			
White and Black Caribbean	4	2.31			
White and Mexican	1	0.58			
White British	122	70.52			
Total	**173**	**100%**			

2.2.2. 16-month Assessment Point

A total of 151 participants (*N* = 79 male infants) contributed at least some data (online questionnaire or in-person sessions) to the 16-month assessment point of the OEEF study. Of these, 78 participants (*N* = 42 male infants) attended the first in-person test session, and a total of 74 participants (*N* = 40 male infants) returned for their second test session approximately one week later. Please see **Table 2** below for demographic information on this sample. Since data collection at the 16-month assessment point was halted because of the COVID-19 pandemic (see **Figure 2**), many families did not have the opportunity to attend in-person sessions due to laboratory closures. Therefore, to increase the sample size and statistical power for the analyses, data from 25 pilot participants (*N* = 13 male infants) were also included in the 16-month dataset. The data collected during piloting was collected under identical administration protocols as in the OEEF study. Of these 25 infants, a total of 24 (*N* = 12 male infants) returned approximately one week later for their second test session.

As per the OEEF study inclusion criteria (described above), one female infant (pilot participant) was excluded from the study due to their low birth weight, and three male infants were excluded from the study due to birth complications leading to health-related concerns.

Table 2. Chapter 2. Demographic Information for the 16-month Sample.

	N	Mean	SD	Min	Max
Infant's age at Session 1 (days)	103	488.86	7.05	475	514
Infant's age at Session 2 (days)	98	498.44	7.40	478	518
Mother's age (years)	91	33.68	4.40	19	47
Father's age (years)	90	35.44	5.17	26	53
Maternal education (years)	90	17.80	2.57	12	25
Paternal education (years)	88	17.18	3.49	11	30
Infant Ethnicity	*N*	%			
Mixed – Other	1	0.97			
Other White	17	16.50			
Prefer not to say	1	0.97			
White and Asian	1	0.97			
White and Black African	1	0.97			
White and Black Caribbean	1	0.97			
White and Chinese	1	0.97			
White and Mexican	1	0.97			
White British	68	66.02			
No information provided	11	10.68			
Total	**103**	**100%**			

Note. Parental age and education (years) were recorded at the 10-month assessment point.

2.2.3. Infant Longitudinal Data

A total of 146 participants (*N* = 74 male infants) contributed at least some data (questionnaires or in-person sessions) to both the 10- and 16-month assessment points. Following the exclusion of 3 participants (as per the longitudinal criteria described above), a total of 71 participants (*N* = 35 males) of the OEEF study attended the first test session at both the 10- and 16-month assessment points and 68 of these (*N* = 34 males) also attended the second test session at both the 10- and 16-month assessment points. Four male participants joined the study at the 16-month assessment point, and so did not contribute data at 10-months.

2.2.4. 3½ year Assessment Point

A total of 101 participants (*N* = 49 male) contributed at least some data (online questionnaire or in-person sessions) to the 3½ year assessment point of the OEEF preschool study. Of these, 94 participants (*N* = 42 male) attended the first in-person test session at the 3½ year assessment point, and 91 infants (*N* = 41 male) returned for their second test session approximately one week later. Please see **Table 3** below for demographic information on this sample. As per the OEEF study inclusion criteria (described above), two male infants were excluded from the study due to birth complications leading to health-related concerns.

Table 3. Chapter 2. Demographic Information for the 3½ year Sample.

	N	Mean	SD	Min	Max
Child's age at Session 1 (months)	94	41.5	0.56	40	43
Child's age at Session 2 (months)	91	41.87	0.56	41	44
Mother's age (years)	93	36.93	4.28	27	50
Father's age (years)	85	38.16	5.07	25	56
Maternal education (years)	92	18.35	2.86	12	30
Paternal education (years)	84	17.80	2.91	11	25
Infant Ethnicity	*N*	%			
Asian	1	1			
Mixed – Other	1	1			
Other White	16	16			
Prefer not to say	1	1			
White and Arabic	1	1			
White and Asian	3	3			
White and Black African	1	1			
White and Black Caribbean	1	1			
White and Mexican	1	1			
White British	71	71			
Did not answer	3	3			
Total	**100**	**100%**			

2.2.5. Infant to Pre-School Longitudinal Data

Following the exclusion of 1 participant (as per the longitudinal criteria described above), 93 participants attended the first in-person test session at 3½ years. Of these:

- 92 participants (*N* = 39 male) attended the first test session at the 10-month assessment point. Of these, 89 (*N* = 37 male) returned for their second test session at 10-months.
- 50 participants (*N* = 21 male) attended the first test session at the 16-month assessment point. Of these, 48 participants (*N* = 20 male) also attended the second test session at 16-months.

Following the exclusion of 1 participant (as per the longitudinal criteria described above), 90 participants attended the second in-person test session at 3½ years. Of these:

- 89 participants (*N* = 39 male) attended the first test session at the 10-month assessment point. Of these, 87 participants (*N* = 37 male) returned for their second test session at 10-months.
- 49 participants (*N* = 21 male) attended the first test session at the 16-month assessment point. Of these, 47 participants (*N* = 20 male) also attended the second test session at 16-months.

- 48 participants (*N* = 20 male) attended the first test session at both the 10- and 16-month assessment points. Of these, 46 participants (*N* = 19 male) also attended the second test session at both the 10- and 16-month assessment points.
- A total of 46 participants (*N* = 19 male) attended all possible test sessions.

2.3. Sample Attrition

The OEEF longitudinal study took place over a period of almost four years (2019 – 2022) and, as with all longitudinal studies, some level of attrition was expected at each assessment point. It is suspected that the attrition rate may have been impacted by the laboratory closures because of the pandemic, which meant that families did not visit the laboratory for in-person sessions for over two years. However, during this time, families were still asked to answer online questionnaires at the planned assessment points. **Figure 2** provides an overview of the sample size at each assessment point, and **Table 4** displays the response rate and session attendance at each assessment point.

Figure 2. Chapter 2. Overview of Sample Size at each Assessment Point.



Note. This figure illustrates the sample size at each assessment point in the OEEF longitudinal study. The top bar at each time point represents the total number of participants who contributed at least some data at that assessment point. No in-person testing happened at time points 3, 4, and 5 and so there is no session attendance data. Pilot participants are not included in these totals. This thesis only includes data from Time 1 (10-months), Time 2 (16-months), and Time 6 (42-months / 3½ years).

Table 4. Chapter 2. Response Rate at each Assessment Point.

	Time 1: 10-months	Time 2: 16-months	Time 3: 24-months	Time 4: 30-months	Time 5: 36-months	Time 6: 42-months
Contributed Data	100%	87%	76%	68%	71%	67%
Session 1 Attendance	83%	45%	-	-	-	54%
Session 2 Attendance	80%	43%	-	-	-	53%

Note. The 16-month assessment point was significantly impacted by the onset of the COVID-19 pandemic in March 2020, after which in-person data collection could not take place (as reflected in the session attendance rates). Pilot participants are not included in these response rates.

3. Materials & Methods

3.1. Methods of Assessment

A variety of assessment methods were used to collect data from participants throughout the OEEF study. At all in-person assessment points, tasks were completed across two sessions. At 10- and 16-months, the first test session lasted for approximately 1 hour and 30 minutes, whilst the second was around 60 minutes in duration. At 3½ years, both testing sessions were approximately 1 hour and 30 minutes in duration. Each method used to collect data included in this thesis is described below and the administration procedure is outlined. Please see **Table 5** for an overview of the assessment methods used in this thesis. Note that additional methodologies (including eye-tracking and electroencephalography tasks and online questionnaires) were administered as part of the OEEF study but are not included in this thesis so are not described here.

3.1.1. Behavioural Tasks

Participants completed a range of behavioural tasks at each assessment point (**Table 5**), some of which were administered on a touchscreen (iPad) whilst others were toy-based or picture-based tasks. The tasks used in this thesis were carefully designed to be appropriate for infants and/or young children; specific details about each task are provided in the Methods section of the relevant chapters of this thesis. Whilst it is not always possible to use the same task at each assessment point (due to differing task demands and the age-related development (i.e., language and motor skill improvements) that occurs between assessment points in infancy and early childhood), tasks were selected only if they could be kept structurally similar (or the same) across assessment points.

Tasks were administered directly to the participant by the experimenter. Before each session, parents were instructed to allow their child to complete each task independently, and not to provide verbal or physical support with the task. Tasks were designed so that the motor demands for all tasks were age-appropriate, such that all participants at each assessment point would have the necessary motor skills to access the task. To keep the attention of the participant and to minimise opportunities for data loss, tasks were designed (where possible) to be as short and engaging as possible. A standard protocol for task administration was followed by all experimenters delivering the test sessions.

3.1.2. Standardised Tests

The Wechsler Preschool and Primary Scales of Intelligence, fourth UK edition (WPPSI-IV-UK; Wechsler, 2013) was administered at the 3½ year assessment point. Two versions of this assessment are available for use depending on the age of the participant (2:6 – 3:11, or 4:0 – 7:7). The 2:6 – 3:11 task battery was administered to the 3½ year-old participants in this study. This assessment consisted of seven tasks which map onto three primary index scales (verbal comprehension, visual-spatial, and working memory) and three ancillary index scales (vocabulary acquisition, non-verbal, and general ability). A full-scale intelligence index can also be generated.

A total of six of the seven available tests were administered: Receptive Vocabulary (~3 minutes), Block Design (~8 minutes), Picture Memory (~4 minutes), Information (~4 minutes), Object Assembly (~9 minutes), and Zoo Locations (~6 minutes). Since the 'Picture Naming' task is not needed to generate either the full scale or any of the primary index scales, it was decided that the 'Picture Naming' task would not be administered. This also enabled the length of time it took to administer the battery to be reduced, which was important since the testing sessions were already very long (~90 minutes).

The WPPSI-IV-UK (Wechsler, 2013) was administered in two parts, split across the two testing sessions. This decision was made following pilot test sessions in which it became clear that it was fatiguing for participants when the battery was administered in one testing session. Splitting the assessment is acceptable according to the administration manual, which allows for the tests to be completed in two sessions if the second session occurs within about a week of the first. As such, the Receptive Vocabulary, Block Design, and Picture Memory tasks (~15 minutes) were administered in the first test session at 3½ years, and the Information, Object Assembly, and Zoo Locations tasks (~19 minutes) were administered in the second test session. Tasks were administered in the same order as they are presented in the manual and were kept the same for all participants. The tasks were administered in accordance with the administration protocol provided in the WPPSI-IV-UK manual.

3.1.3. Functional Near-Infrared Spectroscopy (fNIRS)

At all assessment points, participants completed a response inhibition task, the Early Childhood Inhibitory Touchscreen Task, (ECITT; Holmboe et al., 2021) whilst having their brain activity measured using functional near-infrared spectroscopy (fNIRS). The ECITT is described in full in Chapters 3 and 4. fNIRS is an optical imaging technique that uses near-infrared light to measure the concentration changes of oxygenated and deoxygenated

haemoglobin in the cortex of the brain. Please see Chapter 3 for a detailed description of fNIRS as a neuroimaging technique and an overview of how fNIRS has been used in this thesis.

Table 5. Chapter 2. Overview of Assessment Methods.

Assessment Method	Task	Citation	10-months	16-months	3½ years
Behavioural	Early Childhood Inhibitory Touchscreen Task	Holmboe et al. (2021)	X	X	X
	Toy Prohibition / Glitter Wand	Friedman et al. (2011)	X	X	
	Touchscreen Prohibition	Novel task	X	X	
	Numbers (Early Years Toolbox)	Howard et al. (2022)			X
	Fish & Sharks (Early Years Toolbox)	Howard & Melhuish (2017)			X
	Treasure Delay	Novel task			X
	Gift Delay	Kochanska et al. (2000)			X
	Dinky Toys				X
fNIRS	Early Childhood Inhibitory Touchscreen Task (Blocked version)	Holmboe et al. (2021); Fiske et al. (2022)	X	X	X
Standardised assessment	Wechsler Preschool and Primary Scales of Intelligence – fourth edition, UK	Weschler (2013)			X
Parent-report	Oxford Background Questionnaire-Revised	Novel	X		X

Note. Full references for the citations in this table are available in Appendix A1 (for ease of access), as well as in the full reference list for this thesis.

4. Data Collection

4.1. Testing Sessions

At each assessment point, participants were invited with their parents/caregivers to visit the Oxford University Babylab for two testing sessions, usually spaced about a week apart. Each testing session was administered by two experimenters; the lead experimenter who interacted with the participant and administered the tasks, and the second experimenter who set up the equipment, took detailed notes, indicated timings to the lead experimenter, and scored tasks where necessary. When participants arrived at the Babylab reception, they were invited to play with toys to help them adjust to the new environment and the

experimenters. During this time, the lead experimenter outlined what to expect from the session and asked the parent/caregiver to complete the study consent form and an optional photographic image release form. At 3½ years, the children were invited to choose a sticker chart – stickers were used throughout the session to keep the children motivated after each task. Tasks were administered consecutively in designated testing rooms (see Section 4.2. below) and in the same order for all participants (where possible, may have been a different order in the instance of technical problems or experimenter error). A break was scheduled halfway through the testing session (at the same point for each participant, although additional breaks could be taken where needed) whereby participants and parents returned to the reception area. At the end of the test sessions, participants were thanked for their time and invited to choose a small Babylab-branded gift.

Data were collected by a team of experimenters at each assessment point. At 10-months, a total of 283 testing sessions were conducted. I ran 49 sessions as lead experimenter and two as second experimenter. At 16-months, a total of 148 testing sessions were conducted. I ran 61 sessions as lead experimenter and eight as second experimenter. At 3½ years, a total of 184 testing sessions were conducted. I ran 104 sessions as the lead experimenter and 32 as the second experimenter. In total, I conducted 214 sessions as the lead experimenter and 42 sessions as the second experimenter.

4.2. Testing Rooms

Data collection took place at the Oxford University Babylab in two testing rooms. The first testing room was used for 'behavioural' testing, that is, all tasks that do not involve additional equipment such as eye-tracking or fNIRS. The behavioural testing room was neutral in design and windowless. The room contained a rectangular table, around which the experimenter and the participant sat. In the infant test sessions (10- and 16-month assessment points), the infant sat on the lap of their parent/caregiver to access the tasks at the tabletop. For all tasks administered at the table, the experimenter sat at the head of the table, to the right of the parent and child (see **Figure 3a**). At the 3½ year assessment point, children sat in an age-appropriate highchair that enabled them to access the tasks on the tabletop independently. For some tasks, the experimenter sat at the head of the table to the right of the child (**Figure 3b**), and for others, the experimenter sat opposite the child (**Figure 3c**). A small chair was positioned next to the experimenter (out of sight of the participant) to hold the experimental props. At all assessment points, a second experimenter was positioned behind a large screen (that acted as a room divider) and could observe the session through an external webcam attached to the screen, displayed on a laptop

positioned on a small table behind the screen. Two other cameras were positioned on tripods in the room; one of which provided an ‘over the child’s shoulder’ view of the child completing the tasks on the table, and the second was positioned directly in front of the child to capture their looking behaviour (**Figure 3a**). At the 3½ year assessment point when the experimenter sat directly opposite the child, the second camera was positioned at the head of the table, facing the child.

The second test room was used to collect the fNIRS data at all assessment points. This room was a Desone soundproof booth and contained a large desk (where the fNIRS equipment was positioned) and a small desk to hold a laptop and other equipment. The room also contained a small square table, where the fNIRS task was administered. At all assessment points, participants would sit on the lap of their parent/caregiver and the experimenter would sit on the adjacent edge of the table to administer the task. Two cameras were positioned on tripods in the room; one provided an ‘over the child’s shoulder’ view of the child performing the task, and the second was positioned to record the information on the laptop from which the fNIRS was run (**Figure 3d**).

A third test room (used only at the 10- and 16-month assessment points) was used to complete eye-tracking and EEG tasks as part of the OEEF study. This data is not presented in this thesis.

Figure 3. Chapter 2. Testing Rooms.



Figure 3a. Behavioural testing room set-up for the infant assessment points.

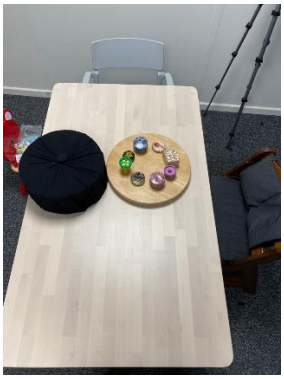


Figure 3b. Behavioural testing room set-up for the 3½ year assessment points; experimenter at the head of the table.

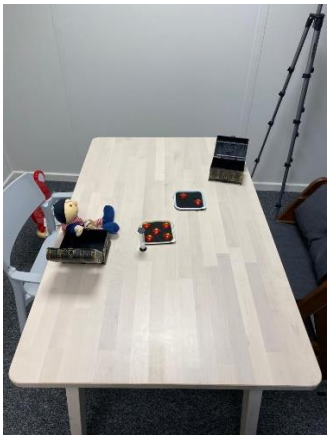


Figure 3c. Behavioural testing room set-up for the 3½ year assessment points; experimenter opposite the child.



Figure 3d. fNIRS testing room set-up for all assessment points.

5. Summary

This chapter provided a general overview of the participant sample, data collection timelines, and methodological approaches applied in the OEEF study, from which this thesis will present data. The next chapter will zoom in on functional near-infrared spectroscopy (fNIRS), the primary methodological technique used in this thesis to investigate the functional neural correlates of response inhibition from infancy and across early childhood.

Chapter 3

A Spotlight on Functional Near-Infrared Spectroscopy (fNIRS)

This chapter aims to introduce fNIRS as a tool for use in developmental cognitive neuroscience research. First, an explanation of the physical mechanisms that support the functionality of fNIRS is provided, as well as an evaluation of the strengths and limitations of fNIRS compared to other neuroimaging modalities. Then, a discussion begins about the ways in which fNIRS has been used in this thesis. This includes a detailed description of the technical parameters of fNIRS, as well as the unique challenges faced by researchers using fNIRS with early developmental populations. Chapters 4, 5, and 6 of this thesis will present empirical research that used fNIRS to measure the neural correlates of response inhibition in infancy and early childhood.

1. fNIRS as an Optical Imaging Technique

fNIRS is an optical imaging technique that uses near-infrared light to measure changes in the concentration of haemoglobin in the blood of the cortex of the brain. Haemoglobin is a protein found in red blood cells that functions to deliver oxygen from the lungs to the rest of the body. As such, haemoglobin can either be oxygenated (i.e., with oxygen; HbO_2) or deoxygenated (i.e., without oxygen, HHb). Near-infrared light (a wavelength of light just outside of the visible light spectrum) interacts with biological tissue such as haemoglobin primarily through *scattering*, where light is forced to travel in non-linear ways by the medium through which it travels, but also, to a lesser extent, by *absorption*, where light is absorbed and converted into energy. The optical properties of haemoglobin are such that it is adequately transparent in the near-infrared light range (~650 – 950 nm, “the optical window”; Scholkmann et al., 2014). This means that the distance near-infrared light can travel through haemoglobin before it is absorbed (absorption coefficient) results in a high enough signal-to-noise ratio for a measurement to be collected. Since the two haemoglobin chromophores have different absorption coefficients within the “optical window”, it is possible to measure concentration changes in these chromophores separately by using two different wavelengths

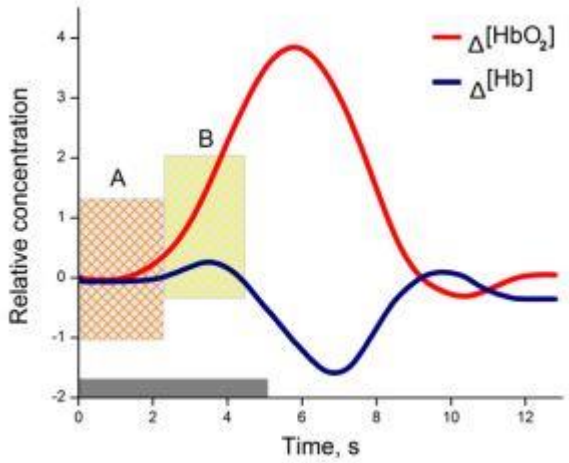
of near-infrared light (~780nm and ~850nm for HHb and HbO_2 respectively; Bulgarelli et al., 2019).

In practice, two wavelengths of near-infrared light are emitted continuously from a continuous wave fNIRS system via optical fibres to optical sources positioned on the participant's scalp. Often, a series of optical sources and detectors (forming source-detector pairs or 'channels') are attached to a fabric cap in a particular configuration (designed to cover study-specific brain regions of interest). The intensity at which near-infrared light is emitted can be manually determined and is often variable depending on the participant's skin colour, hair colour and amount and type of hair, as well as other environmental factors. When near-infrared light is emitted, it must travel through the scalp, skull, and cerebrospinal fluid before it reaches the cortex of the brain. Due to the large amount of scattering that happens in the near-infrared light wavelength, light does not travel in a linear trajectory but instead diffuses randomly through the biological tissue. Near-infrared light that is back-scattered (scattered back in the direction of the source) can be detected by optical detectors that are positioned near the optical source (Bulgarelli, Lloyd-Fox, et al., 2019). As such, fNIRS measures light attenuation by recording the optical intensity of the near-infrared light received by detectors (Kocsis et al., 2006). To estimate changes in concentration of haemoglobin, light attenuation information is incorporated into the modified Beer-Lambert Law, which uses information about the change in absorption coefficient over time and the differential path length factor (the estimated distance travelled by the near-infrared light – note that due to the diffuse scattering of near-infrared light in biological tissue, the distance travelled is larger than the distance between the source and the detector) to estimate changes in concentrations of HbO_2 and HHb over time (Kocsis et al., 2006).

Changes in haemoglobin concentrations in the cortex of the brain occur because of the functional haemodynamic response (or the haemodynamic response function; HRF). When there is an increase in neuronal activity in an area of the brain (for example whilst completing a psychological task), there is an increased metabolic demand for oxygen. To meet this increased demand, the vascular system reacts by dilating to increase blood flow to the brain area to supply oxygen (in the form of HbO_2) to the active neurons (neurovascular coupling). As illustrated in **Figure 1**, following a stimulus there is an increase in HbO_2 (to deliver oxygen to the active neurons) which is accompanied by a decrease in HHb (as the haemoglobin in the blood without oxygen returns to the lungs). At around 8 – 10 seconds post-stimulus, concentrations of HbO_2 and HHb return to a 'baseline' level. This physiological response is relatively slow compared to, for example, the quick event-related potential (ERP) responses recorded with electroencephalography (EEG) that occur in a matter of milliseconds (Sur & Sinha, 2009). It is for this reason that the temporal resolution

offered by EEG cannot be matched by fNIRS. However, the spatial resolution offered by fNIRS is superior to that afforded by EEG, and so better enables functional localisation of brain activity to specific regions of the cortex (Lloyd-Fox et al., 2010).

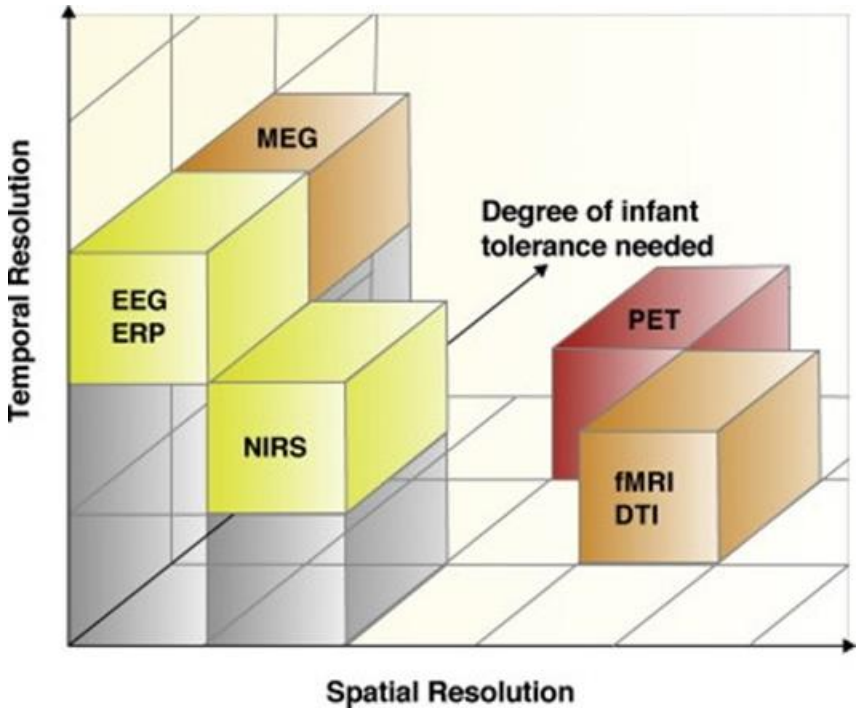
Figure 1. Chapter 3. The Canonical Haemodynamic Response.



Note. This figure is reprinted from Venclove et al. (2015) *(Figure 1) under the Creative Commons Attribution 4.0 International License. The figure caption (above) is the same as that used in the original article.*
Changes in hemoglobin concentration due to neural activity with stimulation from 0 to 5 seconds (grey bar); A - inflow of oxy-Hb*, when total blood volume is relatively unchanged; B - oxy-Hb rises rapidly during vasodilatation as well as total blood volume. *Oxy-Hb = oxygenated haemoglobin.

In comparison to its neuroimaging counterparts (**Figure 2**), fNIRS offers many advantages for the measurement of the neural response in infants and young children (Lloyd-Fox et al., 2010). Unlike fMRI, fNIRS is non-restrictive, affords the participant some degree of movement (more so if using wireless fNIRS technology) and is somewhat tolerant to motion artefacts. This is hugely advantageous when testing infants and young children who do not tolerate sitting still for any length of time! Whilst the spatial resolution and depth sensitivity achieved with fMRI is superior to that achieved by fNIRS, it is still possible with fNIRS to functionally localise activation to specific regions of the cortex at a greater resolution than is achievable with EEG (although note that EEG is also relatively well tolerated by infants). Overall, fNIRS offers a unique solution to some of the problems surrounding imaging the infant brain; it is well-tolerated by infants and young children, relatively inexpensive and easy to set up, and enables the neural correlates of cognition to be functionally localised to specific regions of the cortex.

Figure 2. Chapter 3. Infant Functional Neuroimaging Methods.



Note. Reprinted from Neuroscience & Biobehavioural Reviews, Volume 34, Issue 3, Lloyd-Fox, S., Blasi, A., & Elwell, C. E. (2010). "Illuminating the developing brain: The past, present and future of functional near infrared spectroscopy", pages 269 – 284. Copyright (2010), with permission from Elsevier (License Number: 5559280307589). This figure shows the spatial and temporal resolution of NIRS compared with other infant functional neuroimaging methods. It also illustrates the relative degree of tolerance needed from the infant for each method, ranging from yellow (low) to red (high). EEG, electroencephalography; ERP, event-related potential; MEG, magnetoencephalography; NIRS, near infrared spectroscopy; fMRI, functional magnetic resonance imaging; DTI, diffusion tensor imaging; PET, positron emission tomography. (This figure was inspired by Walsh & Cowey, 2000).

In summary, the introduction of fNIRS to the developmental cognitive neuroscientist's toolkit has enabled researchers to ask and answer questions about the neural correlates of cognition in populations that have not before been within easy reach. Unlike the noisy scanner environment of an fMRI experiment where infants and young children would be required to stay very still (or be asleep), fNIRS is well-tolerated by this population, largely due to the high degree of movement possible whilst wearing an fNIRS cap. This means that even the very youngest participants can be awake during the measurement, opening the possibility to use a range of response-based tasks to measure cognition whilst measuring brain activation. This is a huge step forward from neuroimaging studies that either scan the brains of asleep infants or young children or from those that use passive (viewing-based / looking time) experimental paradigms whilst measuring brain activation. Whilst there are many considerations that must be made when planning and conducting an fNIRS study with developmental populations, this technique promotes the advancement of knowledge in the

field of developmental cognitive neuroscience as, with it, it is possible to functionally localise brain activation to specific regions of the cortex whilst participants are awake and engaged in active tasks, thus being comparable to studies that have previously only been possible with older children and adults.

2. fNIRS for the Measurement of the Neural Correlates of Early Cognition

fNIRS is used in this thesis as a methodological tool to examine the neural correlates of early inhibitory control in infancy and early childhood. Chapter 4 reports on data collected from 10-month-old infant participants (the first assessment point in the OEEF study), Chapter 5 reports on data collected from these same participants, now at 16-months of age (the second OEEF assessment point) and Chapter 6 reports on data from these participants at 3½ years (the final OEEF assessment point). All three studies followed the same experimental design (with minor differences to ensure the task was age-appropriate) and procedure in that fNIRS was used to record neural activation in the PFC and parietal regions whilst participants completed the Early Childhood Inhibitory Touchscreen Task (ECITT; Holmboe et al., 2021), an age-appropriate task designed specifically to measure response inhibition in infants and young children. For ease of reading, a brief description of the ECITT is included below, with full details of the task design and procedure presented in Chapters 4 – 6 of this thesis. These chapters will also include a description of the research aims, hypotheses, methods, and results for the relevant study. Note that many methodological procedures will be identical across the three studies.

The section below outlines the considerations that come into play when designing fNIRS experimental tasks and paradigms for infants and young children and describes the approaches taken in the studies presented in this thesis to overcome or account for these unique issues. Further, specific details about the parameters and design of the fNIRS equipment, as well as procedural details of the fNIRS technical setup used specifically to investigate early inhibitory control in these studies, are described below. Note that some of the content in this section may overlap with the publication associated with the data from the 10-month assessment point (Fiske et al., 2022).

2.1. fNIRS Experimental Design Considerations for Testing Infants and Young Children

Whilst fNIRS affords many advantages that make studying the neural substrates of early cognition more feasible with infants and young children, there are many experimental and

task design considerations that must be carefully evaluated to accommodate the needs of this developing population. For example, tasks used with infants and young children must be age-appropriate, highly engaging, and sensitive to the response styles and abilities of participants at each developmental stage. A significant problem in research with infants and young children is non-responsiveness; whereby participants choose not to engage with the task entirely, disengage with the task when they become bored or distracted, deliberately give wrong answers or simply do not respond at all (Spit et al., 2023). This is particularly important in fNIRS studies, where large numbers of trials are required to increase the signal-to-noise ratio and improve the quality of the signal being measured.

The studies presented in Chapters 4 – 6 of this thesis used a blocked version of the ECITT (Holmboe et al., 2021) alongside fNIRS to examine the functional neural correlates of response inhibition. To provide a brief description, participants were presented with an iPad (in a horizontal configuration) which displayed two blue 'buttons' on the left and right of the screen; one button was blank and the other contained a smiley face icon (see **Figure 3** below). Participants were encouraged by the experimenter to "Touch the happy face". Once the button with the smiley face icon was pressed a short, animated cartoon (~4 s) was played. If the blank button was pressed, there was no change on the screen. The trial continued until the correct button (with the smiley face) was pressed either by the participant or the experimenter. As such, the task is self-paced. The task encouraged the development of a prepotent response by presenting the smiley-face icon on the same side of the screen in 75% of trials. In the remaining 25% of trials, participants needed to exert response inhibition to overcome the prepotent response and respond on the opposite side of the screen.

To increase responsiveness, particularly when compliance is already being tested by wearing the fNIRS cap, the ECITT was designed to be as intuitive and exciting as possible. The variety of animated cartoons with attractive sounds following each correct response played a large role in engagement with the task – useful both to reorient the child's attention to the screen and because participants enjoyed watching different animations, they were more motivated to continue responding. This was evidenced in the unusually high number of trials completed by participants in infancy (36 – 90 individual trials). Similarly, since participants were required to make a motor response to the touchscreen (and the task was self-paced), the task was not passive as is often the case with infant paradigms, therefore increasing the participant's motivation to engage with the task.

Another consideration is that tasks designed to be used alongside fNIRS usually adopt either a block design or an event-related design. A block design is where trials of the same type/condition are presented together in 'blocks' that are separated by a baseline ('rest')

period, whereas an event-related design is where trials are presented individually in random order and are separated by an inter-stimulus interval. It was decided that the ECITT would be adapted to follow a block design when used alongside fNIRS. In brief, the blocked version was divided into two task blocks: the 'control' block, which consisted of six prepotent trials, and the 'experimental' block, which consisted of three prepotent and three inhibitory trials. As such, the proportion of prepotent and inhibitory trials across the blocked ECITT was the same as in the behavioural version (75% prepotent, 25% inhibitory). An example trial sequence for each block type is illustrated in **Figure 3**.

A baseline block (video showing colourful, moving abstract shapes accompanied by pleasant instrumental music) was added to the fNIRS adaptation of the ECITT to represent a period of minimal cognitive effort (reflecting the brain at 'rest'). The haemodynamic response recorded during the baseline (non-task brain activity) could then be used to compare the haemodynamic response during control and experimental blocks (task-related brain activity); see Wilcox & Biondi (2015) for discussion about the inclusion of a baseline event in block design fNIRS tasks. The baseline block was jittered in duration (12 – 17 s) to limit any anticipatory neural activation ahead of task blocks. The task was automatically administered in the same order for all participants: baseline, control, baseline, experimental, baseline, control etc. (see **Figure 4**).

The choice to use a block design for the ECITT was made firstly because a core component of the ECITT's functionality is that it relies on the establishment of a prepotent response. To build up a prepotent response tendency, a relatively fast and continuous stream of stimuli is needed (as in a block design). In fact, there is extensive evidence that prepotency dissipates at longer time intervals/delays (for reviews, see Holmboe et al., 2021 and Simpson et al., 2012). This would be problematic in an event-related design because the core premise of the task, i.e., the overcoming of a prepotent response built up over several trials in a relatively fast-paced sequence, is eroded if there is a long delay between every single trial (i.e., the inter-stimulus interval). For these reasons, it was concluded that a block design was the most suitable for the fNIRS version of the ECITT. This way, the neural responses involved in experimental blocks (where there was some inhibitory demand) compared to control blocks (where there was no inhibitory demand) could be investigated.

Figure 3. Chapter 3. The Blocked ECITT

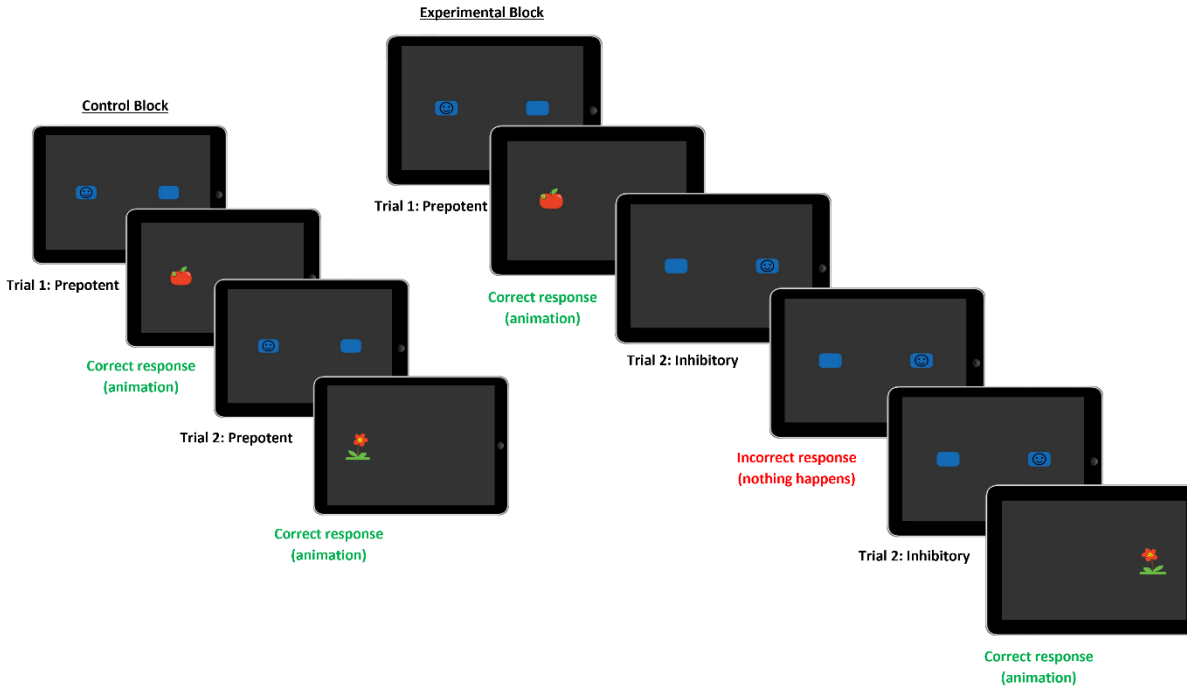
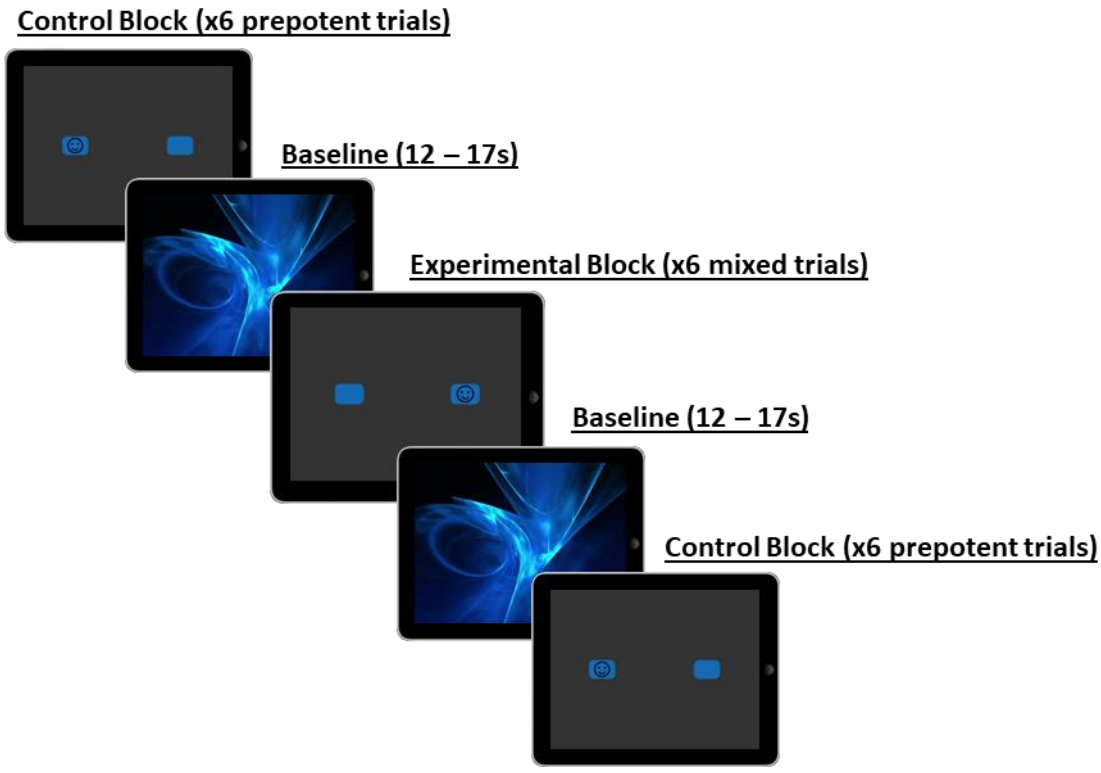


Figure 4. Chapter 3. Sequence of Block Presentation on the Blocked ECITT.



A second reason that a block design was chosen for the ECITT is because it was unlikely that we would be able to obtain the number of trials required for event-related analyses with a population of infants and young children. An event-related design would also have required a jittered inter-stimulus interval between trials (e.g., Mehnert et al., 2013, had an average interstimulus interval of 5500ms, ranging from 3750 – 12000ms). However, an interstimulus interval of this duration is simply not feasible when testing infants and young children, who will not sit and wait for longer than 3 – 4 seconds before they disengage with the task. This would introduce noise to the data and/or mean that data collection had to be stopped early. Additionally, it has been argued that these relatively short inter-stimulus interval durations would not be long enough for the haemodynamic response to return to baseline in infants and young children (Issard & Gervain, 2018). The blocked version of the ECITT had a jittered baseline (12 – 17 s) and appeared after every six (10- and 16-months) or eight (3½ years) trials (instead of after every trial as in an event-related design). The baseline consisted of an engaging but calm video accompanied by classical music – sufficient to maintain the interest of the infant or young child but not enough to be arousing, and therefore being a good proxy for a state of minimal cognitive effort ('rest'). Although it has been argued that the infant brain does not 'rest' like the mature brain, therefore it is important to consider that measurement of brain activity during baseline periods may not truly be indicative of rest in young participants in the same way as adults (Camacho et al., 2020).

2.2. fNIRS Technical Parameters and Challenges

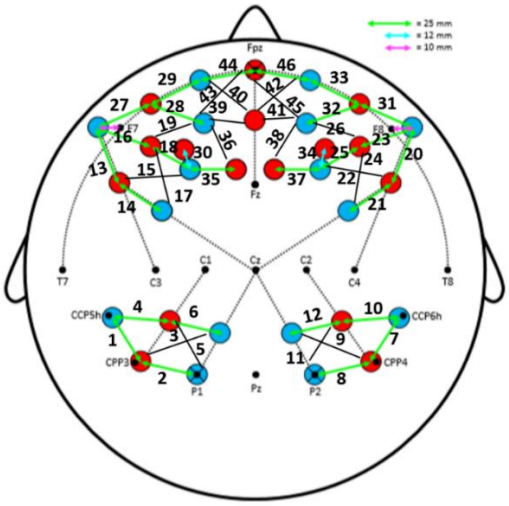
The sections below will describe the specific fNIRS technical parameters that were used for the three fNIRS studies presented in this thesis (Chapters 4, 5, and 6). It will also highlight specific issues that apply to the use of fNIRS with infant and child participants.

2.2.1. Gowerlabs NTS fNIRS system

The Gowerlabs NTS continuous wave fNIRS system was used to collect data at all three assessment points (sampling rate of 10 Hz). To measure changes in the concentration of oxygenated and deoxygenated haemoglobin in the cortex of the brain, near-infrared light was emitted at 780 and 850 nm. The source levels (intensity of light emitted) were manually set to 80% (60% for short separation channels), although these were either manually adjusted or adjusted using the 'auto-level' function when necessary (e.g., depending on the amount and type of hair) to achieve the optimum light saturation levels.

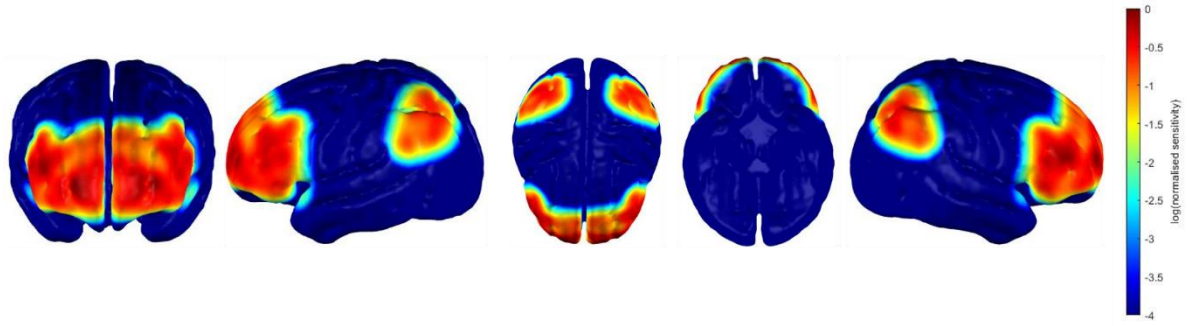
The fNIRS array consisted of 32 optical sensors (source-detector distance of 25 mm) that were fitted to an EasyCap and anchored onto three 10–5 reference points: FpZ, P1 and P2. The 32 optical sensors formed 46 channels that bilaterally covered the PFC and the area around the intraparietal sulcus (see **Figure 5** for a channel map and **Figure 6** for a sensitivity map that indicates the approximate neural areas covered by the array). The probe was designed to cover these areas of the brain because previous literature indicated that these brain regions had been associated with inhibitory control tasks in studies with older children or adult populations (e.g., Mehnert et al., 2013; Tamm et al., 2002).

Figure 5. Chapter 3. fNIRS Probe Channel Map.



Note. Red circles represent source optodes, and blue circles represent detector optodes. Black circles indicate positions that map onto the 10-5 system and optodes with crosses are anchored onto these 10-5 positions. The dotted lines are guidelines. Numbers are the channel numbers.

Figure 6. Chapter 3. fNIRS Probe Sensitivity Heat Map.



Note. This figure was produced using the positions of the optodes in this probe and a 12-month-old infant head model (Shi et al., 2011). These heat maps (displayed on a log normalised scale) are scaled to the maximum sensitivity value in the grey matter mesh. From left to right: frontal view, left view, superior view, inferior view, and right view of the sensitivity of channels in this array. **Image credit: Liam Collins-Jones.**

2.2.2. Short Channels

As well as detecting changes in haemoglobin concentration over time, fNIRS is also sensitive to superficial haemodynamic responses related to physiology (e.g., respiration, Mayer waves and the cardiac signal; Kirilina et al., 2012). To separate out the signal of interest from the physiological noise, it is possible to use short-separation channels where the optical source and detector are positioned close enough together that the attenuated light could only have passed through the scalp and skull, rather than the deeper brain tissue. In this way, signals measured from short-separation channels are measuring only the physiological noise which can then be filtered our using regression techniques in the pre-processing phase (Brigadoi & Cooper, 2015).

For this reason, two short channels were included in the fNIRS probe. However, the separation of the short channels (12 mm) was too large for participants in the current study (10-months, 16-months, and 3½ years) as they were sampling brain data (rather than physiological noise from the scalp and skull). According to Brigadoi & Cooper (2015), the optimum short separation distance is 8.4 mm for an adult head and 2.15 mm for a new-born infant, whereas Emberson et al. (2016) suggest a 1 cm (10mm) distance for a short channel with infant participants (~6 months). Practically, it was not possible to have channels this short due to the limitations of our fNIRS hardware. Therefore, data collected from the short channels were excluded from analyses and physiological noise was filtered out using band-pass filtering. A variety of pre-processing filtering techniques are available, but there is not yet a standardised approach to the removal of physiological noise (see Pinti et al., 2019).

2.2.3. Headgear Placement and Registration

The fNIRS cap was fitted to the participant's head so that the front of the cap sat just above the eyebrows, and the optode anchored to FpZ was positioned centrally between the eyebrows, as illustrated in **Figure 7**. The headgear placement was standardised across participants (as much as possible) to ensure that the optical sensors were indeed covering the brain areas they were designed to cover. At the start of the fNIRS test session, photographs or videos were taken as a record of how the fNIRS cap was positioned on the child's head. If there was significant cap movement during the session, additional photographs/videos were recorded at the end of the session to document the movement of the cap on the head. The validity of the headgear placement was assessed by independent coders who viewed the photographs and videos and rated the headgear placement using a simple coding scheme. Headgear placement was coded as 'good' if the edge of the EasyCap was sat straight on the head and on the eyebrows or just very slightly above the eyebrows, with the central optode (FpZ) in the centre of the forehead, level with the

eyebrows. Headgear placement was coded as ‘acceptable’ if the cap was sitting a little high and/or a little lop-sided on the head with the central optode (FpZ) slightly off-centre but looked acceptable overall. Headgear placement was coded as ‘poor’ if the cap was sitting very high (halfway up the forehead or higher) and/or was not on straight at all, with the central optode being nowhere near the centre of the forehead (more than halfway over the eyebrow, from the middle of the eyebrow and beyond). Headgear placement that was rated ‘poor’ was deemed invalid and the participant’s fNIRS data was not included in the data analysis.

Figure 7. Chapter 3. fNIRS Headgear Placement.



Note. The image shows a 10-month-old participant wearing the fNIRS headgear. Parental consent has been granted for the use of this image.

Many participants were excluded in each of the fNIRS studies (see Chapters 4 – 6 for details) due to poor cap placement. This was necessary as incorrectly positioned caps would likely mean that optodes were covering different regions of the brain than intended. There are many unique challenges that come with accurately placing fNIRS headgear on awake infants and young children. Firstly, the participant is very unlikely to stay still and so it becomes increasingly difficult to fit a cap on the head of a fidgeting or fussing participant. Secondly, the cap is much smaller than an adult fNIRS cap (but appropriate to the infants’ head size) which can make for a fiddlier fitting, and thirdly, the participant is far less likely than an adult to tolerate the experimenter moving the cap whilst on their head to improve the position and signal quality. A further issue is that this is very time-sensitive in that if the participant becomes fussy or distressed by the cap fitting, it is important to start the task as quickly as possible to distract the participant from the cap and regain their attention and

interest. The longer between cap fitting and task onset, the more likely the participant will refuse to participate.

A final issue involves the digitisation of optode positioning in relation to the participant's head measurements and key reference points. This is a necessary step for the registration of the fNIRS probe to the scalp, and to support the localisation of channels to specific brain regions. In studies with adults and older children, this process can be relatively straightforward in that a 3D digitiser tool (such as a Polhemus) can be used to record these measurements. This process can be time-consuming, involves putting a sensor at different positions on the head, and requires the participant to continue wearing the fNIRS headgear after the task has been completed. For many reasons, this is simply not a feasible option with awake infant participants (although was possible with the sample of 3½ year-olds, however, it was not possible to use this data; see Chapter 6). Recent advances in technology such as smartphone-based photogrammetry (Mazzonetto et al., 2022) or video-based automatic spatial co-registration methods (Jaffe-Dax et al., 2020) have provided a fundamental step forward to resolving the difficulty in registering optode positions in early developmental populations.

2.2.4. fNIRS Event Markers and Timing

In our fNIRS setup (see **Figure 3d,** Chapter 2), the NTS system was connected via USB to a laptop (the 'fNIRS laptop') that controls the NTS system. The NTS system was connected via USB to a second laptop (the 'sync laptop') used to send an exact time stamp (custom MATLAB script) to the data stream recorded by the NTS system. The time stamp was generated from the internal laptop clock that was synced to the Apple server immediately before each test session. The internal iPad time (on which the task was administered) was automatically synced to the Apple server (+/- 5 ms) at least once a day. Because the fNIRS continuous data stream does not have an internal clock variable, the time stamp signal was used to align the event markers (collected by the task software on the iPad) with the brain data collected by the NTS system (custom MATLAB script). Any discrepancy between the iPad time and the generated time-stamp marker will mean that there is a slight misalignment between the actual time the task block started and the time at which the event marker is positioned. Small random lags or discrepancies (typically a few hundred milliseconds) in internal computer clocks are common and small lags are unlikely to bias the data in any systematic way. In rare cases of greater temporal misalignment, it would be expected to add only a small amount of measurement error to the data, given the slow temporal nature of the haemodynamic response. Since this measurement error would be the same across all task

block types, any slight timing disparity is very unlikely to induce spurious effects in the results.

2.2.5. fNIRS Testing Procedure

Participants were seated on the parent / caregiver's lap and positioned at a small table (see **Figure 3d**, Chapter 2). The optical fibres (wires) connected to the fNIRS headgear were positioned on the parent / caregiver's shoulder and secured in place by a Velcro strap fastened around the base of the parent's neck. This was done to prevent the child's movement being restricted by the weight and the position of the wires. At the 10- and 16-month assessment points, the infant was distracted by the second experimenter using toys or bubbles whilst the lead experimenter positioned the fNIRS cap onto the infant's head. At the 3½ year assessment point, participants were watching a child-friendly cartoon on a laptop (positioned on the table) to distract them whilst the experimenter positioned the headgear. Once satisfied with the positioning, photographs or videos were taken of the cap position on the child's head. The second experimenter then sent the time stamp signal to the NTS stream, and once received, the lead experimenter began administering the task to the participant. At the 10- and 16-month assessment points, once the task was complete, the lead experimenter removed the fNIRS cap from the child and the Velcro strap from the parent's shoulders and the session would be complete. At the 3½ year assessment point, once the task was complete the lead experimenter resumed the cartoon video for the child to watch and used a stylus connected to a Polhemus digitizer to localise the position of the optodes on the participant's head, as well as the nasion, inion, and left and right preauricular points. After this, the lead experimenter removed the fNIRS cap from the child and the Velcro strap from the parent's shoulders and the session was complete.

2.2.6. fNIRS Pre-processing and Statistical Analysis Approaches

The fNIRS data presented in this thesis were pre-processed in HoMER2 (Huppert et al., 2009), a MATLAB toolkit that has built-in functionality to pre-process and analyse fNIRS data. The pre-processing pipeline and statistical analysis approach used in the studies presented in this thesis are described in the Methods section of Chapters 4 - 6.

Since the use of fNIRS for experimental purposes is still a *relatively* new field, there is a lack of standardisation in the approaches taken to pre-process and analyse fNIRS data, and as such, there is still no 'gold-standard' approach. As a result of this lack of standardisation, many pre-processing pipelines and analysis techniques are used in the field, yet methodologies that have been used successfully with adult fNIRS data do not always work

appropriately with infant or toddler fNIRS data. This is due to the characteristics of fNIRS data from early developmental populations in that they are more frequently plagued with motion artifacts (Di Lorenzo et al., 2019), can show inverted responses, and often do not adhere to the canonical shape of the haemodynamic response (Issard & Gervain, 2018).

Recently, Gemignani & Gervain (2021) compared five different pre-processing pipelines that had been commonly used in the infant fNIRS literature, and from this, made some recommendations for infant fNIRS researchers to improve signal-to-noise quality. These included having strict inclusion criteria to preserve data quality, rejecting bad quality trials, and correcting for motion artefacts. However, since there are several motion correction techniques available that all manage motion in different ways, different techniques could lead to different outcomes (Gemignani & Gervain, 2021). In an effort to standardise the pre-processing of infant fNIRS data, Di Lorenzo et al. (2019) tested different motion correction techniques in HomER2 on real infant datasets collected from samples of a similar age to our infant participants. It was concluded that the use of spline interpolation (Scholkmann et al., 2010) followed by wavelet filtering (Molavi & Dumont, 2012) offered the most effective approach to motion correction in infant fNIRS data. As such, this approach was followed in the pre-processing of the fNIRS data presented in this thesis.

There are two common methods used to estimate the HRF: block-averaging or the general linear model (Yücel et al., 2021). Whilst the general linear model allows for additional regressors of interest to be modelled with the HRF, it assumes that the HRF takes a canonical shape. On the other hand, the block-averaging approach does not make assumptions about the shape of the HRF and so is more appropriate for use with infant fNIRS data where the shape of the HRF can be highly variable and non-canonical (Gemignani & Gervain, 2021; Issard & Gervain, 2018). In the studies presented in this thesis, each trial of the ECITT was followed by a short animation, which meant that the haemodynamic responses fluctuated within blocks. To deal with this variability within blocks and to ensure no assumptions were made about the shape of the HRF, the baseline-corrected averaging approach was selected for the analysis of the infant fNIRS data presented in this thesis. The block-averaging approach is frequently used to analyse infant fNIRS data in the literature (e.g., Behrendt et al., 2020; de Klerk et al., 2018; Perdue et al., 2019).

2.2.7. Improving Transparency and Reproducibility in fNIRS Studies

It is worth noting that recently within the fNIRS community, there have been efforts to identify best practices and improve the reproducibility of fNIRS studies (Schroeder et al., 2023;

Yücel et al., 2021). For example, Yücel et al. (2021) have produced detailed guidelines to support researchers in preparing an fNIRS study in attempt to encourage the community to enhance the reliability and credibility of their research, and Schroeder et al. (2023) have highlighted how using study preregistrations can improve the transparency of fNIRS study design, pre-processing and analysis procedures.

To strengthen the credibility of my own research, the hypotheses, data processing pipelines and analysis plans were registered on the Open Science Framework. In doing so, I was removing the researcher degrees of freedom by explicitly stating my intentions *a priori*, clearly describing my data processing approach, and freely providing materials that can be used by others following this approach. The 10-month study presented in Chapter 4 of this thesis (and published in Fiske et al. (2022)) was largely exploratory (due to the lack of any previous fNIRS research on this topic), but I pre-registered hypotheses for the secondary level of analysis to improve the transparency of the study. Since the 16-month fNIRS study (presented in Chapter 5) was a methodological replication of the 10-month study, I pre-registered all my hypotheses, analysis plans, and data processing pipelines before analysing the data. Similarly, the hypotheses and analysis plans for the study presented in Chapter 6 with 3½ year-olds were pre-registered but it is embargoed as it contains the results of previous unpublished work. However, for this thesis, it can be accessed here and should be treated as confidential. The methodological approach used in these studies is novel, and so replication and/or reproduction is strongly encouraged – both to validate the methodology and to strengthen the reliability of our results. These pre-registrations and open data act as a 'recipe book' that other researchers can follow to replicate or reproduce these studies (Schroeder et al., 2023).

3. Summary

This chapter aimed to shine a light on the use of fNIRS in developmental cognitive neuroscience. Specifically, this chapter provided an explanation of the physical mechanisms through which fNIRS measures neural activation, highlighted the value that fNIRS can add to developmental neuroimaging, and discussed the unique challenges that must be considered when conducting fNIRS studies with infants and young children. This chapter also outlined the ways in which fNIRS is used in this thesis to measure neural activation during a cognitive task in early developmental populations.

Chapter 4

The Neural Correlates of Response Inhibition in 10-month-old Infants

This chapter will report on an empirical study that used fNIRS to investigate the functional neural correlates of response inhibition in infancy. Data presented in this chapter were collected from 10-month-old infant participants at the first assessment point in the OEEF study. Infants were required to complete the blocked version of the Early Childhood Inhibitory Touchscreen Task (ECITT; Holmboe et al., 2021), an age-appropriate measure of response inhibition, whilst their brain activity was measured using fNIRS.

The information and data included in this chapter are based on the published article by Fiske et al. (2022), with permission from the co-authors of this paper and in compliance with the CC-BY license. An author contribution statement that outlines the role of each author in the preparation of this published study is included in Appendix B1.

1. Background

Response inhibition can be reliably measured in infancy from as early as the second half of the first year of life (Diamond, 1985; Hendry et al., 2021; Holmboe et al., 2008, 2018), and inhibitory control development continues across toddlerhood before rapidly improving in the pre-school years (Hendry et al., 2016). However, it is very difficult to measure response inhibition in early life. For example, due to the still-developing language skills and the rudimentary working memory ability of infants, many canonical measures of response inhibition (e.g., the Go / No–Go or Stop Signal Task) cannot be used with this young population. Therefore, researchers have had to rely either on resting state studies (e.g., Whedon et al., 2020) or on eye-tracking tasks, such as the looking version of the A-not-B task (e.g., Bell & Fox, 1992; Broomell & Bell, 2022), or the Freeze-Frame task (Holmboe et al., 2018), to measure response inhibition in infancy. However, since eye-tracking tasks are often more passive (i.e., requiring only a saccadic response from the infant) than the

canonical tasks used with older populations that require a motoric response, it is difficult to compare the results from studies with infants to those with young children and adults. As a result, it has not previously been possible to reliably establish the developmental trajectory of response inhibition from its emergency in infancy and across early childhood.

A novel measure of response inhibition, the ECITT (Holmboe et al., 2021), has recently been developed as an age-appropriate task that can be used with infants as young as 10-months (Hendry et al., 2021) but also across the lifespan (Holmboe et al., 2021). In this way, the same task can be used to assess response inhibition at various points in development, allowing for a direct comparison of inhibitory performance at different age points or for the examination of improvements with age. By keeping the same task, the possibility that differences in inhibitory performance are due to inherent task-related factors is removed, something which can often be a methodological problem in longitudinal or cross-sectional research. The ECITT relies on the development of a prepotent response by ensuring that, on 75% of trials, the target (a smiley) appears on the same side of the screen. On the less frequent trials (25%) where the smiley appears on the contralateral side of the screen, response inhibition is required to inhibit the prepotent response and instead make the correct response on the opposite side of the screen. Since this task requires very limited instructions (with the only instruction being “Can you touch the happy face?”) and has minimal working memory requirements, it is appropriate for use with infants and young children. However, unlike other tasks used with this population, the ECITT requires an active, motoric response so is more comparable to tasks used with older children and adults.

A large body of research with older children and adults has consistently identified regions of the PFC, specifically the right inferior frontal cortex (IFC; for review, see Aron et al., 2014) and regions of the parietal cortex (e.g., Cope et al., 2020; Durston et al., 2002) as being involved in response inhibition tasks. However, very little is known about the neural correlates of response inhibition as it emerges in infancy. Most existing knowledge stems from EEG studies (Bell & Fox, 1992; Bell & Wolfe, 2007; Broomell et al., 2021). For example, Cuevas et al. (2012) found increased coherence across regions of the PFC, although no increase in EEG power, when there was an increased inhibitory demand in a looking A-not-B task. Whilst this literature has provided insight into the broad underlying function of the frontal cortex, the spatial limitations of EEG measurement do not allow activation to be localised to specific brain regions. Similarly, the sensitivity of EEG to motion artefacts (which is particularly problematic with infant participants) has driven researchers to use response inhibition tasks that minimise movement (i.e., passive tasks), to increase the signal-to-noise

ratio. As such, our understanding of the neural correlates of response inhibition in early development has been limited by these methodological challenges.

With the addition of fNIRS to developmental cognitive neuroscience research, it has recently become feasible to localise the functional neural substrates of EF to specific regions of the developing cortex in young children (e.g., Buss et al., 2014; Monden et al., 2015; Moriguchi et al., 2018). An fNIRS study examining response inhibition in older children (4 – 6 years) and adults found increased activation in the right PFC and parietal cortex when inhibition was required during a Go / No-Go task, although children showed weaker functional connectivity between frontal and parietal regions than did adults (Mehnert et al., 2013). Yet, even with technological advances that mean fNIRS is feasible with awake, active infants and toddlers, few fNIRS studies have been conducted that investigate the neural correlates of executive function with children under 2 years of age (although for examples, see, Kerr-German et al., 2022; Kerr-German & Buss, 2020; Reyes et al., 2020; Wijeakumar et al., 2019). Further, there have been no studies that have used fNIRS to investigate the neural correlates of response inhibition in children under 2 years of age. To help bridge the existing knowledge gap about the neural mechanisms underlying early inhibitory control development, the current study employed fNIRS alongside an age-appropriate measure of response inhibition to investigate the functional neural substrates of response inhibition in 10-month-old infants.

2. Method

2.1. Participants and Exclusions

Full demographic information for the sample of 10-month-old participants is available in Chapter 2 of this thesis. Participants completed two versions of the ECITT – the behavioural ECITT was completed in the first test session, and the blocked ECITT was completed alongside fNIRS in the second test session approximately one week later. Following sample-level exclusions, 141 infants contributed behavioural ECITT data, and 135 infants contributed both behavioural ECITT and blocked ECITT data to this study. Following exclusions (see **Table 1**), the final sample of behavioural ECITT data consisted of 128 participants, and the blocked ECITT sample consisted of 121 participants. A total of 112 infants (*N* = 53 males) had valid ECITT data from both sessions.

fNIRS data from the 121 participants who contributed valid blocked ECITT data were assessed against inclusion criteria to determine the validity of the fNIRS data collected whilst

the ECITT was completed (**Table 1**). The final sample of participants with valid fNIRS data was 59, thus there was considerable fNIRS data attrition (~51% of data excluded). Of the 59 infants with valid fNIRS and blocked ECITT data, 57 infants also contributed valid behavioural ECITT data.

Table 1. Chapter 4. 10-month Data Exclusions.

Behavioural ECITT (Session 1)	***N***
Less than 16 trials completed (including at least 2 valid inhibitory trials)	9
Less than 60% accuracy on prepotent trials	4
Total Excluded	**13**
Percentage Excluded	**9.22%**
Total Included	**128**
Blocked ECITT (Session 2)	***N***
Did not complete task	2
Less than 2 blocks of each condition completed	11
Less than 60% accuracy on prepotent trials	**1**
Total Excluded	**14**
Percentage Excluded	**10.37%**
Total Included	**121**
fNIRS Data	***N***
Data file was lost	1
Refused to wear fNIRS cap	3
Did not complete at least 3 blocks of each type (6 blocks total)	16
fNIRS cap was removed before the minimum number of blocks had been completed	3
fNIRS cap placement was invalid	19
Did not have at least 3 valid blocks of each type (6 valid blocks total)	13
Did not meet pre-processing data quality criteria	7
Total Excluded	**62**
Percentage Excluded	**51.24%**
Total Included	**59**

2.2. Apparatus and Stimuli

2.2.1. Gowerlabs NTS fNIRS system

The Gowerlabs Ltd. NTS continuous wave fNIRS system was used to collect data from participants. The fNIRS probe consisted of 32 optical sensors forming 46 channels that bilaterally covered the PFC and the area around the intraparietal sulcus. A full description of the fNIRS system and probe design is provided in Chapter 3 of this thesis.

2.2.2. Early Childhood Inhibitory Touchscreen Task (ECITT)

The ECITT (Holmboe et al., 2021) is a novel touchscreen task designed specifically to measure response inhibition in infants and young children. The ECITT measures response inhibition by encouraging the development of a prepotent response to one side of the screen on 75% of trials ('prepotent' trials) and requiring participants to inhibit the prepotent response and instead respond to the opposite side of the screen on the remaining 25% of trials ('inhibitory' trials). Please see Holmboe et al. (2021) for a full description of the software, stimuli, and task validation information.

Before the task, infants were allocated to either the 'left' or the 'right' prepotent side; this meant that all prepotent trials (75% of all trials) would appear on this side of the screen. The allocated prepotent side remained the same for all participants across all assessment points and across both versions of the task (behavioural ECITT in Session 1 and blocked ECITT in Session 2). However, if infants made an incorrect response on the first trial of the behavioural ECITT at the 10-month assessment point (N = 21), the prepotent side was switched and the task re-started, both to ensure the build-up of a prepotent response and because it was assumed that this may potentially be indicative of the infant having a strong side bias. This decision was made to minimise the additional noise that a predisposed side bias (to either the left or the right) would potentially add to the data.

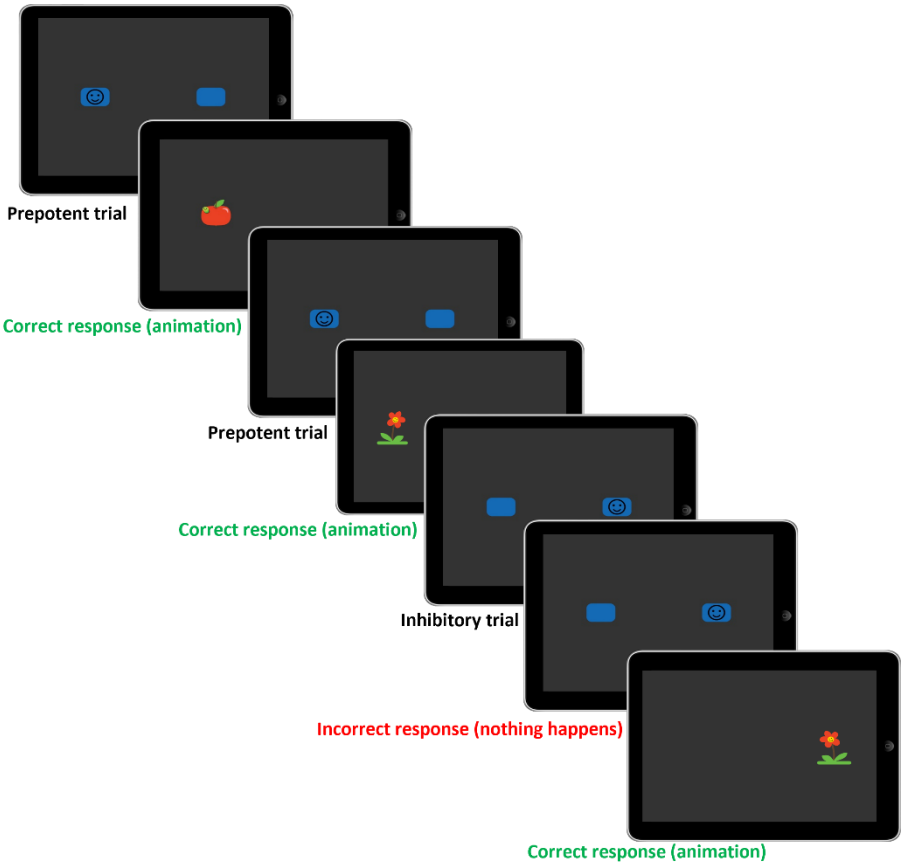
2.2.2.1. Behavioural ECITT

The behavioural version of the ECITT (administered in Session 1) consisted of 32 trials, of which 75% were prepotent (no inhibitory demand) and 25% were inhibitory (inhibitory demanding). An example trial sequence is illustrated in **Figure 1** below. Trials were presented in a random order, with the constraints that the smiley face (target) was always presented in the prepotent location on the first trial and could not appear in the inhibitory location for more than two consecutive trials.

Before the task began, the experimenter completed a demonstration trial. This consisted of one blue button (containing the smiley face icon) in the centre of the screen and the experimenter instructed the infant to "Watch what happens when I touch the happy face". Once the infant was looking at the screen, the experimenter touched the happy face and the short, animated cartoon played. The demonstration trial was followed by at least one practice trial, where the infant was asked "Can you touch the happy face?". More practice trials were presented as needed if the experimenter determined that the infant was slow to respond or unsure about touching the iPad. The experimenter always cued the first

experimental trial by pointing to the smiley face icon and instructed the infant to “Touch the happy face”. As such, the first trial was always coded as invalid during offline video coding, as was any trial after this where the target location was cued either by the parent or the experimenter (see section ‘Behavioural Data Processing’ below).

Figure 1. Chapter 4. The Behavioural ECITT.



2.2.2.2. Blocked ECITT

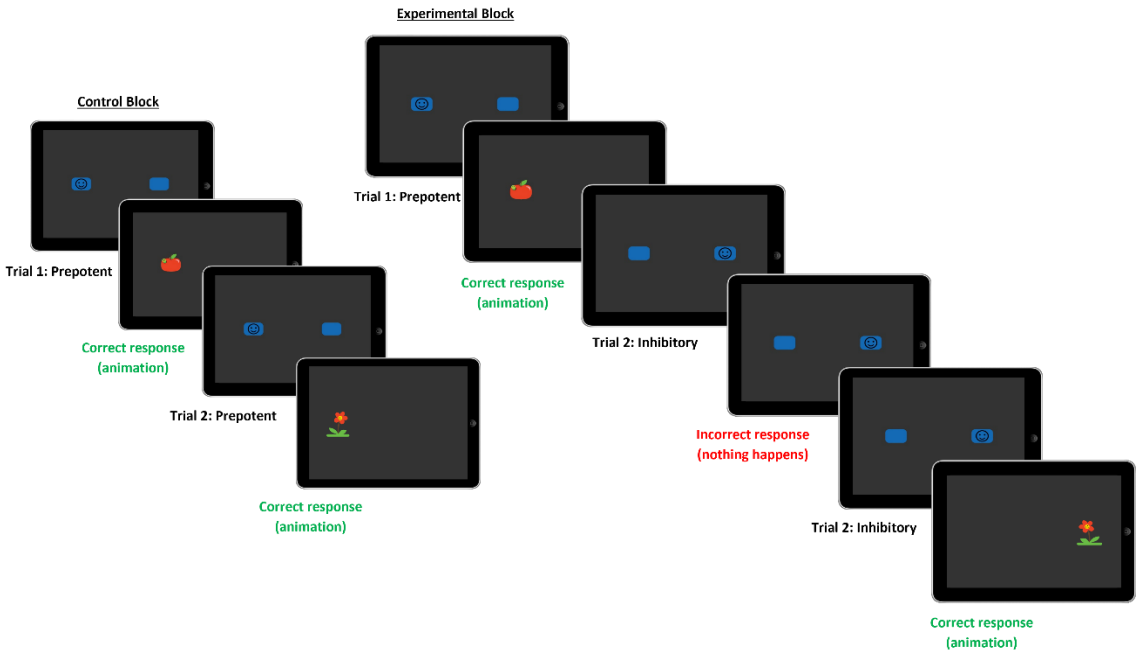
The blocked version of the ECITT (administered in Session 2) was adapted from the behavioural version of the ECITT to be appropriate for use with fNIRS. The blocked version was divided into two task blocks: the ‘control’ block, which consisted of six prepotent trials, and the ‘experimental’ block, which consisted of three prepotent and three inhibitory trials. Task blocks were separated by baseline blocks that consisted of a video showing colourful moving abstract shapes accompanied by pleasant, calming instrumental music (see video). As such, the proportion of prepotent and inhibitory trials across the blocked ECITT was the same as in the behavioural version (75% prepotent, 25% inhibitory). As in the behavioural version, the first experimental trial was always cued by the experimenter and so coded as invalid during offline video coding, as was any trial after this where the target location was

cued either by the parent or the experimenter (see section 'Behavioural Data Processing' below).

Unlike the behavioural version, there were no demonstration or practice trials and there was no set stopping point. As such, infants continued playing the task until the experimenter identified signs of fussiness, distraction, or inattention from the infant. The experimenter attempted to encourage the infant to continue playing until they had completed at least three blocks of each type (control, experimental) to ensure sufficient fNIRS data had been collected. An example trial sequence for each block type is illustrated in **Figure 2**, and a short video of an infant completing some trials of the blocked ECITT is available here.

The number of blocks of each type completed by infants with valid fNIRS data ranged from 3 – 7 (Control: *M* = 4.85, Experimental: *M* = 4.58), with a mean duration of 43 s (*SD* = 17 s) for control blocks and 49 s (*SD* = 18 s) for experimental blocks. Overall, infants with valid fNIRS data completed between 6 – 14 blocks of trials (*M* = 9.43), which is equivalent to 36 – 84 individual trials. Please see Fiske et al. (2022) for further details regarding the software, stimuli, and task.

Figure 2. Chapter 4. The Blocked ECITT.



2.3. Procedure

For both sessions, infants were seated on their caregiver's lap and positioned at a table, adjacent to the experimenter. The behavioural version of ECITT (Session 1) was

administered in the behavioural testing room (see Figure 3a in Chapter 2) and the blocked version of the ECITT (Session 2) was administered in the fNIRS testing room (see Figure 3d in Chapter 2). The behavioural ECITT began with a single demonstration trial followed by at least one practice trial before the first experimental trial began. There were no demonstration or practice trials in the blocked ECITT. In both versions of the task, the first trial was always cued by the experimenter with the instruction “Can you touch the happy face?”. Verbal encouragement was given when necessary to increase engagement but was kept to a minimum, especially during the fNIRS session. During both versions of the task, the experimenter removed the iPad from the infant’s reach (although still within sight) during the animations that occurred after each trial (both sessions) and during baseline blocks (Session 2 only) to minimise the possibility of premature or accidental responses. Please see ‘fNIRS Testing Procedure’ in Chapter 3 for further details about setting up the test session, including the fitting of the fNIRS cap.

3. Data Processing

3.1. Behavioural Data Processing

Trial-level accuracy data were automatically recorded by the ECITT software as 0 (incorrect) or 1 (correct). To account for the fact that infants’ motor systems are still developing and that precise touches to the blue ‘button’ (24 x 13 mm) may be more difficult, a larger response area (44 x 44m) surrounded the blue ‘button’. In this way infants had a larger area within which their response was recorded if a touch was detected; see example here. The accuracy and validity for each trial was reviewed manually through offline video coding. This is because responses were not always detected by the touchscreen due to the nature of infant responses (i.e., wet fingers due to having hands in mouth, responding with their fingernail or the back of their hand etc.,). This could add a potential source of noise to the data, and so by manually coding this data offline, data that were invalid could be excluded to diminish the noise caused by the technology not recognising the infants’ ‘messy’ responses. Since the task is response-contingent, the duration of each trial varied depending on how long the infant took to respond. No minimum or maximum trial length was imposed, although during video coding, trial lengths of < 300 ms or > 5000 ms were manually excluded. This coding was conducted in Microsoft Excel, using output from the ECITT software recorded during the testing session (template available here). The same coding scheme was used to code both versions of the ECITT. **Table 2** below provides details of the inter-coder reliability for the accuracy and validity coding.

Infants' looking behaviour during baseline blocks (Session 2 only) was coded offline from videos recorded during the session. Two trained coders used the Observer XT (version 15) video coding software to determine the validity of the baseline based on the infant's looking behaviour. The infant's looking behaviour during the baseline was only considered as valid if the infant was looking at the screen or somewhere neutral for at least 60% of the baseline duration. The onset and offset of baseline, control, and experimental blocks were marked to allow for durations to be calculated. ECITT trial responses in control and experimental blocks had already been coded in Excel using the coding scheme described above. The infant's looking behaviour during baselines was coded as either: looking at the iPad screen (watching the video) or looking somewhere else neutral (e.g., the table), looking at the faces of the experimenter / parent, or 'other' (e.g., infant was crying, fussing, or moving). See here for the full baseline coding scheme and see **Table 2** for details of the inter-coder reliability.

Table 2. Chapter 4. ECITT Inter-Coder Reliability.

	N of coders	N of videos (*N* of coding instances)	Test	Accuracy	Validity
Behavioural ECITT	3	17 (534)	Fleiss' kappa	κ = .959	κ = .886
Blocked ECITT	2	21 (833)	Cohen's kappa	κ = .920	κ = .850
Baseline Looking Behaviour	2	41 (1,715)	Cohen's kappa	N/A	κ = .850

For both versions of the ECITT, the software automatically recorded trial-level accuracy data, and trial validity was determined via offline video coding. From this, trial-level accuracy variables were generated for each trial type (prepotent, inhibitory) and were scored as either 0 (incorrect) or 1 (correct). Mean accuracy variables (prepotent, inhibitory) were generated for each participant and included the mean accuracy across all valid prepotent trials (mean prepotent accuracy) and the mean accuracy across all valid inhibitory trials (mean inhibitory accuracy). Additionally, an accuracy inhibitory score was generated for each participant and was used as an index of infants' response inhibition performance. The score was calculated as: (1 – (mean prepotent accuracy – mean inhibitory accuracy)/mean prepotent accuracy), such that a larger accuracy inhibitory score indicated better response inhibition.

3.1.1. Response Time Data

The ECITT software automatically recorded trial-level response time data (time from trial onset to the first touch in the response area, recorded in ms). However, it was decided that

response time data obtained from 10-month-old infants could not be considered reliable. From the experience of administering the task to 10-month-olds, several factors were identified that are likely to impact response time. For example, infants are very easily distracted and so response times can be prolonged due to momentary (or sustained) disengagement. Similarly, infants sometimes touch the screen by accident (e.g., when grabbing the iPad to hold it, or placing one hand on the screen for balance as they respond with the other hand) and so the response time recorded is inaccurate. Therefore, it was determined that it was not appropriate to use response time data from 10-month-old and so response time data were not manually corrected or analysed.

3.2. fNIRS Data Processing

3.2.1. Block Exclusions (Blocked ECITT)

Before the fNIRS data could be processed, a series of data quality checks were conducted which led to the identification (and subsequent exclusion) of invalid ECITT task blocks. Trial blocks (control, experimental) were identified as invalid during trial-level video coding if: they were not fully completed by the participant (e.g., the experimenter or parent completed one or more trials, or the participant stopped responding), the participant was excessively crying, fussing, or moving, there were issues with headgear (e.g., infant pulling out optodes) or technical difficulties.

Trial blocks were also invalid if the duration was longer than the mean duration + 2 SD for each block type (10-months: Control = 77 s, Experimental = 85 s). These long blocks were excluded from analysis because when participants take this length of time to respond, it is often due to boredom or a distraction that causes the infant to disengage from the task. During this time, the brain signal is unlikely to be related to the task and thus noise is introduced into the data. However, since we are keen to capture individual differences in task performance and brain activation, the criterion of the mean duration + 2 SD was chosen to ensure that those longer blocks of trials in which infants are responding to the task in a valid way but have a slower response style were not excluded. Invalid blocks of trials or baselines (identified in baseline coding) were manually excluded from processing in HomER2 (Huppert et al., 2009) using the ‘stim toggle on/off’ functionality.

3.2.2. Pre-processing in MATLAB and HomER2

A custom MATLAB script (written by Dr Robert Cooper) was used to convert the universal output format (.txt) files recorded by the NTS system into .nirs format, and to import event markers (start of each block) from the ECITT software and time sync information into the .nirs datafile. Data were then entered into HomER2 (Huppert et al., 2009) for pre-processing (see **Table 3** for full details of the processing stream parameters). First, raw intensity data were converted to optical density data. Then, any channels that either had very high or very low optical density were excluded at the participant level. Participants with more than 2/3 of channels excluded at this point were not included in further analysis (*N* = 7). A motion artefact identification function highlighted motion artefacts at the channel level which were then corrected using spline interpolation and wavelet transformation (Di Lorenzo et al., 2019). Following the removal of most motion artefacts, a bandpass filter was applied to remove non-brain physiological signals from the data. Finally, the optical density data were converted to haemoglobin concentration data.

Oxygenated haemoglobin (HbO_2) and deoxygenated haemoglobin (HHb) concentration change data from each channel were block averaged over a period of 47 seconds. Baseline concentration change data (two seconds) were subtracted from the average haemoglobin concentrations in the 45 second experimental window and the baseline-corrected data were divided into nine five-second time bins (45 s). However, subsequent analyses were focused on a refined time window of 37 seconds (two seconds of data from valid baseline blocks and 35 seconds of data from valid task blocks). This decision was made because, since the task is self-paced, each block for each participant varied in duration and so for some participants, the last two time-bins (35 – 45 s) captured baseline data for some participants and task data for others. When investigating the duration of each individual block completed by each of the participants with valid fNIRS data (*N* = 59), it was found that the minimum average duration of control blocks was 31 seconds. This means that all participants contributed control block data of at least 31 seconds (time bin seven; 30 – 35 s), however only 49 participants had a mean control block duration of between 35 – 40 seconds (time bin eight), reducing to 26 participants who had a mean control block duration that exceeded 40 seconds (time bin nine). For experimental blocks, the minimum average duration was 36 seconds (time bin eight; 35 – 40 s), meaning that all participants contributed experimental block data up until time bin eight. However, only 43 participants had a mean experimental block duration that exceeded 40 seconds (time bin nine). As such, the block time course was limited to 35 seconds to ensure that all time windows contained only task block data for all participants, rather than a mixture of task block data for some participants and baseline data for others.

3.2.3. Preparation of Data for Repeated Measures Analysis

A series of custom MATLAB scripts (written by Prof. Jun Yin) was used to convert the processed output file generated from HomER2 (Huppert et al., 2009) to a format where statistics can be generated (e.g., comparison between the two conditions, *t*- and *p*-value for each time bin and amplitudes for all time bins). A further custom MATLAB script (written by Dr Carina de Klerk) was used to convert the output files from the script above into a format that can be used to conduct repeated measures analyses. The output of this script is a datafile with one row per participant, and one column per time bin (9), channel (46), chromophore (2), and condition (3; control, experimental, difference). As such, average haemoglobin concentration data were available for each: individual (*N* = 59), chromophore (HbO_2, HHb), channel (*N* = 46), block type (control, experimental, difference), and time bin (*N* = 7).

Table 3. Chapter 4. Homer2 Pre-Processing Stream.

Function	Modifier	Parameter
hmrIntensity2OD		
enPruneChannels	dRange	1e-03 1e+03
	SNRthresh	2
	SDrange	0.0 45.0
	reset	0
hmrMotionArtifactByChannel	tMotion	1.0
	tMask	1.0
	STDEVthresh	15.5
	AMPthresh	0.40
hmrMotionCorrectSpline	p	0.99
	turnon	1
hmrMotionCorrectWavelet	iqr	1.5
	turn_on	1
hmrMotionArtifactByChannel	tMotion	1.0
	tMask	1.0
	STDEVthresh	15.5
	AMPthresh	0.40
hmrBandpassFilt	hpf	0.010
	lpf	0.80
hmrOD2Conc	ppf	5.2 4.8
enStimIncData_varagin	1	0.0 0.0
hmrBlockAvg	trange	-2.0 45.0

4. Study Hypotheses and Analysis Approach

4.1. Behavioural Hypotheses and Analysis Plans

4.1.1. ECITT Condition Effects

Based on evidence from previous studies that have used the ECITT with infants and toddlers (Hendry et al., 2021; Holmboe et al., 2021), it was predicted that on both versions of the ECITT, infants' mean accuracy would be significantly greater on prepotent trials (where there is no inhibitory demand) than on inhibitory trials (where there is an inhibitory demand). To test this hypothesis, a paired *t*-test was conducted with the mean inhibitory accuracy and mean prepotent accuracy variables using data from the sample of participants with valid behavioural ECITT data (*N* = 128). This hypothesis was tested on the blocked ECITT data using a 2 x 2 mixed analysis of variance (ANOVA) described in Section 4.1.3. below.

4.1.2. Between-Session Consistency and Test Re-Test Reliability

Based on previous research (Hendry et al., 2021), it was predicted that there would be no significant group-level difference in performance on the behavioural ECITT in Session 1 and the blocked ECITT in Session 2. To determine whether mean performance levels were stable across sessions, three paired *t*-tests were conducted with mean inhibitory accuracy, mean prepotent accuracy, and the accuracy inhibitory score as the dependent variables. Based on previous research (Hendry et al., 2021), it was also predicted that a correlation with at least a medium effect size would be observed ($r \geq .3$) between performance on the behavioural ECITT (Session 1) and the blocked ECITT (Session 2), indicating test re-test reliability. Three Pearson's correlation analyses (mean inhibitory accuracy, mean prepotent accuracy, accuracy inhibitory score) were conducted to examine the test re-test reliability of the task across the two sessions.

4.1.3. Group Performance Differences

The sample of participants with valid blocked ECITT data (*N* = 121) were divided into two sub-samples depending on whether only valid ECITT data was provided (*N* = 62) or whether valid fNIRS data was also provided (*N* = 59). It was hypothesised that there would be no significant performance differences between sub-samples. This is because there are a number of reasons why participants may not have contributed valid fNIRS data, and so it is highly unlikely that these exclusions were systematically related to infant's inhibitory control

abilities. To test whether accuracy significantly differed by trial type or between sub-samples, a 2 × 2 mixed ANOVA with trial type (inhibitory or prepotent) as the within-subjects factor and sub-sample (valid ECITT data only or valid ECITT and fNIRS data) as the between-subjects factor, and accuracy as the dependent variable was conducted. Additionally, an independent *t*-test was conducted with the accuracy inhibitory score as the dependent variable.

4.2. fNIRS Hypotheses and Analysis Plans

Due to the paucity of existing infant fNIRS studies examining response inhibition, this study was exploratory in that there were no specific hypotheses about which areas of the cortex would be more active when inhibition was required. However, based on previous findings with older children and adults regarding the neural correlates of response inhibition, the fNIRS probe was designed to bilaterally cover the prefrontal cortex and the area around the intraparietal sulcus. No specific hypotheses were put forward regarding the time course of the block type effect. That is, which time bins across the block time course would demonstrate a significant block type effect (thus providing information about how the block type effect develops across the block duration). Once the group-level analyses had been conducted, hypotheses and analysis plans for the brain-behaviour individual differences analyses were pre-registered on the Open Science Framework.

4.2.1. fNIRS Group-Level Analyses

Data from 42 (of 46) channels were included in the group-level analyses. Two channels (Channel 11, right superior parietal and Channel 15, left middle frontal gyrus) were excluded from analyses because, following pre-processing, less than 70% of participants contributed data to these channels. Data from the two short separation channels (Channels 30 and 34) were also excluded (see ‘Short Channels’ in Chapter 3). To identify channels demonstrating a significant haemodynamic response (increase in HbO_2 and/or HHb decrease) from baseline over time, separate repeated measures ANOVAs (per channel) were conducted with time bin (7 levels; 7 time bins each of 5 s duration) and block type (2 levels; control, experimental) as within-subject factors. A significant main effect of time would indicate significant haemodynamic concentration changes from baseline across the experimental window (35 s). A significant main effect of block type, or a significant time × block type interaction, would indicate that the haemodynamic response differed between experimental and control blocks.

4.2.2. fNIRS Time Course Analyses

Once channels showing a significant block type effect had been identified, paired *t*-tests were conducted in each 5-second time bin (0 – 35 s) on haemoglobin concentration data from each channel (in channel space). The paired t-tests were conducted between matched variables: e.g., HHb data from time-bin X of Channel Y during the control block was compared to HHb data from time-bin X of Channel Y during the experimental block. Since the purpose of this analysis was to examine the time course of the significant block type effect (change over time bins), 'time bin' was treated as a categorical variable for each planned comparison.

4.2.3. Head Modelling, Channel Localisation, and Image Reconstruction

This work was completed Dr Liam Collins-Jones for the published paper associated with this study (Fiske et al., 2022). Section 2.6.5. of this published article includes a description of the process undertaken to produce an age-appropriate head model, localise the channels in the fNIRS probe to their cortical positions on this head model, and reconstruct an image of changes in haemodynamic concentration data on this head model. Please see Appendix B2 for the anatomical labels of the channels in the probe.

4.2.4. Individual Differences Analyses

Correlational analyses were conducted to investigate whether individual differences in neural activation in specific channels (or channel-pairs) across the identified time bins were associated with individual performance differences in the accuracy inhibitory score. Channels that were identified in the group-level analyses as showing a significantly larger increase in HbO_2 concentration and/or a significantly larger decrease in HHb concentration in experimental compared to control blocks were used as indices of neural activation. See the pre-registration and Section 5.3. below for specific details of these tests.

4.3. Statistical Analyses

All statistical analyses were conducted in SPSS version 27. All variables were tested against the parametric test assumptions, and when these were violated, appropriate non-parametric equivalents were also used to test for convergence (see Appendix B3 for details and for results of non-parametric tests). Greenhouse-Geisser corrected degrees of freedom and significance values were used because the channel-level fNIRS data did not meet the sphericity assumption required for repeated measures ANOVA. The procedure for controlling

the false discovery rate (FDR; Benjamini & Hochberg, 1995) was used where multiple tests were conducted. Confidence intervals (CI; 95%) were calculated on 1000 bootstrap samples.

5. Results

5.1. Behavioural Results

5.1.1. ECITT Condition Effects

As hypothesised, results demonstrated that, in both sessions, mean accuracy was significantly higher on prepotent trials than on inhibitory trials (**Table 4**).

Table 4. Chapter 4. Performance on the ECITT.

	Inhibitory accuracy	Prepotent accuracy	Test Statistic	*p*	Effect size
Behavioural ECITT (Session 1)	.515 (.308)	.879 (.110)	t (127) = -12.908	**<.001**	d = -1.141
Blocked ECITT (Session 2)	.553 (.288)	.920 (.087)	F (1, 119) = 161.411	**<.001**	ηp^2 = .576

Note. Mean (SD) are reported for the inhibitory and prepotent accuracy variables. Statistically significant results are highlighted in bold.

5.1.2. Between-Session Consistency and Test Re-Test Reliability

Results of the paired t-tests (**Table 5**) indicated that the mean inhibitory accuracy variable and the accuracy inhibitory score remained stable across sessions, as predicted. However, against the hypothesis, infants' mean prepotent accuracy was significantly higher on the blocked ECITT in Session 2 (M = .925, SD = .082) than on the behavioural ECITT in Session 1 (M = .883, SD = .109). Results of Pearson correlation analyses were aligned with the hypothesis and indicated significant test re-test reliability between infants' ECITT performance in Session 1 and Session 2 for all three behavioural variables (**Table 5**).

Table 5. Chapter 4. ECITT Between-Session Consistency and Test Re-Test Reliability.

	Between-Session Consistency		**Test Re-Test Reliability**			
	Test Statistic	*p*	Effect size (*d*)	Correlation coefficient	*p*	Confidence interval
Mean inhibitory accuracy	*t* (111) = .941	.349	-.089	*r* (110) = .543	**<.001**	.384, .669
Mean prepotent accuracy	*t* (111) = -4.017	**<.001**	-.380	*r* (110) = .321	**<.001**	.081, .526
Accuracy inhibitory score	*t* (111) = .073	.942	.007	*r* (110) = .482	**<.001**	.296, .638

Note. Statistically significant results are highlighted in bold. Only participants who contributed valid data from both sessions were included in these analyses.

5.1.3. Group Performance Differences

Results of the 2 × 2 mixed ANOVA conducted on the blocked ECITT data demonstrated that, as expected, there was no significant main effect of sub-sample: F (1, 119) = .000, p = .994, ηp^2 = .001, and no significant trial by sub-sample interaction: F (1, 119) = .278, p = .599, ηp^2 = .002. Results of an independent *t*-test confirmed that there was also no significant difference in the accuracy inhibitory score between those with valid fNIRS data (N = 59; M = .600, SD = .332) and those without valid fNIRS data (N = 62; M = .623, SD = .340): t (119) = .497, p = .620, d = .336.

5.2. fNIRS Group-Level Results

41 channels (of 42 included in analyses) were identified through the results of the repeated measures ANOVAs as showing a significant main effect of time (results reported in Appendix B4). These channels demonstrated a significant increase in HbO_2 and/or significant decrease in HHb from baseline over the 35 second block time course. Following correction for the FDR (84 comparisons), all channels retained significance (except Channel 6, left superior parietal; HbO_2, which was then excluded from further analyses). Results of repeated measures analyses with the remaining 40 channels revealed six channels that also showed a significant main effect of block type (greater HbO_2 increase/HHb decrease in experimental compared to control blocks), or a significant time × block type interaction, see **Table 6**. None of the significant effects survived correction for the FDR (84 comparisons: 42 channels × 2 chromophores). See **Figure 3** for a *t*-statistic reconstructed image of significant haemoglobin concentration differences between conditions projected onto the cortex.

The anatomical labels of channels showing significant block-type effects were identified using the process described in Fiske et al. (2022). Note that this work was completed by Dr Liam Collins-Jones as part of his role as a collaborator on the project and co-author on the

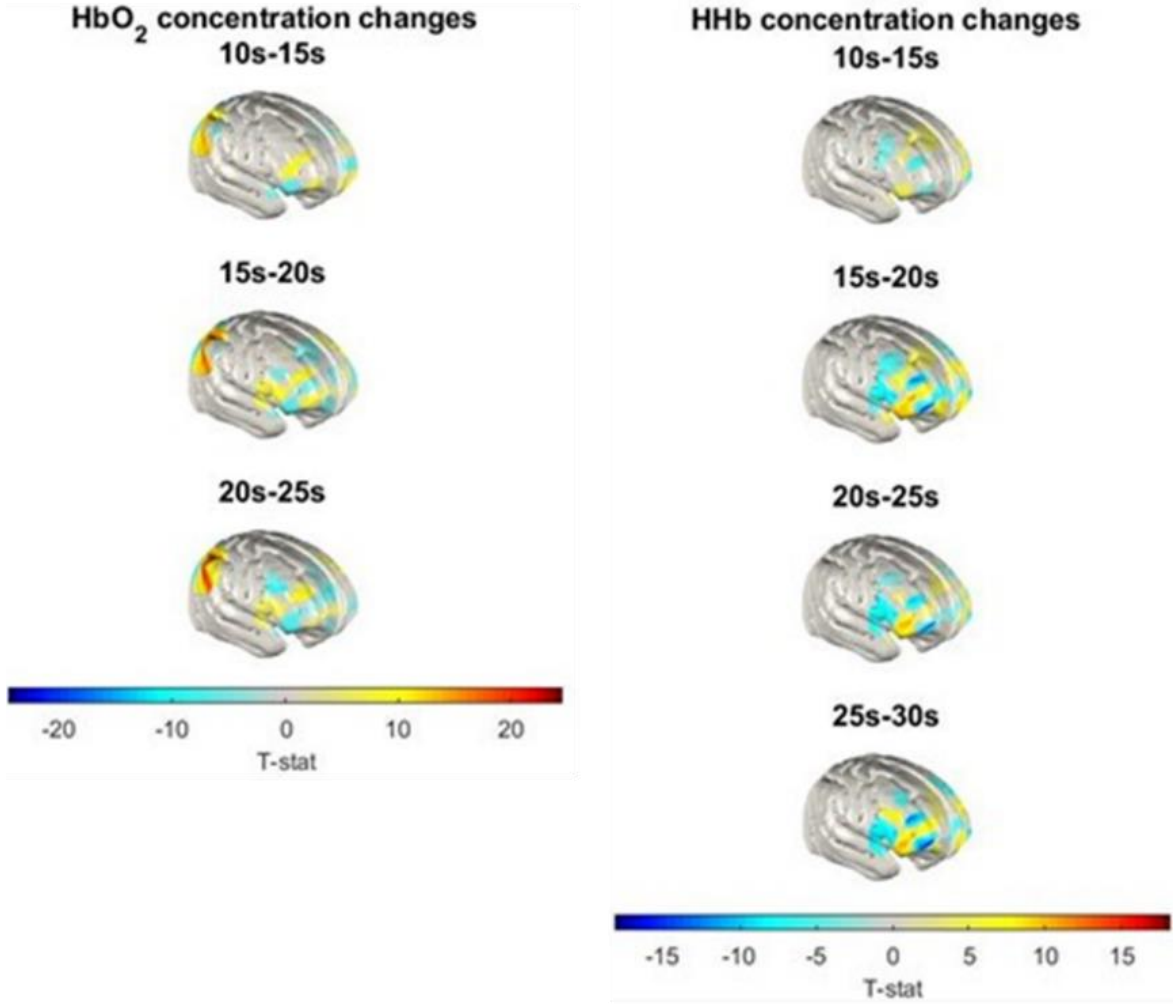
publication. Following this process, two pairs of channels showing significant HbO_2 effects and one pair of channels showing significant HHb effects were formed. From the HbO_2 signal, Channels 10 and 12 were found to overlay the right parietal cortex (Channel 10; right inferior parietal gyrus, Channel 12; right superior parietal gyrus), and Channels 25 and 26 were localised as covering the right middle frontal gyrus (which is situated in the ventral region of the right DLPFC; Petrides & Pandya, 2012). From this point onwards, Channels 25 and 26 are referred to as covering the right DLPFC. From the HHb signal, Channels 32 and 33 were identified to be covering the orbital PFC (Channels 32 and 33; right orbital middle frontal gyrus). Note that for the time course analysis (below), the HbO_2 data from Channel 32 was considered independently (rather than as part of the variable generated with the DLPFC pair; Channels 25 and 26). This decision is justified in the pre-registration of the individual differences analysis plans.

Table 6. Chapter 4. Significant HbO_2 and HHb Concentration Change Differences Between Block Types.

Channel	Location	Signal	Effect	Statistic
10	Right inferior parietal cortex	HbO_2	Main effect of block type	F (1, 51) = 6.374, p = .015, ηp^2 = .111
			Time × block type interaction	F (3.307, 168.653) = 3.258, p = .019, ηp^2 = .060
12	Right superior parietal cortex	HbO_2	Main effect of block type	F (1, 50) = 5.113, p = .028, ηp^2 = .093
25	Right DLPFC	HbO_2	Main effect of block type	F (1, 55) = 4.139, p = .047, ηp^2 = .070
			Time × block type interaction	F (3.915, 215.306) = 3.172, p = .015, ηp^2 = .055
		HHb	Main effect of block type	F (1, 55) = 9.457, p = .003, ηp^2 = .147
26	Right DLPFC	HbO_2	Time × block type interaction	F (3.907, 218.819) = 3.224, p = .014, ηp^2 = .054
32	Right OFC	HbO_2	Time × block type interaction	F (4.105, 229.852) = 3.874, p = .004, ηp^2 = .065
		HHb	Main effect of block type	F (1, 56) = 8.041, p = .006, ηp^2 = .126
			Time × block type interaction	F (3.923, 219.713) = 5.170, p = .001, ηp^2 = .085
33	Right OFC	HHb	Time × block type interaction	F (2.850, 165.322) = 3.910, p = .011, ηp^2 = .063

Note. All six channels showed a significant main effect of time (p < .05). DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

Figure 3. Chapter 4. Group-level *T*-statistic Image of the Contrast in Haemoglobin Concentration Changes Between Block Types



Note. Group-level T-statistic images of the contrast in concentration changes of HbO_2 (left) and HHb (right) between experimental and control blocks (experimental – control). Images are displayed in the space of a cortical surface derived from averaged structural MRI data of a 12-month-old cohort of infants (Shi et al., 2011). Using this approach, all displayed T-statistic values are significantly different across block types (paired t-test) at the alpha level of $p < .01$. The HbO_2 figure (left) covers the 10 – 25 second time frame, and the HHb figure (right) covers the 10 – 30 second time frame with which the analyses in significant channels were conducted. Since there was no significant HHb effects in parietal regions, the HHb figure (right) only shows activation in frontal regions. A MATLAB version of this figure is available on OSF (https://osf.io/rbg2y).

Image produced by Dr Liam Collins-Jones. Caption as in Fiske et al. (2022), Figure 4.

5.2.1. fNIRS Time Course Analyses

The results of paired *t*-tests (**Table 7**) that were conducted on the channels or channel pairs showing significant block type effects revealed the time course of the block type effect. Note that for Channel 32 (HbO_2), the significant effect occurred in the first time-bin (0 – 5 seconds of the block time course) where it would be expected for activation to still be building at the start of the block, and the difference was in the opposite direction to what was observed for

the other channels. Therefore, no further analyses were conducted, nor interpretations made, regarding the HbO_2 effect found in Channel 32. See **Figure 4** – **Figure 9** for the haemodynamic response function (HRF) plots for channels showing significant block type effects. Note that **Figure 4** - **Figure 9** show 45 s of the block time course, whereas analyses were only conducted from 0 – 35 s. Time bins 8 and 9 (35 – 45 s) were excluded because, due to the variable block duration (contingent on the duration of infants' responses), these time bins captured baseline data from some participants and task data from others, rendering these time bins unsuitable for analysis.

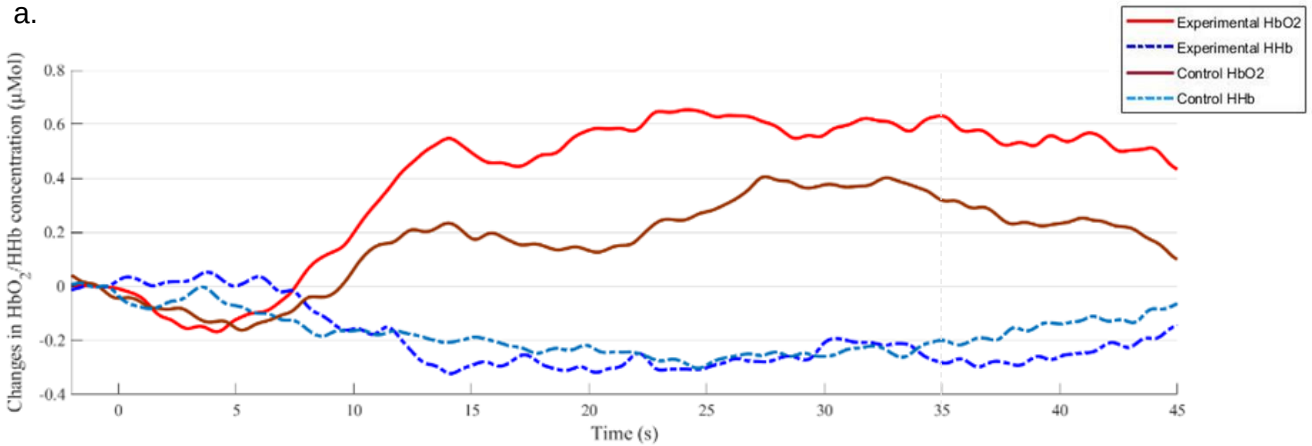
Table 7. Chapter 4. Time Course of the Significant HbO_2 or HHb Block Type Effects.

Time Bin (s)	Right parietal (HbO_2)	Right DLPFC (HbO_2)	Right OFC (HbO_2)	Right DLPFC (HHb)	Right OFC (HHb)
0 – 5	*t* (47) = −0.687, *p* = .495, *d* = −0.099	*t* (53) = 1.082, *p* = .284, *d* = 0.147	***t* (56) = 2.379, *p* = .021, *d* = 0.315**	*t* (55) = 1.749, *p* = .086, *d* = 0.234	*t* (56) = −0.328, *p* = .744, *d* = −0.043
5 – 10	*t* (47) = −1.175, *p* = .246, *d* = −0.170	*t* (53) = −0.007, *p* = .994, *d* = −0.001	*t* (56) = 0.806, *p* = .424, *d* = 0.107	***t* (55) = 2.174, *p* = .034, *d* = 0.291**	*t* (56) = 0.509, *p* = .613, *d* = 0.067
10 – 15	***t* (47) = 2.485, *p* = .017*, *d* = −0.359**	***t* (53) = −2.478, *p* = .016, *d* = 0.337**	*t* (56) = −1.489, *p* = .142, *d* = −0.197	***t* (55) = 2.898, *p* = .005*, *d* = 0.387**	***t* (56) = 2.802, *p* = .007*, *d* = 0.371**
15 – 20	***t* (47) = −3.335, *p* = .002*, *d* = −0.481**	***t* (53) = −2.055, *p* = .045, *d* = −0.280**	*t* (56) = −1.752, *p* = .085, *d* = −0.232	***t* (55) = 3.180, *p* = .002*, *d* = 0.425**	***t* (56) = 2.771, *p* = .008*, *d* = 0.367**
20 – 25	***t* (47) = −3.541, *p* = .001*, *d* = −0.511**	*t* (53) = −1.812, *p* = .076, *d* = −0.247	*t* (56) = −0.469, *p* = .641, *d* = −0.062	***t* (55) = 3.557, *p* = .001*, *d* = 0.475**	***t* (56) = 3.104, *p* = .003*, *d* = 0.411**
25 – 30	*t* (47) = −1.995, *p* = .052, *d* = −0.288	*t* (53) = −1.472, *p* = .147, *d* = −0.200	*t* (56) = 0.442, *p* = .660, *d* = 0.059	***t* (55) = 2.145, *p* = .036, *d* = 0.287**	***t* (56) = 3.049, *p* = .004*, *d* = 0.404**
30 – 35	*t* (47) = −1.947, *p* = .058, *d* = −0.281	*t* (53) = −1.721, *p* = .091, *d* = −0.234	*t* (56) = −0.005, *p* = .996, *d* = −0.001	*t* (55) = 1.837, *p* = .072, *d* = 0.245	***t* (56) = 2.495, *p* = .016*, *d* = 0.330**

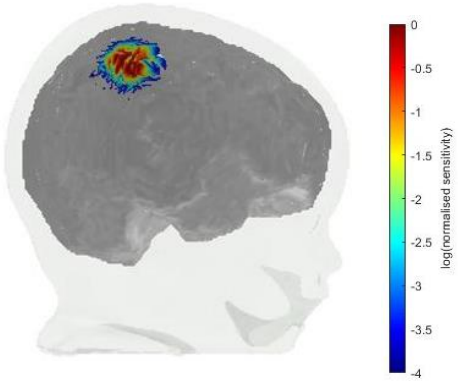
Note. Statistically significant results are highlighted in bold. * = significant after correcting the FDR (7 comparisons). Right parietal (HbO_2) = Channels 10 and 12, Right DLPFC (HbO_2) = Channels 25 and 26, Right orbital PFC (HbO_2) = Channel 32, Right DLPFC (HHb) = Channel 25, Right OFC (HHb) = Channels 32 and 33.

Figure 4. Chapter 4. Haemodynamic Response Function for Channel 10 (Right Inferior Parietal Gyrus).

a.



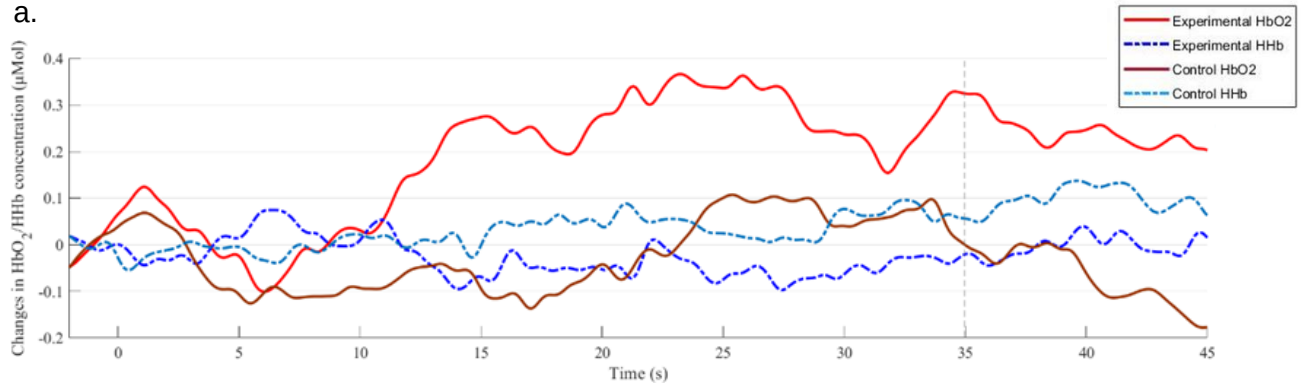
b.



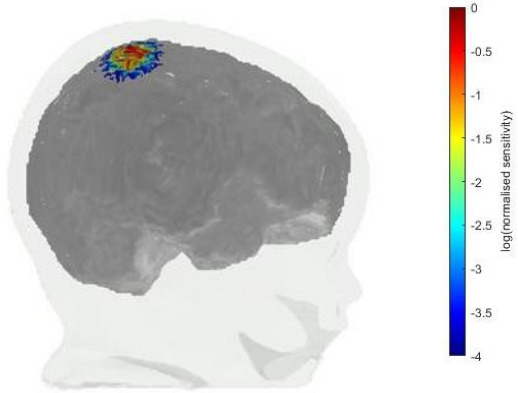
Note. a. Average haemodynamic response function for Channel 10 (*N* = 52) from -2 seconds (baseline) to 45 seconds of the block time-course.
b. Sensitivity profile illustrating the position of Channel 10 on the cortex and the channel sensitivity (heat map: red = more sensitive, blue = less sensitive).

Figure 5. Chapter 4. Haemodynamic Response Function for Channel 12 (Right Superior Parietal Gyrus).

a.

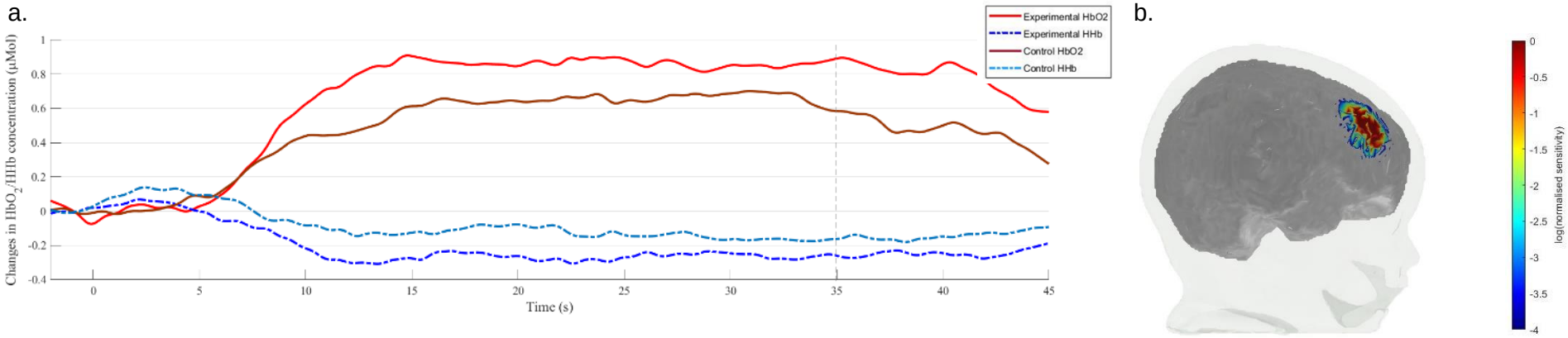


b.



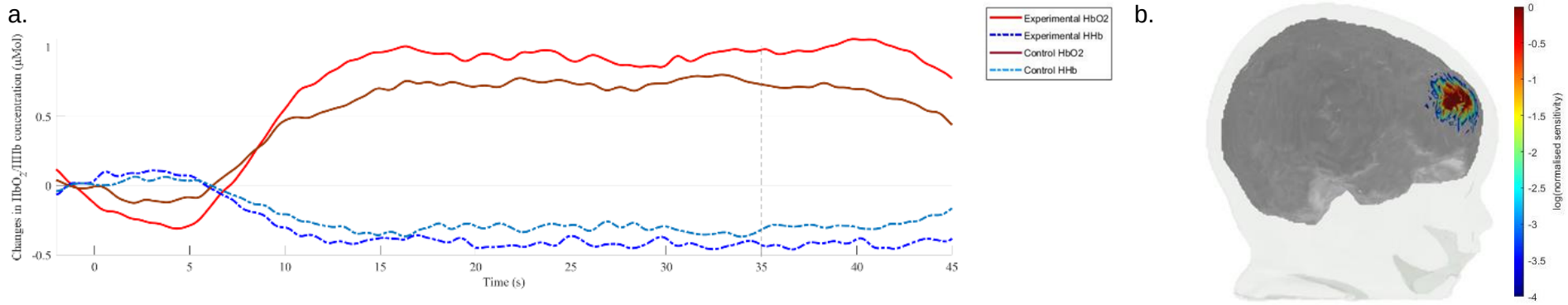
Note. a. Average haemodynamic response function for Channel 12 (*N* = 51) from -2 seconds (baseline) to 45 seconds of the block time-course.
b. Sensitivity profile illustrating the position of Channel 12 on the cortex and the channel sensitivity (heat map: red = more sensitive, blue = less sensitive).

Figure 6. Chapter 4. Haemodynamic Response Function for Channel 25 (Right DLPFC).



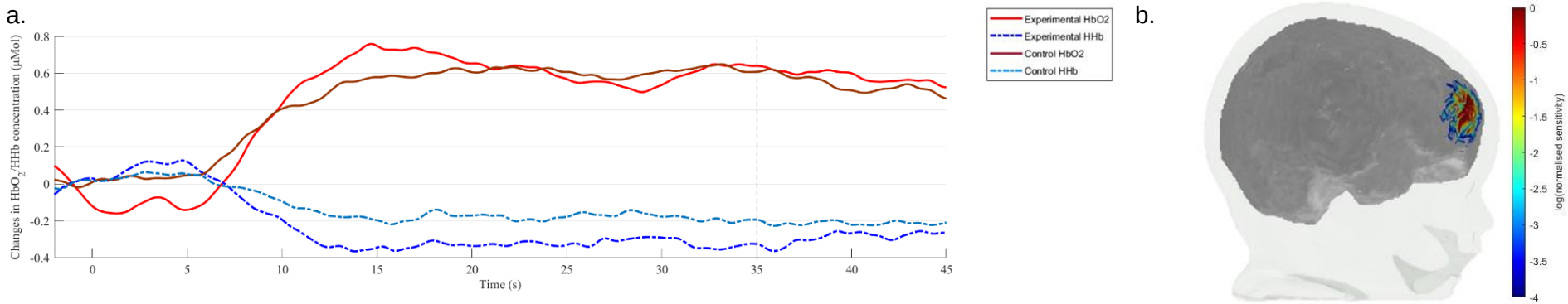
Note. a. Average haemodynamic response function for Channel 25 (*N* = 56) from -2 seconds (baseline) to 45 seconds of the block time-course.
b. Sensitivity profile illustrating the position of Channel 25 on the cortex and the channel sensitivity (heat map: red = more sensitive, blue = less sensitive).

Figure 7. Chapter 4. Haemodynamic Response Function for Channel 26 (Right DLPFC).



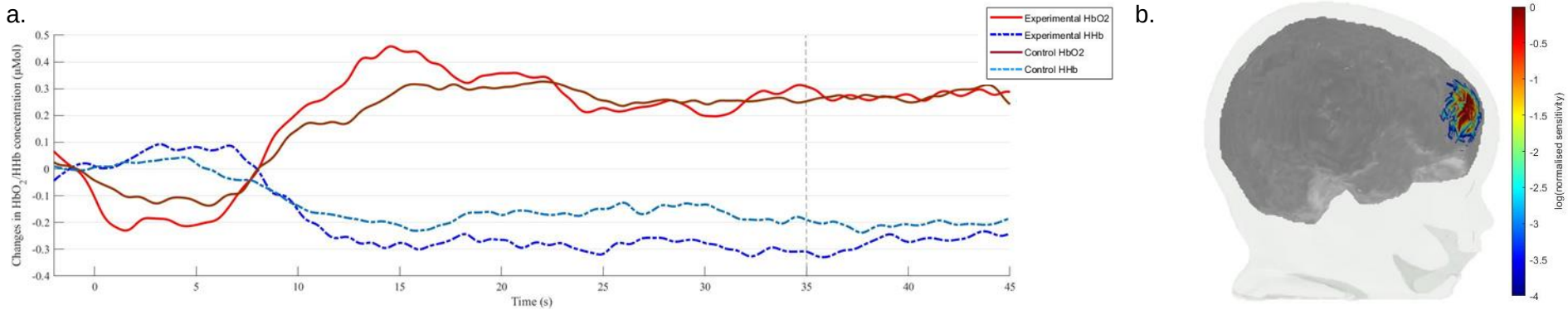
Note. a. Average haemodynamic response function for Channel 26 (*N* = 57) from -2 seconds (baseline) to 45 seconds of the block time-course.
b. Sensitivity profile illustrating the position of Channel 26 on the cortex and the channel sensitivity (heat map: red = more sensitive, blue = less sensitive).

Figure 8. Chapter 4. Haemodynamic Response Function for Channel 32 (Right Orbital PFC)



Note. a. Average haemodynamic response function for Channel 32 (*N* = 57) from -2 seconds (baseline) to 45 seconds of the block time-course.
b. Sensitivity profile illustrating the position of Channel 32 on the cortex and the channel sensitivity (heat map: red = more sensitive, blue = less sensitive).

Figure 9. Chapter 4. Haemodynamic Response Function for Channel 33 (Right Orbital PFC)



Note. a. Average haemodynamic response function for Channel 33 (*N* = 59) from -2 seconds (baseline) to 45 seconds of the block time-course.
b. Sensitivity profile illustrating the position of Channel 33 on the cortex and the channel sensitivity (heat map: red = more sensitive, blue = less sensitive).

5.3. Individual Differences Analyses

5.3.1. Individual Differences Hypotheses

Once channels showing significant block type effects had been identified, three confirmatory hypotheses were pre-registered to investigate individual differences. These correlational analyses aimed to investigate whether neural activation was associated with individual differences in infants' accuracy inhibitory score. Although not certain about the applicability already in infancy, the following hypotheses were based on the underlying assumption that greater neural activation may be associated with better performance (e.g., Rubia et al., 2006; Smith et al., 2017). It was predicted that:

1) A larger difference in HbO_2 concentration between experimental and control blocks (larger HbO2 difference score) from 10-25 s in the right lateral PFC (Channels 25 and 26) will be associated with significantly better response inhibition performance (higher accuracy inhibitory score).
2) A larger difference in HbO_2 concentration between experimental and control blocks (larger HbO2 difference score) from 10-25 s in the right parietal channel pair (Channels 10 and 12) will be associated with significantly better response inhibition performance (higher accuracy inhibitory score).
3) A larger difference in HHb concentration between control and experimental blocks (larger HHb difference score; HHb expected to be lower in experimental than control blocks) from 10-25 s in Channel 25 (right PFC) will be associated with significantly better response inhibition performance (higher accuracy inhibitory score).

5.3.2. Individual Differences Variables

To perform these analyses, four new variables were generated: 'HbO_2 right DLPFC (Channels 25 & 26) Bins 3 – 5', 'HbO_2 right parietal (Channels 10 & 12) Bins 3 – 5', 'HHb Channel 25 Bins 3 – 5', and 'HHb right OFC (Channels 32 & 33) Bins 4 – 6'.

For single channel variables, the HHb difference variable was calculated for each time bin, and then an average HHb difference variable was calculated by adding the HHb difference variable for each time bin and dividing by the number of time bins. Variables consisting of channel pairs were generated as follows: First, the HbO_2 difference / HHb difference variable was calculated separately for each channel and each time bin [e.g., HbO_2 difference, Channel 25, Time Bin 3]. Then, the HbO_2 difference / HHb difference variable was averaged across channel pairs, separately for each time bin [e.g., HbO_2 difference, Channel 25 & 26, Time Bin 3]. Finally, an average HbO_2 difference / HHb difference variable was calculated by

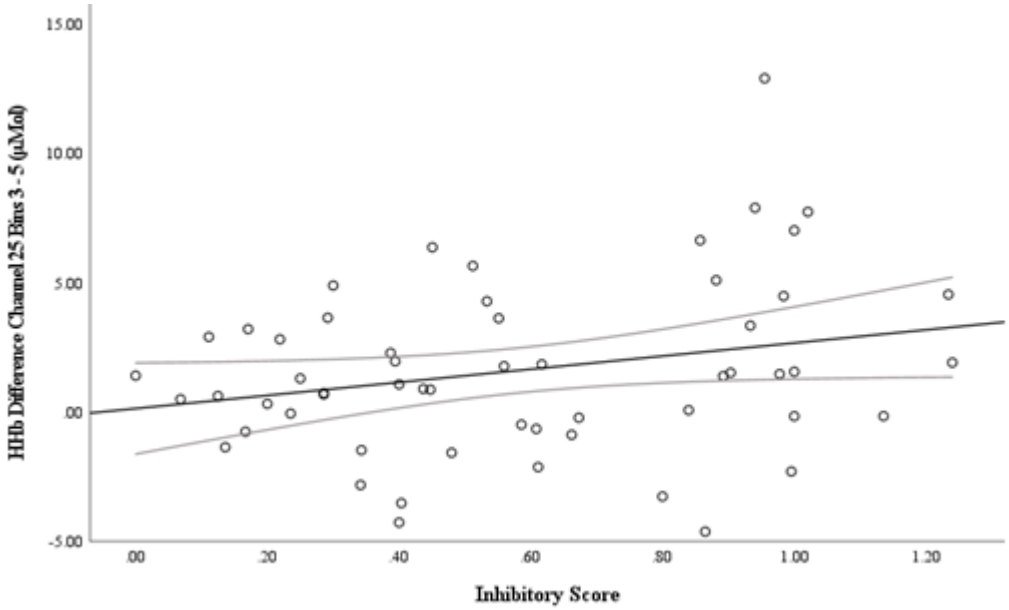
adding the HbO_2 difference / HHb difference variable for each time bin and dividing by the number of time bins [e.g., HbO_2 difference, Channel 25, Bins 3 – 5]. Note that the difference in HbO_2 concentration between blocks was calculated as: (experimental *minus* control), whereas the difference was HHb concentration between blocks is calculated as: (control *minus* experimental). By calculating the subtractions in this way, more activation in experimental (i.e., more HbO_2 and less HHb) compared to control blocks is indicated by a positive difference score.

5.3.3. Individual Differences Results

Results of the confirmatory Pearson's correlational analyses revealed that, contrary to prediction, there was no significant association between individual differences in the accuracy inhibitory score and HbO_2 difference in the right DLPFC channel pair: r (57) = -.056, p = .338, [*CI* = -.287, .156], or the HbO_2 difference in the right parietal channel pair: r (53) = .171, p = .106, [*CI* = -.134, .423]. However, as hypothesised there was a modest positive association between accuracy inhibitory score and HHb difference in Channel 25 (right DLPFC): r (54) = .255, p = .029, [*CI* = .016, .446), see **Figure 10**. Although this significant effect did not survive the procedure for controlling the FDR (N = 3 comparisons).

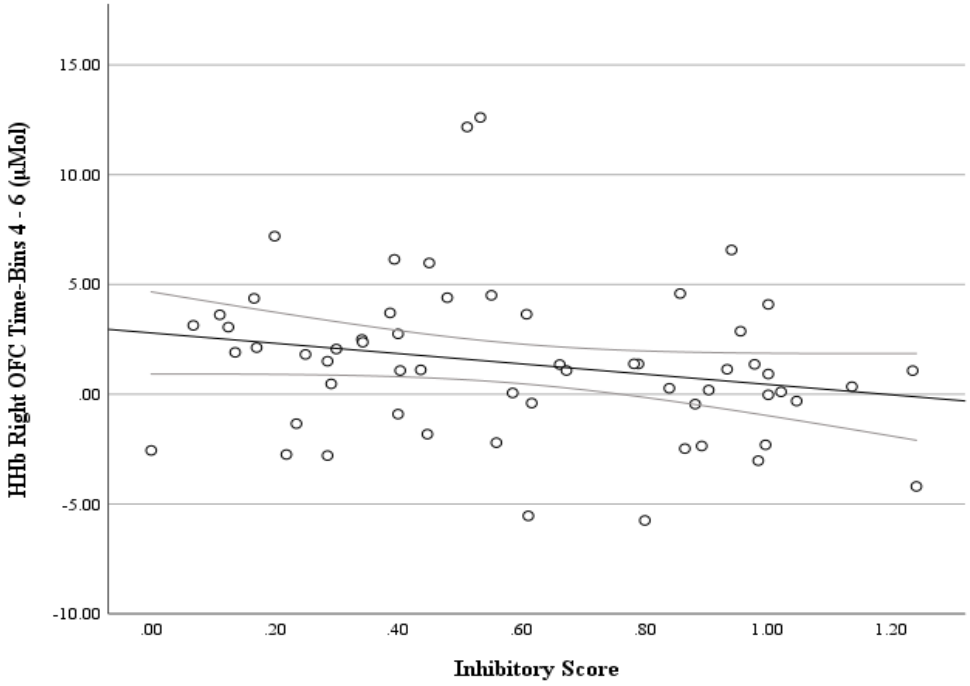
Results of an exploratory Pearson's correlation revealed that there was no significant association between the accuracy inhibitory score and HHb difference in the right orbital PFC channel pair: r (57) = -.222, p = .092, [*CI* = -.416, -.013], see **Figure 11**. However, when running an exploratory Pearson's correlation with the HHb difference variable with data *only* from Channel 33 (right OFC), there was a significant association: r (57) = -.273, p = .036, [*CI* = -.476, -.056], see **Figure 12**. Although this was no longer significant after controlling for the FDR (N = 2 comparisons).

Figure 10. Chapter 4. Association Between the HHb Difference Score (Channel 25, Bins 3 - 5) and the Accuracy Inhibitory Score.



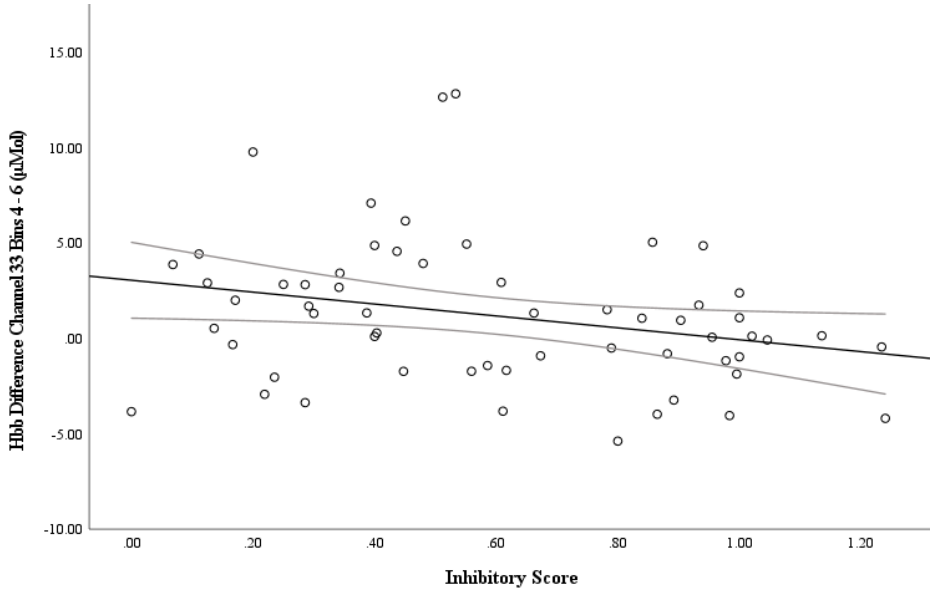
Note. A larger accuracy inhibitory score reflects better response inhibition performance. A larger HHb difference score reflects a larger decrease in HHb in experimental blocks (compared to control blocks) in time-bins 3 – 5 for Channel 25 (overlaying the right DLPFC). Grey lines represent 95% confidence intervals.

Figure 11. Chapter 4. Association Between the HHb Difference Score (right OFC, Bins 4 - 6) and the Accuracy Inhibitory Score.



Note. A larger accuracy inhibitory score reflects better response inhibition performance. A larger HHb difference score reflects a larger decrease in HHb in experimental blocks (compared to control blocks) in time-bins 4 – 6 for Channels 32 and 33 (overlaying the right OFC). Grey lines represent 95% confidence intervals.

Figure 12. Chapter 4. Association Between the HHb Difference Score (Channel 33, Bins 4 - 6) and the Accuracy Inhibitory Score.



Note. A larger accuracy inhibitory score reflects better response inhibition performance. A larger HHb difference score reflects a larger decrease in HHb in experimental blocks (compared to control blocks) in time-bins 4 – 6 for Channel 33 (overlaying the right OFC). Grey lines represent 95% confidence intervals.

5.3.4. Further Exploratory Individual Differences Analyses

Additional exploratory analyses (not pre-registered) were conducted to investigate whether there were associations between performance on the ECITT (prepotent accuracy, inhibitory accuracy) and brain activation. Note that here, channel data were not limited to specific time bins showing significant effects, as they were in the pre-registered analyses. Results are reported in Appendix B5.

There was a significant association between prepotent accuracy and activation (HbO_2 difference) in Channel 10 (right inferior parietal): r (50) = -.294, p = .034, *CI* = -.555, .008, which suggests that poorer prepotent accuracy was associated with more activation in the right inferior parietal cortex. There was also a significant association between infants' inhibitory accuracy and activation in Channel 26 (HbO_2; right DLPFC): r (55) = -.285, p = .032, *CI* = -.502, -.075, and in Channel 33 (HHb; right OFC): r (57) = -.302, p = .020, *CI* = -.509, -.039, such that poorer inhibitory accuracy was associated with greater recruitment of the right DLPFC and the right OFC. Additionally, there was a significant association between the accuracy inhibitory score (index of inhibitory performance) and activation in Channel 33 (HHb, right OFC): r (57) = -.313, p = .016, *CI* = -.542, -.043. This suggests that poorer inhibitory performance was associated with greater recruitment of the right OFC. Although note that these significant exploratory associations did not survive correction for the FDR (N = 24 comparisons).

6. Discussion

The aim of the study presented in this chapter was to identify the functional neural correlates of response inhibition in 10-month-old infants. In this study, response inhibition was measured using the ECITT, a novel, age-appropriate task that required infants to make a manual response to the touchscreen. Brain activation was measured using fNIRS, a neuroimaging technique that is suitable for use with early developmental populations. Since no previous research has used fNIRS to investigate inhibitory control in this age group, and alongside a response inhibition task that required infants to make a manual response (as opposed to a passive eye-tracking task), this study has lowered the age at which it is possible to localise the functional neural substrates of response inhibition, already in the first year of life.

6.1. The ECITT as an Index of Infant Response Inhibition

Prior to the development of the ECITT (Holmboe et al., 2021), response inhibition in infancy was often measured using looking or reaching versions of the A-not-B / delayed response task (e.g., Bell & Adams, 1999; Broomell & Bell, 2022; Cuevas et al., 2012). Whilst this measure has been well-validated and used consistently within the literature, the task structure is fundamentally different to that used to measure response inhibition in older children and adults (i.e., the Go / No-Go or Stop Signal tasks). The ECITT bridges this gap by enabling the measurement of response inhibition in infancy using a task format that closely mirrors those used in research with older populations, yet with the working memory, instruction following, and language demands reduced. The ECITT is effective at capturing response inhibition, as evidenced by the results of the current study which found that infants were significantly more accurate on prepotent trials than on inhibitory trials. These trial type effects replicate the results of previous research that used the ECITT with this early developmental population (Hendry et al., 2021; Holmboe et al., 2021).

The results of this study have also demonstrated that the ECITT is age-appropriate for 10-month-old infants, with mean accuracy on prepotent trials being high (as intended to develop a strong prepotency), and with mean accuracy on inhibitory trials around the level of chance. Similarly, the task is successful at engaging infants, as evidenced by the very high number of trials completed (~ 36 – 84 individual trials). This number of trials is very unusual in infant research yet is beneficial as it provides a more reliable measurement which is particularly important due to the ‘messy’ nature of responses in this young population. Similarly, the findings from this study demonstrated moderate test re-test reliability between the two versions of the ECITT (confirming findings from previous studies with the same age group;

Hendry et al., 2021), suggesting that the ECITT is a reliable measure of response inhibition in infancy.

When comparing performance between sessions, it was found that infants performed significantly better on prepotent trials on the blocked ECITT (Session 2) than on the behavioural ECITT (Session 1). It is possible that the improved performance in the second session is due to practice or training effects and increasing familiarity with the task demands. Alternatively, this may be due to structural differences between the tasks. For example, the control blocks in the blocked ECITT have six prepotent trials in a row, which may increase the strength of the prepotency compared to in the behavioural version of the task. Future research will continue to investigate whether infants' prepotent accuracy on the ECITT differs between the two versions of the task.

6.2. The Neural Correlates of Response Inhibition in 10-month-old Infants

The fNIRS results identified that pairs of channels overlying the right DLPFC, right OFC, and right parietal cortex were more active when inhibition was required (experimental blocks), compared to when no inhibition was required (control blocks). These regions of the brain are consistent with regions identified in similar fNIRS studies investigating response inhibition in young children (e.g., Mehnert et al., 2013), and with fMRI studies across development (e.g., Cope et al., 2020). This suggests that already in the first year of life, infants are using the same areas of the brain as older children and adults when inhibitory control is required. By examining associations between inhibitory performance on the ECITT and brain activation, it was possible to understand individual differences in response inhibition. In the current study, it was found that a larger HHb concentration difference in the right DLPFC was associated with *better* inhibitory performance, whereas a larger HHb concentration difference in the right OFC was associated with *poorer* inhibitory performance (although note that these effects did not survive the procedure for controlling the FDR). These findings might cautiously suggest that, at 10-months of age, distinct areas of the right frontal cortex play a differential role in successful response inhibition in infancy.

Research by Chevalier et al. (2019) with 5 – 9 year old children demonstrated that activation in different regions of the PFC was sensitive to varying cognitive control demands, whereby competitive contexts elicited more activation in the left ventrolateral PFC and left DLPFC, and neutral or cooperative conditions elicited more activation in the right DLPFC. If it is the case that different regions of the PFC are recruited for different components or contexts of inhibitory control, it may be that the role of the OFC in inhibition reflects the processing of erroneous responding and the associated lack of immediate reward, especially in infants

who struggle with the inhibitory demand of the task (and therefore make more errors). Previous research has suggested that the OFC is active during perseveration – i.e., continuing to respond to the non-rewarded (incorrect) stimulus on inhibitory trials (Happaney et al., 2004; Rolls, 2004), and so supports the association found in this current study whereby activation in the right OFC was associated with poorer inhibitory control (i.e., more perseveration). Overall, this could suggest that the activation in the right OFC in this study is linked to perseveration; the *failure* to inhibit. In this way, it might be expected that there would be a reduction in activation in the right OFC as infants become better inhibitors. This will be explored in Chapters 5 and 6, where response inhibition is measured at 16-months and at 3½ years.

On the other hand, the role of the DLPFC in response inhibition may be related to the mental preparation of an action (Pochon et al., 2001) or the planning of a motor response (D'esposito et al., 2000; Tang et al., 2020), which would be necessary to complete a trial of the ECITT. These action planning demands are likely to be higher on inhibitory trials, as the infant is required not only to prepare a response to a new location but also to inhibit the prepotent response. This makes sense in the context of the results of the current study, whereby increased activation in the right DLPFC was associated with better inhibitory control performance (i.e., more successful action plans). More broadly within the literature, it has been argued that the DLPFC may play a generic role in a multitude of cognitive demands (Duncan & Owen, 2000; Ridderinkhof et al., 2004). For example, fMRI studies with adults have found that the DLPFC has an integrative role in moving from short-term memory representations to goal-directed motor behaviour (Ridderinkhof et al., 2004), as well as in updating reward expectation based on past choices (Barraclough et al., 2004). In relation to the ECITT, the DLPFC may be recruited to support in the monitoring and updating of reward (animation) based on previous correct responses to the target. This could explain the finding that greater activation of the DLPFC (more efficient reward monitoring and goal directed motor behaviour) would be reflective of greater accuracy on the task, resulting in better response inhibition performance.

However, it remains unclear whether the role of the DLPFC in the ECITT is related only to error monitoring and the planning and execution of the motor response (in support of the inhibition of the prepotent response), or whether it is also involved in the actual *stopping* process. Whilst it is difficult to disentangle the different task demands to isolate the neural mechanisms responsible for the stopping of the prepotent motor response in the ECITT, research by Chatham et al. (2012) examined performance on several inhibitory control tasks that only differed in their motoric stopping demands. The authors propose that the cognitive control mechanism underpinning inhibitory control in all tasks is context-monitoring, and that

this is the primary control process involved in inhibition. They suggest that stopping a motoric response or replacing a motor plan is still likely underpinned by activation in the PFC, but argue that in canonical response inhibition tasks, the primary control demands on the PFC are due to context-monitoring. It is unknown whether the same cognitive control processes required for stopping are the same in infancy as in adults, and so more research is needed that examines the role of the PFC and other areas of the cortex in inhibition and attempts to disentangle the motoric stopping process from facets of cognitive control.

Finally, it must be considered that the brain-behaviour associations found in the current study were weak and did not survive correction for the FDR. As such, it is strongly recommended that these associations are pre-registered and replicated in future research to confirm their validity. Until then, interpretations should be considered with caution. Nonetheless, these results provide new evidence for associations between individual differences in inhibitory control and neural activation in areas of the PFC in infancy; a preliminary but promising trend to be followed up in future research.

6.3. Limitations and Future Directions

By design, the fundamental difference between the two block types in the ECITT are that one block imposes inhibitory demands (experimental block) whilst the other does not (control block). This design underlies the interpretation in the current study that the block type effects observed in channels within the PFC and parietal cortex are related to inhibitory demand. Specifically, that increases in activation in experimental blocks (compared to control blocks) is related to the need to use inhibitory control that is present only in experimental blocks. However, it is important to consider other potential explanations that may offer alternative interpretations of the results. For example, another inherent difference between the block types is that only the experimental block contained inhibitory trials, and these occurred less frequently than prepotent trials which were common throughout the task. It may be that the brain activation found in this study was in response to the low frequency of the inhibitory trials themselves, rather than the inhibitory demand that they imposed (Wijeakumar et al., 2015). Similarly, Erika-Florence et al. (2014) proposed that activation in inferior frontal regions during inhibitory tasks is related to the processing of infrequent stimuli (unrelated to inhibitory demands) and when novel tasks are presented, rather than when prepotent responses must be inhibited. Instead, the authors argue for the role of domain general fronto-parietal networks (which the inferior frontal cortex is part of) that support broad cognitive functions, including executive processes (Erika-Florence et al., 2014). This line of enquiry makes a fruitful area for future research (with this data set) that investigates

emerging functional connections between frontal and parietal regions that are recruited in the ECITT, and for research with new data that probes the involvement of this domain general fronto-parietal network in a range of executive tasks, already in infancy. More broadly, this moves research away from a component approach where the functionality of specific brain regions are investigated in isolation, and towards thinking of these brain regions as being connected by a series of functional networks (Menon, 2013; Power et al., 2010).

Another difference between block types was the timing of the reward (animated cartoon); whilst the frequency of the animation did not change between block types, it was often the case that infants made more incorrect responses in the experimental block (due to the inhibitory demand), and until a correct response was made the animation did not appear. As such, neural activation in reward-processing areas such as the OFC found in this study may be related to reward anticipation (Happaney et al., 2004; Rolls, 2004) instead of the inhibitory demand. These lines of enquiry cannot be teased apart in the current study but make for an important and interesting direction for future research into the functional correlates of cortical brain regions in the first year of life.

Similarly, it could be argued that the experimental blocks of the ECITT also contain switching demands, as infants are required not only to inhibit their prepotent response, but to switch their response from the prepotent side (on prepotent trials) to the opposite side on inhibitory trials (and back again); see Hendry et al. (2021) for reports on switching in the ECITT. As with many EF tasks, it is difficult to isolate the two demands (switching and inhibition) Nonetheless, the higher frequency of prepotent trials leads to the development of a prepotency that needs to be overcome on inhibitory trials, and so is clear that inhibition is required in the ECITT.

It is also necessary to consider that at 10-months of age, the brain is very much still undergoing important structural and functional maturation processes. For example, the neurovascular system that underpins the haemodynamic response is still developing in infancy and so may not function in the same way as in adults (Kozberg & Hillman, 2016), and so it can be difficult to interpret neural responses measured from these early developmental populations. Additionally, metabolic processes that relate to the energy demands of the haemodynamic response are still not fully understood in the infant brain (Siddiqui et al., 2017), and so further physiological research is needed that will help support the interpretations that can be made from studies that measure functional HRF, such as this.

Finally, it cannot be ignored that there was substantial attrition of fNIRS data in this current study (~50%). Whilst this is not uncommon in infant fNIRS studies (Baek et al., 2023), it

does limit the current study by reducing the statistical power and the generalisability of the results to broader populations of infants. As such, replication of these results in larger, more diverse samples of infants would help both to strengthen the conclusions of the current study and to further uncover the functional neural correlates of response inhibition in infancy.

6.4. Strengths and Implications

This study is the first to elucidate the functional neural substrates of response inhibition in 10-month-old infants using fNIRS and an age-appropriate, manual response task. This novel finding that infants activate similar regions of the PFC and parietal cortex during response inhibition as do older children and adults will be of significant interest to the field. This is because it provides an insight into the early emergence of response inhibition and the associated functions of the PFC and parietal cortex, already in the first year of life.

This study was able to measure response inhibition in infants using a task that is structurally similar to those used in studies with older children and adults (e.g., the Go / No-Go task and the Stop Signal task), thus making the results of this study comparable with the broader literature. This is beneficial for the field, as by comparing studies that assess response inhibition in similar ways across the lifespan, it may be possible to begin to identify a developmental trajectory of response inhibition. It is worth noting however, that although the tasks share important characteristics such as requiring participants to develop and then inhibit a prepotent motor response, there are some differences between the demands of the tasks. For example, Go / No-Go and Stop Signal tasks require participants to inhibit a prepotent response by stopping the response (i.e., making no motor response), whereas the ECITT requires participants to inhibit the prepotent response and instead make an alternative response to the screen. This is a necessary difference as it is not possible to instruct infants to withhold a response, but it is possible for them to respond to a target stimuli in an alternative location. As such, this task is extremely beneficial in allowing researchers to examine inhibitory control in infants in a way that more closely mirrors methods used in older populations.

Another important strength of this study was that (despite the attrition) a large sample of infants were tested, something that is quite unusual in infant fNIRS studies due to the many difficulties surrounding collecting neuroimaging data from early developmental populations. Additionally, due to the infants' engagement with the ECITT, a considerable number of trials were completed which contributed to the high quality of behavioural data. In this way, this research has provided further evidence for the validity of the ECITT as an age-appropriate measure of response inhibition for use with infants as young as 10-months of age.

Finally, this research has advanced infant fNIRS research by demonstrating that it is feasible for infants in the first year of life to complete an active, response-based task during an fNIRS session, where previously only passive eye-tracking or resting state tasks had been used. This research may encourage future studies in the field of infant fNIRS research to employ a broader range of task types and methodologies to assess the neural correlates of early development.

7. Conclusion

Overall, this study has provided new evidence about the neural substrates of response inhibition in the first year of life. Regions of the right DLPFC, OFC, and parietal cortex were significantly more active when inhibition was required. Preliminary associations were found between increased activation in the right DLPFC and better response inhibition performance, and between increased activation in the right OFC and poorer response inhibition performance. By showing that infants are recruiting the same regions of the PFC and parietal cortex as do older children and adults when inhibition is required, this research will contribute to our understanding of how the maturation of the PFC and parietal cortex underpins, supports, and scaffolds the emergence of response inhibition performance. This study also demonstrated the utility of the paradigm in which it is possible to use an active, response-based task (as an index of response inhibition) alongside fNIRS with early developmental populations. Since no prior research exists that has investigated the functional neural substrates of infant inhibitory control using a methodological paradigm comparable to that used with older children and adults, it is important that this line of research continues. This will enable new knowledge about the emergence of response inhibition and the underlying neural correlates across the transition from infancy to toddlerhood, a period of significant developmental change.

Chapter 5

Response Inhibition in the Transition to Toddlerhood: Neural Correlates and Behavioural Development

Following on from the previous chapter that reported on the functional neural correlates of response inhibition in 10-month-old infants, the current chapter presents data from the same cohort of participants, now at 16-months of age (the second OEEF assessment point). The study reported in this chapter follows a near-identical methodological approach as used in Chapter 4 (with some exceptions that are clearly outlined), with the overarching aim of investigating the behavioural development and neural correlates of response inhibition in the second year of life. Extending the work presented in Chapter 4, this current chapter follows the same sample of participants from 10- to 16-months of age to ask important questions about developmental change across this key transition from infancy to toddlerhood.

The study reported in this chapter was pre-registered on the Open Science Framework before analysis. The research questions, hypotheses, variables, and analyses were specified in detail in the pre-registration, and so this chapter will direct the reader to the pre-registration where relevant. The co-authors of this pre-registration have permitted the content to be used in the context of the current thesis. An author contribution statement is included in Appendix C1 to outline the role of each author in the preparation of this pre-registered study, which will be referred to in this thesis as Fiske et al. (in prep). Preprint available here.

1. Background

The transition from late infancy into toddlerhood represents a fundamental period in early development. During this time, the PFC undergoes structural and functional maturation processes that parallel the emergence and improvement of behavioural executive function skills, such as response inhibition (Diamond, 2002; Fiske & Holmboe, 2019). Despite the importance of this developmental period, it has been argued that this transitional phase represents a ‘black box’, in that little is known about the emergence and development of response inhibition and the underlying neural substrates in children under 2 years of age (Fiske & Holmboe, 2019; Kerr-German et al., 2023). This is likely due to methodological

limitations surrounding the lack of age-appropriate tasks and the suitability of neuroimaging techniques, as discussed in Chapter 4.

Taking steps towards decoding the 'black box' of developmental research on EFs, the study presented in Chapter 4 uncovered the neural correlates of response inhibition in 10-month-old infants. Regions of the right dorsolateral prefrontal cortex (DLPFC), right orbital frontal cortex (OFC), and right parietal cortex were identified as being more active when inhibition was required. This current chapter follows this same cohort of participants, now at 16-months of age, at the start of their transition to toddlerhood. The aim of the current study was to examine the behavioural development of response inhibition from infancy to toddlerhood and to examine whether the same brain regions that were associated with response inhibition at 10-months of age were still recruited at 16-months.

2. Method

2.1. Participants and Exclusions

Full demographic information for the sample of 16-month-old participants is available in Chapter 2 of this thesis. Following sample-level exclusions, 99 participants contributed data to Session 1 only, and 94 participants contributed data to both sessions. It is worth noting that the participant sample at 16-months was limited in that data collection had to stop prematurely because of the COVID-19 pandemic. As such, many participants who were tested at 10-months were unable to return for their session at 16-months, so the sample size is smaller than planned at this assessment point. To supplement this, 16-month data from pilot participants (under the same administration protocol as the longitudinal study) are included in the current sample.

Following exclusions (see **Table 1**), the final sample of behavioural ECITT data (Session 1) consisted of 77 participants, and the blocked ECITT sample (Session 2) consisted of 81 participants. A total of 67 participants (*N* = 33 males) had valid ECITT data from both sessions. A total of 65 participants contributed valid behavioural ECITT data, and a total of 62 participants contributed valid blocked ECITT data, at both the 10- and 16-month assessment points.

fNIRS data from the 81 participants who contributed valid blocked ECITT data were assessed against inclusion criteria to determine the validity of the fNIRS data collected whilst the blocked ECITT was completed (**Table 1**). The final sample with valid fNIRS data consisted of 43 participants. Whilst there was considerable fNIRS data attrition (~47% of

data excluded), this is comparable to that of other fNIRS studies with similarly aged participants (e.g., Bulgarelli et al., 2019, and see Baek et al., 2023). Of the 43 toddlers with valid fNIRS and blocked ECITT data, 36 toddlers also contributed valid behavioural ECITT data. Valid fNIRS data is available at both the 10- and 16-month assessment points for a total of 18 participants.

Table 1. Chapter 5. 16-month Data Exclusions.

Behavioural ECITT (Session 1)	***N***
Less than 16 trials completed (including at least 2 valid inhibitory trials)	2
Less than 60% accuracy on prepotent trials	19
Software failure: data did not save	1
Total Excluded	**22**
Percentage Excluded	**22.22%**
Total Included	**77**
Blocked ECITT (Session 2)	***N***
Less than 2 blocks of each condition completed	8
Less than 60% accuracy on prepotent trials	4
Video of session was not recorded	1
Total Excluded	**13**
Percentage Excluded	**13.83%**
Total Included	**81**
fNIRS Data	***N***
Refused to wear fNIRS cap	8
Did not complete at least 3 blocks of each type (6 blocks total)	3
fNIRS cap was removed before the minimum number of blocks had been completed	5
fNIRS cap placement was invalid	16
Did not have at least 3 valid blocks of each type (6 valid blocks total)	4
Did not meet pre-processing data quality criteria	2
Total Excluded	**38**
Percentage Excluded	**46.91%**
Total Included	**43**

2.2. Apparatus, Stimuli, and Procedure

The same fNIRS apparatus (Gowerlabs NTS fNIRS system) and stimuli (ECITT; Holmboe et al., 2021) used in Chapter 4 were used in the current study and the administration procedure was identical at both the 10- and 16-month assessment points. See the ‘Apparatus and Stimuli’ and ‘Procedure’ sections of Chapter 4 for full details.

The number of blocks (of each type) completed by participants with valid fNIRS data on the blocked version of the ECITT ranged from 3 – 8 (Control: *M* = 5.22, Experimental: *M* = 5.04), with a mean duration of 35 s (*SD* = 9.8 s) for control blocks and 42 s (*SD* = 11.7 s) for

experimental blocks. Overall, toddlers with valid fNIRS data completed between 6 – 15 blocks of trials (*M* = 10.27), which is equivalent to 36 – 90 individual trials.

3. Data Processing

The data processing procedures were near-identical at both the 10- and 16-month assessment points; deviations are noted below. Please see the equivalent section of Chapter 4 for full details about data processing and preparation.

3.1. Behavioural Data Processing

Details of the inter-coder reliability achieved for the accuracy and validity coding for both versions of the ECITT and the baseline looking behaviour coding are reported in **Table 2**.

For the 16-month dataset, coders were also trained to identify trials in which the reaction time needed correcting (i.e., because the child's first response was not detected by the iPad) and to use specialised software (developed by Henrik Dvergsdal) to make the necessary timing corrections. Note that any video software that allows frame-by-frame playback and displays times with millisecond accuracy can be used to correct response times. Videos of the session were recorded at a frame rate of 33 ms per frame, and as such, the accuracy of the corrected response times is limited to this margin of error.

Table 2. Chapter 5. ECITT Inter-Coder Reliability.

	N of coders	N of videos (*N* of coding instances)	Test	Accuracy	Validity
Behavioural ECITT	3	20 (644)	Fleiss' kappa	κ = .943	κ = .840
Blocked ECITT	2	20 (1234)	Cohen's kappa	κ = .953	κ = .882
Baseline looking behaviour	2	20 (1,064)	Cohen's kappa	N/A	κ = .890
Reaction time correction – behavioural ECITT	2	20 (94)	Intraclass correlation	.974	N/A
Reaction time correction – blocked ECITT	2	20 (98)	Intraclass correlation	.989	N/A

3.2. fNIRS Data Processing

As described in Chapter 4, before the fNIRS data could be processed a series of data quality checks were carried out which led to the identification (and subsequent exclusion) of invalid

ECITT task blocks. Trial blocks were invalid (and excluded) if the duration was longer than the mean duration + 2 SD for each block type (Control = 54 s, Experimental = 65 s). The same data preparation and pre-processing procedures as described in Chapter 4 were used to process the fNIRS data in the current study. Data were entered into HomER2 (Huppert et al., 2009) for pre-processing. Participants with more than 2/3 of channels excluded following the pruning of poor-quality channels were not included in further analysis (*N* = 2 excluded, 43 valid data files remaining). Oxygenated haemoglobin (HbO_2) and deoxygenated haemoglobin (HHb) concentration change data from each channel were block averaged over 37 seconds (containing 2 s of data from valid baseline blocks and 35 s of data from valid task blocks). Baseline concentration change data (two seconds) were subtracted from the average haemoglobin concentrations in the 35-second experimental window and the baseline-corrected data were divided into seven five-second time bins. Data were then prepared for repeated measures analyses following the same processes as outlined in Chapter 4.

4. Study Hypotheses and Analysis Approach

The hypotheses, variables, and analysis plans were defined and pre-registered before analysis. For full details, please see https://osf.io/hpb4s. The same behavioural variables as described in Chapter 4 were used in the current study, and descriptions of additional reaction time variables used at 16-months are provided in the 'Measured variables' section of the pre-registration. Note that in the current study, an adjustment was made to how the 'accuracy inhibitory score' was generated for participants who were more accurate on inhibitory trials than prepotent trials (i.e., the opposite performance pattern than expected). Here, the accuracy inhibitory score was calculated as: (1 – (mean prepotent accuracy – mean inhibitory accuracy) × mean prepotent accuracy). This was done to avoid inflating the scores for these participants and so is a more accurate representation of individual accuracy performance. This adjustment was only made for a minority of participants (N = 11/ 80 participants in Session 1, and N = 10 / 81 participants in Session 2).

Before submitting the pre-registration, the anatomical labels of brain regions covered by channels in the probe at 16-months were generated by Dr Liam Collins-Jones to support the predictions of channels and brain regions, considering changes in head size and other physiological changes from 10- to 16-months of age. Please see Appendix C2 for the anatomical labels of all channels in the probe.

4.1. Pre-registered Behavioural Hypotheses and Analysis Plans

4.1.1. ECITT Condition Effects

Based on evidence from previous studies that have used the ECITT with infants and toddlers (Hendry et al., 2021; Holmboe et al., 2021), it was predicted that mean accuracy would be significantly greater on prepotent trials (where there is no inhibitory demand) than on inhibitory trials (where there is an inhibitory demand) and that participants would respond significantly faster on correct prepotent trials than on correct inhibitory trials. For the sample of participants with valid behavioural ECITT data (N = 77 with valid data, but only N = 61 included in analyses as the N = 16 pilot participants data have already been analysed by Hendry et al. (2021)), two paired *t*-tests were conducted to test the hypotheses that accuracy (prepotent > inhibitory) and reaction time (inhibitory > prepotent) significantly differed by trial type.

4.1.2. Behavioural Development from 10 – 16-months

Based on findings from Hendry et al. (2021) where the ECITT task was also used with 10- and 16-month-old participants (independent from this sample, except for Session 1 data from 13 pilot participants), it was hypothesised that there would be no significant improvement in performance (accuracy inhibitory score) on either version of the ECITT from 10- to 16-months. Similarly, based on Hendry et al. (2021), it was predicted that there would be no significant correlation between performance on either version of the ECITT at 10-months and 16-months.

In line with the analysis plan, two Pearson's correlation analyses were conducted to examine whether there was a significant association between performance (accuracy inhibitory score) on the behavioural ECITT (Session 1) at 10-months and 16-months, and the blocked ECITT (Session 2) at 10-months and 16-months. To examine developmental progression across assessment points (performance improvement with age), a fully factorial 2 × 2 linear mixed model was conducted with trial type (prepotent, inhibitory) and age (10-months, 16-months) as within-subjects factors, and mean accuracy from Session 1 as the dependent variable. A second linear mixed model was also conducted using mean accuracy from the Session 2 data as the dependent variable.

4.1.3. Between-Session Consistency and Test Re-Test Reliability

In line with previous research (Hendry et al., 2021) and the results of the 10-month dataset in Chapter 4, it was predicted that there would be no significant group-level difference in performance (mean accuracy and median reaction time) between the behavioural ECITT (Session 1) and the blocked ECITT (Session 2). To assess the group-level stability of accuracy and reaction time across sessions, two separate 2 × 2 repeated measures ANOVAs with trial type (prepotent, inhibitory) and session (behavioural ECITT in Session 1, blocked ECITT in Session 2) as within-subjects factors were conducted. Additionally, five paired *t*-tests were conducted to determine whether mean performance levels were stable across sessions.

Again, based on these previous results, it was also hypothesised that performance (mean accuracy and median reaction time) would be significantly correlated across sessions with at least a medium effect size of $r \geq .3$. Five Pearson's correlation analyses were conducted to examine the test re-test reliability of the task across the two sessions.

4.1.4. Group Performance Differences

The sample of participants with valid blocked ECITT data ($N = 81$) was divided into two sub-samples depending on whether only valid ECITT data was provided ($N = 43$) or whether valid fNIRS data was also provided ($N = 38$). Based on findings from the 10-month dataset in Chapter 4, it was expected that there would be no significant performance differences between those with and those without valid fNIRS data. This is because there are a number of reasons why participants may not have contributed valid fNIRS data, and so it is highly unlikely that these exclusions were systematically related to infant's inhibitory control abilities To test whether accuracy significantly differed by trial type and/or between sub-samples, a 2 × 2 mixed ANOVA with trial type (within-subjects factor) and sub-sample (between-subjects factor) was conducted. A second 2 × 2 mixed ANOVA (trial type, sub-sample) was conducted with the median reaction time variables. Additionally, it was predicted that there would be no significant difference in the accuracy inhibitory score between groups. To test this hypothesis, an independent *t*-test was conducted with the accuracy inhibitory score as the dependent variable.

4.2. Pre-registered fNIRS Hypotheses and Analysis Approach

Following pre-processing and block averaging of the fNIRS data, average haemoglobin concentration data were available for each: individual ($N = 43$), chromophore (HbO_2, HHb), channel ($N = 46$), condition (control, experimental, difference (control – experimental)), and

time bin (*N* = 7). Additional variables were generated for the individual differences analysis (described in the Results section). The analyses described below were conducted using the same processes as described in the equivalent sections in Chapter 4.

4.2.1. fNIRS Group-Level and Time Course Analyses

In line with the pre-registered analysis plan, the first level of analysis was conducted to investigate the hypothesis that the six pre-registered channels covering the areas of interest (as identified at 10-months) were showing significant block type effects at the group level. The analyses were conducted at the channel level on Channels 10 and 12 (right parietal cortex), Channels 25 and 26 (right DLPFC), and Channels 32 and 33 (right OFC). This was based on the findings reported in Chapter 4, where these channels were found to be showing significant block type effects. Once the initial confirmatory analysis had been conducted, exploratory analyses were conducted on the remaining channels in the fNIRS probe to investigate whether any additional channels were showing significant block type effects.

Confirmatory analyses were conducted to examine the time course of the block type effect on the pre-registered channels that had been identified as showing significant block type effects. Following this, exploratory analyses were conducted on the remaining channels that were showing significant block type effects to investigate the time course of this effect. No specific hypotheses were proposed regarding the time course of the block type effect.

4.2.2. Individual Differences Analyses

The purpose of these analyses was to investigate associations between block type-dependent haemoglobin concentration changes and response inhibition performance on the blocked ECITT. Provided that the pre-registered channels showed significant block type effects, the following predictions were made based on the results from the 10-month dataset (Chapter 4, Fiske et al., 2022). Firstly, it was predicted that there would be a significant positive correlation between the haemodynamic response (HbO_2 difference and/or HHb difference) in channels overlying the right DLPFC (Channels 25 and 26) and the accuracy inhibitory score. Secondly, it was predicted that there would be a significant negative correlation between the haemodynamic response (HbO_2 difference and/or HHb difference) channels overlying the right OFC (Channel 33) and the accuracy inhibitory score.

4.2.3. Neural Development from 10- to 16-months

Exploratory statistical analyses were conducted to investigate the longitudinal development of neural activation from 10- to 16-months. However, since only a small sample of participants contributed valid fNIRS data at both 10- and 16-months (N = 18), statistical power for significance testing was limited. This analysis acts as a preliminary evaluation of the data and should be followed up in future work with a larger sample.

4.3. Statistical Analysis

All statistical analyses were conducted in SPSS version 29. All variables were tested against the parametric test assumptions, and when violated, appropriate non-parametric equivalents were used (see Appendix C3 for details and for results of non-parametric tests). Greenhouse-Geisser corrected degrees of freedom and significance values were used because the channel-level fNIRS data did not meet the sphericity assumption required for repeated measures ANOVA. The procedure for controlling the FDR (Benjamini & Hochberg, 1995) was used where multiple tests were conducted. CIs (95%) were calculated on 1000 bootstrap samples.

5. Results

5.1. Behavioural Results

5.1.1. ECITT Condition Effects

In line with the predicted effects, results demonstrated that, in both sessions, mean accuracy and median reaction time significantly differed by trial type. That is, participants were significantly more accurate and responded significantly faster on prepotent trials than on inhibitory trials (see **Table 3**).

Table 3. Chapter 5. Performance on the ECITT.

	Inhibitory accuracy	Prepotent accuracy	Test Statistic	*P*	Effect size
Session 1	.486 (.340)	.921 (.082)	*t* (60) = -9.304	**< .001**	*d* = -1.191
Session 2	.536 (.324)	.924 (.088)	*F* (1, 79) = 102.745	**< .001**	ηp^2 = .565
	Inhibitory median RT	**Prepotent median RT**	**Test Statistic**	***P***	**Effect size**
Session 1	1627 (514)	1457 (356)	*t* (52) = 2.604	**.006**	*d* = .358
Session 2	1454 (418)	1280 (216)	*F* (1, 75) = 19.435	**< .001**	ηp^2 = .206

Note. Mean (SD) is reported for the inhibitory and prepotent accuracy variables. RT = reaction time. Mean median RT (SD) are presented in milliseconds. Median RT only includes correct, valid trials. Statistically significant results are highlighted in bold.

5.1.2. Behavioural Development from 10- to 16-months

Results of confirmatory Pearson's correlation analyses revealed that there was no significant association between performance (accuracy inhibitory score) on the behavioural ECITT (Session 1) at 10-months and 16-months: *r* (63) = .144, *p* = .126, *CI* = -.128, .385, or on the blocked ECITT (Session 2) at 10- and 16-months: *r* (60) = -.044, *p* = .368, *CI* = -.275, .196.

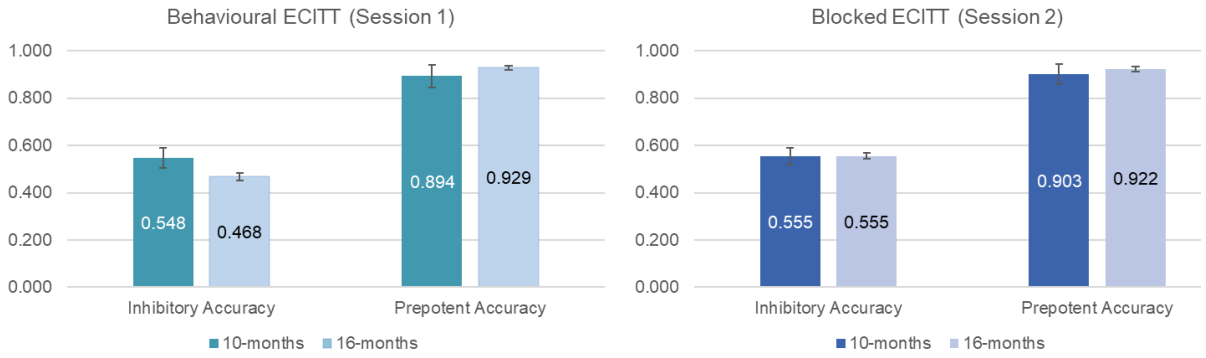
Results of the two repeated measures linear mixed models (2 × 2: trial type, age) with mean accuracy as the dependent variable are reported in **Table 4** (estimated marginal means are reported in **Table 5**). Results (**Figure 1**) demonstrated that, in both sessions, there was a significant main effect of trial type, whereby participants were significantly more accurate on prepotent than on inhibitory trials. There was no significant main effect of age, nor a significant trial type × age interaction. These results are in line with the hypothesis that there would be no significant performance (accuracy) improvement from 10- to 16-months.

Table 4. Chapter 5. Behavioural Development from 10- to 16-months.

Session 1	**Test Statistic**	***p***	**Effect size (ηp^2)**
Trial type	*F* (1, 64) = 168.030	**<.001**	.724
Age	*F* (1, 64) = .000	.983	.000
Interaction	*F* (1, 64) = 1.107	.294	.013
Session 2	**Test Statistic**	***p***	**Effect size (ηp^2)**
Trial type	*F* (1, 61) = 149.127	**<.001**	.710
Age	*F* (1, 61) = .109	.743	.002
Interaction	*F* (1, 61) = .093	.762	.002

Note. Statistically significant results are highlighted in bold.

Figure 1. Chapter 5. Behavioural Development from 10- to 16-months.



Note. The reported values represent the mean, and the error bars represent the standard error. *N* = 65 for behavioural ECITT (Session 1, excluding *N* = 13 pilot participants), and *N* = 62 for blocked ECITT (Session 2).

Table 5. Chapter 5. Behavioural Development from 10- to 16-months; Estimated Marginal Means.

Session 1		**Estimated marginal mean**	**Standard error**	**Confidence interval**
Trial type	Inhibitory	.492	.031	.429, .555
	Prepotent	.912	.008	.897, .928
Age	10-months	.703	.021	.661, .744
	16-months	.702	.021	.660, .744
Interaction	Inhibitory 10-months	.508	.040	.429, .587
	Inhibitory 16-months	.476	.043	.390, .562
	Prepotent 10-months	.897	.012	.873, .922
	Prepotent 16-months	.928	.009	.910, .946
Session 2		**Estimated marginal mean**	**Standard error**	**Confidence interval**
Trial type	Inhibitory	.555	.026	.503, .608
	Prepotent	912	.009	.894, .930
Age	10-months	.729	.017	.695, .763
	16-months	.739	.022	.694, .783
Interaction	Inhibitory 10-months	.555	.035	.485, .625
	Inhibitory 16-months	.555	.043	.470, .641
	Prepotent 10-months	.903	.012	.880, .926
	Prepotent 16-months	.922	.011	.900, .944

5.1.3. Between-Session Consistency and Test Re-Test Reliability

Descriptive statistics for participants with valid data from both sessions are presented in **Table 6**.

Table 6. Chapter 5. Descriptive Statistics for ECITT Performance.

		Session 1		**Session 2**	
	N	Mean	SD	Mean	SD
Mean inhibitory accuracy	67	.476	.349	.575	.313
Mean prepotent accuracy	67	.920	.082	.936	.076
Accuracy inhibitory score	67	.526	.385	.624	.355
Median inhibitory reaction time (ms)	56	1656	506	1442	382
Median prepotent reaction time (ms)	56	1438	327	1286	216

Contrary to the hypotheses, the results of the paired t-tests (**Table 7**) indicated that the mean inhibitory accuracy and accuracy inhibitory score were significantly higher, and median reaction times were significantly faster in the blocked ECITT (Session 2) than in the behavioural ECITT (Session 1). This aligns with the results of the repeated measures ANOVAs (reported in **Table 8**, estimated marginal means reported in **Table 9**) where there was a significant main effect of session, in that participants were significantly more accurate and responded significantly faster on the blocked ECITT than on the behavioural ECITT. No significant trial type × session interaction effects were found.

Pearson correlation analyses indicated significant test re-test reliability between mean inhibitory accuracy, accuracy inhibitory score and median prepotent reaction time in Session 1 and Session 2, as hypothesised (see **Table 7**). Contrary to expectations, the correlation coefficients for median inhibitory reaction time and mean prepotent accuracy were not significant.

Table 7. Chapter 5. ECITT Between-Session Consistency and Test Re-Test Reliability.

	Between-Session Consistency			**Test Re-Test Reliability**		
	Test Statistic	*p*	Effect size (*d*)	Correlation coefficient	*p*	Confidence interval
Mean inhibitory accuracy	*t* (66) = -2.638	**.010**	-.322	*r* (65) = .572	**<.001**	.403, .711
Mean prepotent accuracy	*t* (66) = -1.193	.237	-.146	*r* (65) = .082	.508	-.177, .368
Accuracy inhibitory	*t* (66) = -2.247	**.014**	-.274	*r* (65) = .536	**<.001**	.375, .688
Median inhibitory reaction time	*t* (55) = 2.832	**.003**	.378	*r* (54) = .216	.055	-.009, .430
Median prepotent reaction time	*t* (55) = 3.645	**<.001**	.487	*r* (54) = .397	**.001**	.129, .583

Note. Significant results are highlighted in bold. *p*-values for the accuracy inhibitory and median reaction time variables are one-tailed. *p*-values for the mean accuracy variables are two-tailed.

Table 8. Chapter 5. ECITT Between-Session Consistency (Repeated Measures ANOVA).

Accuracy	**Test Statistic**	***p***	**Effect size (ηp^2)**
Trial type	*F* (1, 66) = 111.442	**<.001**	.628
Session	*F* (1, 66) = 9.712	**.003**	.128
Interaction	*F* (1, 66) = 3.841	.054	.055
Reaction Time	**Test Statistic**	***p***	**Effect size (ηp^2)**
Trial type	*F* (1, 55) = 28.483	**<.001**	.341
Session	*F* (1, 55) = 13.298	**<.001**	.195
Interaction	*F* (1, 55) = .795	.376	.014

Note. Statistically significant results are highlighted in bold.

Table 9. Chapter 5. ECITT Between-Session Consistency (Estimated Marginal Means).

Accuracy		**Estimated marginal mean**	**Standard error**	**Confidence interval**
Trial type	Inhibitory	.525	.036	.454, .597
	Prepotent	.928	.007	.913, .942
Session	1	.698	.020	.657, .739
	2	.755	.019	.717, .793
Interaction	Inhibitory S1	.476	.043	.391, .561
	Inhibitory S2	.575	.038	.499, .651
	Prepotent S1	.920	.010	.900, .940
	Prepotent S2	.936	.009	.917 .954
Reaction Time (ms)		**Estimated marginal mean**	**Standard error**	**Confidence interval**
Trial type	Inhibitory	1549	47	1456, 1642
	Prepotent	1362	31	1300, 1423
Session	1	1547	49	1449, 1645
	2	1364	37	1290, 1438
Interaction	Inhibitory S1	1656	68	1520, 1791
	Inhibitory S2	1442	51	1340, 1544
	Prepotent S1	1438	44	1350, 1525
	Prepotent S2	1286	29	1228, 1344

5.1.4. Group Performance Differences

Results of the 2 × 2 mixed ANOVA conducted on the blocked ECITT data with accuracy as the dependent variable (**Table 10**, estimated marginal means reported in **Table 11**) demonstrated a significant main effect of trial type whereby participants were significantly more accurate on prepotent trials than on inhibitory trials. There was no significant main effect of sub-sample and no significant trial by sub-sample interaction. These results align with the hypothesis that there would be no significant performance differences between sub-samples.

Results of the 2 × 2 mixed ANOVA with reaction time as the dependent variable (**Table 10**, estimated marginal means reported in **Table 11**) revealed a significant main effect of trial type in that participants responded significantly faster on prepotent trials than on inhibitory trials. There was also a significant main effect of sub-sample, in that participants who contributed valid fNIRS data were significantly faster at responding than those without valid fNIRS data. There was no significant trial by sub-sample interaction. Whilst these results demonstrate the expected trial type effect, it was not expected that there would be a significant difference in overall median reaction time between sub-samples.

Finally, as predicted, results of an independent *t*-test revealed that there was no significant difference in the accuracy inhibitory score between those participants with valid fNIRS data (*M* = .541, *SE* = .052) and those without valid fNIRS data (*M* = .645, *SE* = .064): *t* (79) = 1.265, *p* = .105, *d* = .282.

Table 10. Chapter 5. Group Performance Differences: Results of Mixed ANOVAs.

Accuracy	**Test Statistic**	***P***	**Effect size (ηp^2)**
Trial type	*F* (1, 79) = 102.745	**< .001**	.565
Sub-sample	*F* (1, 79) = 1.195	.278	.015
Interaction	*F* (1, 79) = 1.412	.238	.018
Reaction Time	**Test Statistic**	***P***	**Effect size (ηp^2)**
Trial type	*F* (1, 75) = 19.627	**< .001**	.207
Sub-sample	*F* (1, 75) = 6.456	**.013**	.079
Interaction	*F* (1, 75) = .221	.640	.003

Note. Statistically significant results are highlighted in bold.

Table 11. Chapter 5. Group Performance Differences (Estimated Marginal Means).

Accuracy		**Estimated marginal mean**	**Standard error**	**Confidence interval**
Trial type	Inhibitory	.539	.036	.467, .610
	Prepotent	.924	.010	.904, .943
Sub-sample	No fNIRS data	.751	.027	.698, .804
	fNIRS data	.711	.025	.662, .761
Interaction	No data Inhibitory	.581	.052	.477, .686
	No data Prepotent	.921	.014	.893, .950
	Data Inhibitory	.496	.049	.398, .594
	Data Prepotent	.926	.013	.900, .953
Reaction Time (ms)		**Estimated marginal mean**	**Standard error**	**Confidence interval**
Trial type	Inhibitory	1459	47	1366, 1553
	Prepotent	1285	24	1238, 1332
Sub-sample	No fNIRS data	1452	46	1361, 1544
	fNIRS data	1292	43	1297, 1378
Interaction	No data Inhibitory	1549	68	1412, 1685
	No data Prepotent	1356	34	1287, 1424
	Data Inhibitory	1370	64	1242, 1498
	Data Prepotent	1214	32	1150, 1278

5.2. fNIRS Group-Level Results

Confirmatory analyses: In the pre-registration, it was hypothesised that six channels (found to be showing significant block type effects at 10-months) would also show significant block type effects at 16-months. These channels were: Channels 10 and 12 (overlying the right parietal cortex), Channels 25 and 26 (covering the right DLPFC), and Channels 32 and 33 (right OFC). Following pre-processing, Channels 10 and 12 (right parietal) were excluded from the confirmatory group-level analysis because less than 70% of participants contributed data to these channels. As such, repeated measures ANOVAs were conducted on data from the remaining four channels.

The results of the repeated measures ANOVA revealed that all four channels demonstrated a significant main effect of time (i.e., the haemoglobin concentration changed over time from baseline; see Appendix C4). Channels 25 and 26 (right DLPFC), and Channels 32 (right OFC) showed a significant main effect of time in both the HbO_2 and HHb signal, whereas Channel 33 only showed a significant main effect of time in the HHb signal. Following correction for the FDR (eight comparisons; four channels × two chromophores), all channels retained significance for the main effect of time. A significant main effect of block type was observed in the HHb signal for Channel 33 (see **Table 12**), suggesting that the HHb concentration in this channel was differentiated by block type. A significant time × block type interaction was found in the HbO_2 signal for Channel 26 (see **Table 12**), suggesting that there was a significant difference in HbO_2 concentration between experimental and control conditions, and that this difference was dependent on the time bin. These effects did not survive correction for the FDR (*N* = 8 comparisons; four channels × two chromophores).

Exploratory analyses: In line with the pre-registered analysis plan, exploratory repeated measures analyses were conducted on the remaining channels in the fNIRS probe to examine whether there are any additional channels showing significant block type effects or interactions. It was planned that these analyses would be conducted on 38 channels, however it was found during pre-processing that there were six channels for which less than 70% of participants contributed data (Channels 3 and 5 (left superior parietal gyrus), 9 (right angular gyrus), 11 (right superior parietal gyrus), 15 (left middle frontal gyrus) and 22 (right middle frontal gyrus)) and so these channels were excluded from the analysis.

Of the 32 channels included in the exploratory repeated measures analyses, a total of 21 channels demonstrated a significant main effect of time in the HbO_2 and / or the HHb signal (see Appendix C4). Following correction for the FDR (*N* = 64 comparisons; 32 channels × two chromophores), the main effect of time remained significant in 14 channels. Of the channels showing a significant main effect of time, a significant block type effect was

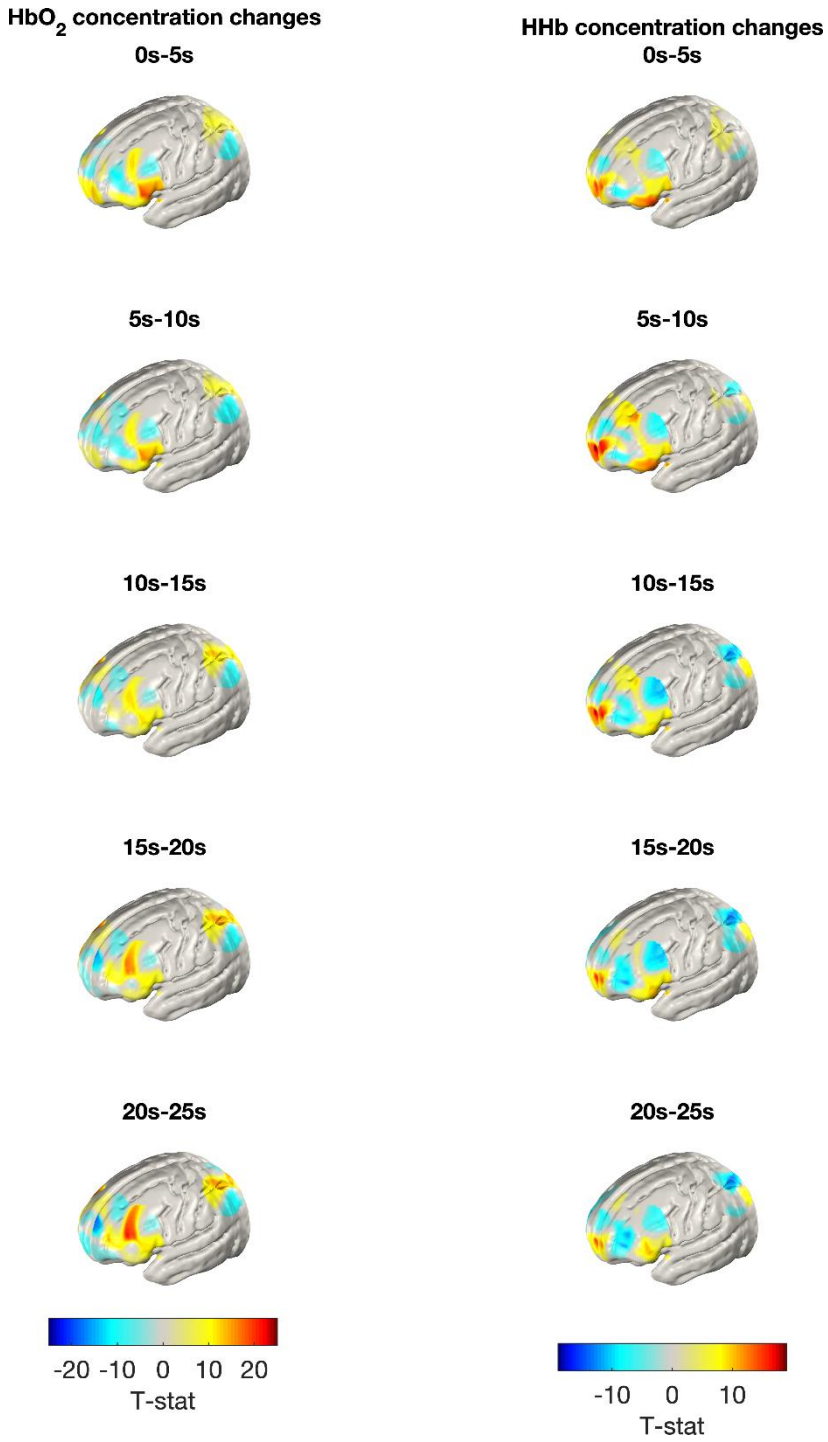
observed in the HHb signal in four channels: Channel 6 (left parietal), Channel 23 (right IFG), Channel 28 (left DLPFC), and Channel 29 (left OFC; see **Table 12**). These effects did not survive correction for the FDR (64 comparisons). See **Figure 2** and **Figure 3** below for *t*-statistic images of significant haemoglobin concentration differences between conditions.

Table 12. Chapter 5. Significant HbO_2 and HHb Concentration Change Differences Between Block Types.

Location	Hemisphere	Channel	Signal	Statistic
Superior parietal gyrus	Left	6	HHb	F (1, 38) = 5.530, p = .024, ηp^2 = .127
IFG	Right	23	HHb	F (1, 42) = 4.191, p = .047, ηp^2 = .091
DLPFC	Left	28	HHb	F (1, 41) = 8.495, p = .006, ηp^2 = .172
	Right	**26**	HbO_2	F (3.557, 128.065) = 2.595, p = .046, ηp^2 = .067
OFC	Left	29	HHb	F (1, 41) = 4.158, p = .048, ηp^2 = .092
	Right	**33**	HHb	F (1, 42) = 4.370, p = .043, ηp^2 = .094

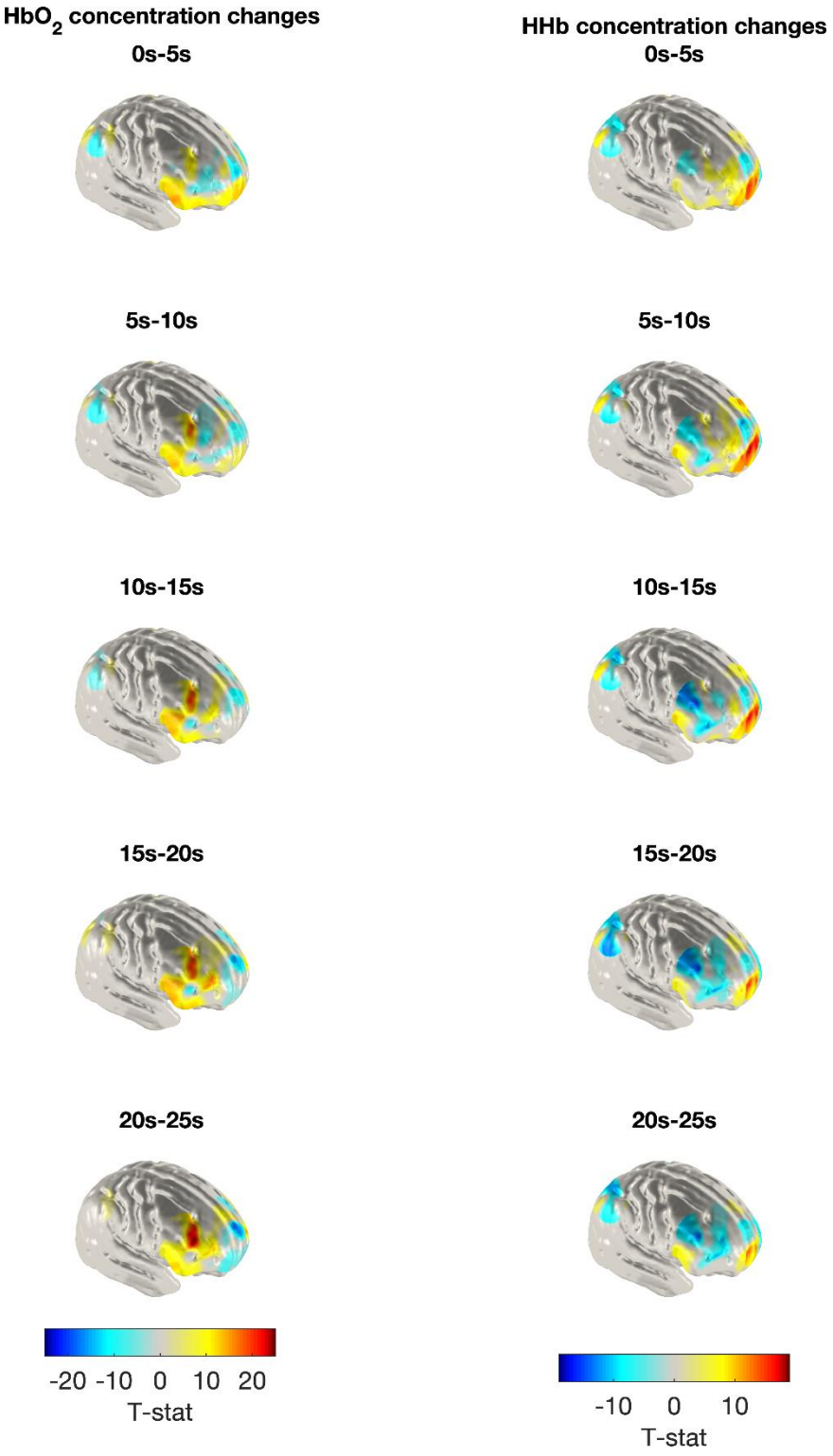
Note. Bolded channels also showed significant effects in the 10-month study. IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

Figure 2. Chapter 5. Group-Level *T*-Statistic Image of the Contrast in Haemoglobin Concentration Changes Between Block Types in the Left Hemisphere.



Note. Group-level T-statistic images of the contrast in concentration changes of each chromophore (HbO_2 on the left and HHb on the right) between experimental and control blocks (experimental – control) in the left hemisphere. Images are displayed in the space of a cortical surface derived from averaged structural MRI data of a 12-month-old cohort of infants (Shi et al., 2011). Using this approach, all displayed T-statistic values are significantly different across block types (paired t-test) at the alpha level of $p < .01$. **Image produced by Dr Liam Collins-Jones.**

Figure 3. Chapter 5. Group-Level *T*-Statistic Image of the Contrast in Haemoglobin Concentration Changes Between Block Types in the Right Hemisphere.



Note. Group-level T-statistic images of the contrast in concentration changes of each chromophore (HbO_2 on the left and HHb on the right) between experimental and control blocks (experimental – control) in the right hemisphere. Images are displayed in the space of a cortical surface derived from averaged structural MRI data of a 12-month-old cohort of infants (Shi et al., 2011). Using this approach, all displayed T-statistic values are significantly different across block types (paired t-test) at the alpha level of $p < .01$. **Image produced by Dr Liam Collins-Jones.**

5.2.1. fNIRS Time Course Analyses

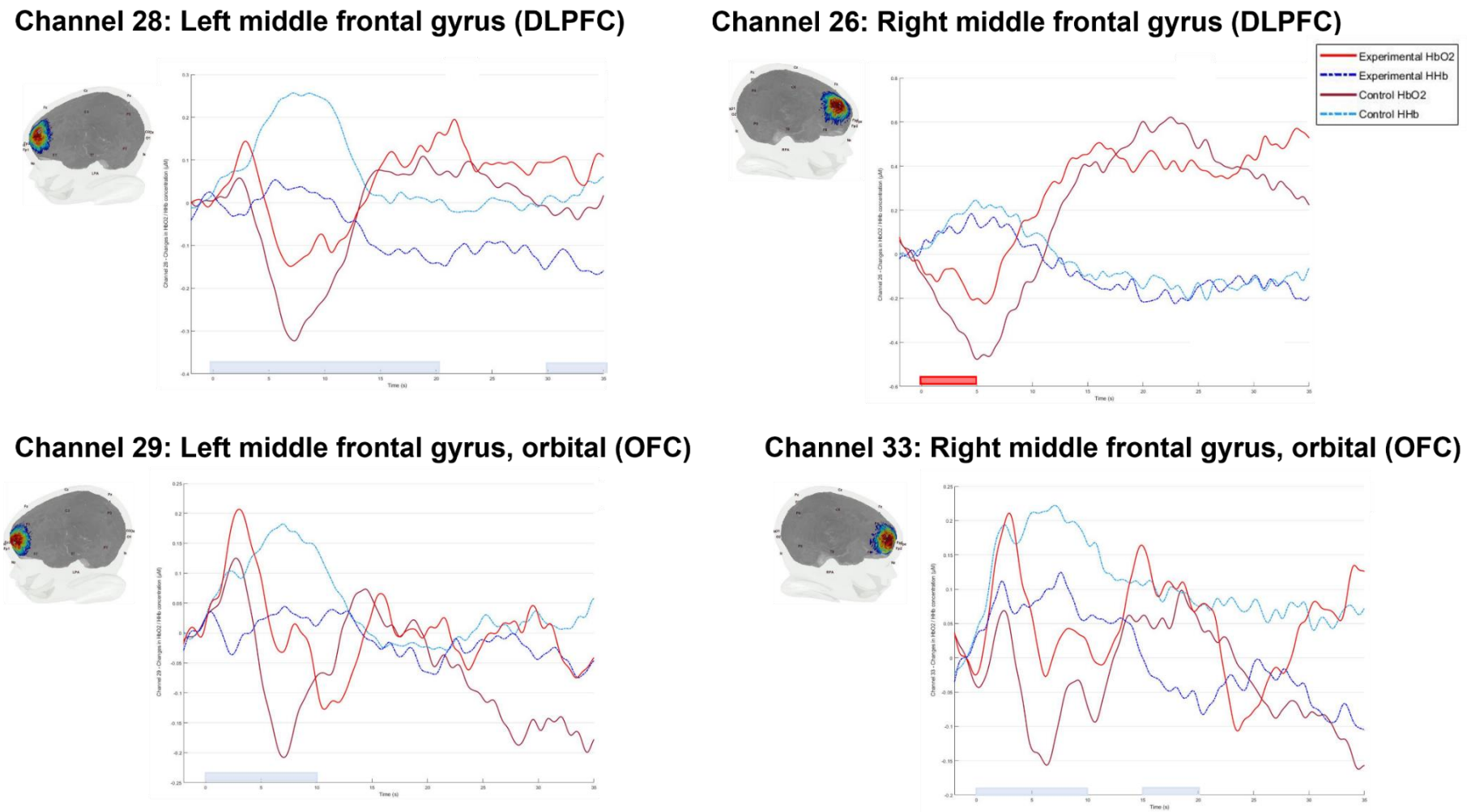
To examine the time course of the significant effects, paired *t*-tests were conducted on the six channels identified in the primary analyses as showing significant block type effects; results are reported in **Table 13**. See also **Figure 4**, where the time bins showing significant block type effects are highlighted in each channel with either a blue (HHb) or red (HbO_2) bar. Regarding the HbO_2 interaction effect found in Channel 26 from 0 – 5 s , it was decided following examination of the HRF patterns for each channel (see **Figure 4**), that no further planned analyses would be conducted, and that the result should be considered preliminary and so interpretations will be made very cautiously. Since the only significant effects in this channel were observed in the first 5 seconds of the block time course (and are not observed again afterwards), it is likely that this effect is reflecting anticipatory neural responses, rather than actual brain response that are differentiated by task conditions.

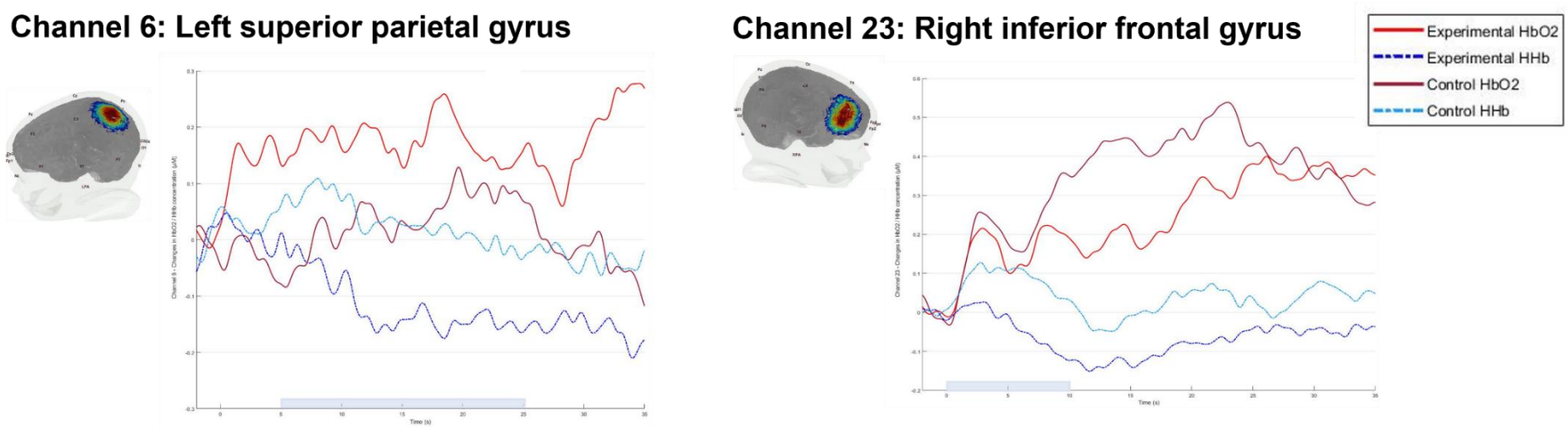
Table 13. Chapter 5. Time Course of the Significant HbO_2 or HHb Block Type Effects.

Location	Channel	Signal	0 – 5s	5 – 10s	10 – 15s	15 – 20s	20 – 25s	25 – 30s	30 – 35s
Left superior parietal gyrus	6	HHb	*t* (38) = .713, *p* = .480, *d* = .114	***t* (38) = 2.051, *p* = .047, *d* = .328**	***t* (38) = 2.385, *p* = .022, *d* = .382**	***t* (38) = 2.089, *p* = .043, *d* = .335**	***t* (38) = 2.083, *p* = .044, *d* = .334**	*t* (38) = 2.013, *p* = .051, *d* = .322	*t* (38) = 1.808, *p* = .078, *d* = .290
Right IFG	23	HHb	***t* (42) = 2.285, *p* = .027, *d* = .348**	***t* (42) = 2.293, *p* = .027, *d* = .350**	*t* (42) = 1.364, *p* = .180, *d* = .208	*t* (42) = 1.777, *p* = .083, *d* = .271	*t* (42) = 1.634, *p* = .110, *d* = .249	*t* (42) = .974, *p* = .336, *d* = .148	*t* (42) = 2.011, *p* = .051, *d* = .307
Left DLPFC	28	HHb	***t* (41) = 2.454, *p* = .018*, *d* = .379**	***t* (41) = 3.192, *p* = .003*, *d* = .493**	***t* (41) = 2.738, *p* = .009*, *d* = .423**	***t* (41) = 2.069, *p* = .045, *d* = .319**	*t* (41) = 1.526, *p* = .135, *d* = .235	*t* (41) = 1.728, *p* = .092, *d* = .267	***t* (41) = 2.567, *p* = .014*, *d* = .396**
Right DLPFC	26	HbO_2	***t* (36) = -2.040, *p* = .049, *d* = -.335**	*t* (36) = -1.926, *p* = .062, *d* = -.317	*t* (36) = -1.039, *p* = .306, *d* = -.171	*t* (36) = -.312, *p* = .757, *d* = -.051	*t* (36) = .998, *p* = .325, *d* = .164	*t* (36) = .124, *p* = .902, *d* = .020	*t* (36) = -1.506, *p* = .141, *d* = -.248
Left OFC	29	HHb	***t* (41) = 2.764, *p* = .009*, *d* = .427**	***t* (41) = 2.676, *p* = .011*, *d* = .413**	*t* (41) = 1.482, *p* = .146, *d* = .229	*t* (41) = 1.013, *p* = .317, *d* = .156	*t* (41) = 1.134, *p* = .263, *d* = .175	*t* (41) = .835, *p* = .409, *d* = .129	*t* (41) = 1.504, *p* = .140, *d* = .232
Right OFC	33	HHb	***t* (42) = 2.031, *p* = .049, *d* = .310**	***t* (42) = 2.119, *p* = .040, *d* = .323**	*t* (42) = 1.314, *p* = .196, *d* = .200	***t* (42) = 2.085, *p* = .043, *d* = .318**	*t* (42) = 1.546, *p* = .130, *d* = .236	*t* (42) = 1.236, *p* = .223, *d* = .189	*t* (42) = 1.945, *p* = .058, *d* = .297

Note. Statistically significant results are highlighted in bold. * = significant after correcting the FDR (7 comparisons).
IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

Figure 4. Chapter 5. Haemodynamic Response Function for Channels Showing Significant Block Type Effects.





Note. This figure illustrates the average haemodynamic response function from -2 seconds (baseline) to 35 seconds of the block time-course for channels showing significant block type effects. The change in concentration in HbO_2 and HHb (μM) for each channel are represented on the y-axis, time bin is plotted on the x-axis. Bars (blue = HHb, red = HbO_2) on the x-axis indicate the time-bins where there is a significant block type effect (note that these time-bin effects did not survive the correction for the FDR (7 comparisons)). Sensitivity profiles illustrate the position of each channel on the cortex and the channel sensitivity (heat map: red = more sensitive, blue = less sensitive).

5.3. Individual Differences Analyses

In line with the pre-registration, correlational analyses were conducted to investigate whether individual differences in neural activation in specific channels (showing significant block type effects across the identified time bins) were associated with individual performance differences in the accuracy inhibitory score. To perform these analyses, five new variables were generated: 'HHb Channel 6 Bins 2 – 5', 'HHb Channel 23 Bins 1 – 2', 'HHb Channel 28 Bins 1 – 4 and Bin 7', 'HHb Channel 29 Bins 1 – 2', and 'HHb Channel 33 Bins 1 – 2 and Bin 4'. These variables were calculated in line with the pre-registered analysis plan, where it was explained that these difference variables will be generated only for channels showing significant block type effects at the group-level analysis stage.

Contrary to prediction, results of the confirmatory Pearson's correlational analyses (**Table 14**) revealed there was no significant association between the accuracy inhibitory score and the HHb difference variable (time bins 1, 2, and 4) for Channel 33. The exploratory Pearson's correlations (**Table 14**) revealed that there were no significant associations between the accuracy inhibitory score and the HHb difference variable for all four channels.

Table 14. Chapter 5. Individual Differences Analyses.

Location	Hemisphere	Channel	Signal	Time Bins	Statistic
Superior parietal gyrus	Left	6	HHb	2 – 5	*r* (37) = -.234, *p* = .151, *CI* = [-.468, .033]
IFG	Right	23	HHb	1 – 2	*r* (41) = -.032, *p* = .840, *CI* = [-.289, .261]
DLPFC	Left	28	HHb	1, 4, 7	*r* (40) = -.212, *p* = .177, *CI* = [-.478, .140]
OFC	Left	29	HHb	1 – 2	*r* (40) = -.070, *p* = .661, *CI* = [-.356, .245]
	Right	33	HHb	1, 2, 4	*r* (41) = .227, *p* = .072, *CI* = [-.112, .518] [a]

Note. [a] = Confirmatory analyses. IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

5.4. Further Exploratory fNIRS analyses

It was stated in the pre-registered analysis plan that only channels that were showing a significant main effect of time would be considered when investigating block type effects. However, when conducting the pre-registered exploratory analyses, three channels were identified as showing a significant main effect of block type in the HHb signal, but with no significant main effect of time (results reported in Appendix C5). These channels were localised to be covering the right parietal cortex (Channel 8), the right IFG (Channel 20), and the right IFG, orbital (Channel 31); see **Table 15**. However, these block type effects did not

survive correction for the FDR (64 comparisons). Exploratory paired *t*-tests were conducted on these three channels to investigate the time course of these block type effects; results are reported in **Table 16**. No significant associations were found when conducting exploratory individual differences correlation analyses on data from these three channels: Channel 8, bins 4, 5, and 7; $p = .130$, Channel 20, bin 1; $p = .920$, Channel 31, all bins; $p = .770$.

The activation found in these channels, whilst clustering in the same regions as other channels showing significant effects, was exploratory (not pre-registered) and the effects did not survive the procedure for controlling the FDR. As such, these results will be treated as preliminary and will be interpreted with caution. HRF plots for these channels can be found in Appendix C5.

Table 15. Chapter 5. Further Exploratory fNIRS Analyses: Preliminary Block Type Effects.

Location	Hemisphere	Channel	Signal	Main Effect of Block Type
Inferior parietal (angular gyrus)	Right	8	HHb	F (1, 35) = 5.000, p = .032, ηp^2 = .116
IFG	Right	20	HHb	F (1, 41) = 4.087, p = .050, ηp^2 = .090
IFG, orbital	Right	31	HHb	F (1, 42) = 13.681, p <.001, ηp^2 = .246

Note. These are preliminary effects as channels did not show a significant main effect of time. Note also that these block type effects did not survive the procedure for controlling the FDR. IFG = inferior frontal gyrus.

Table 16. Chapter 5. Time Course of the Preliminary Block Type Effects.

Location	Channel	Signal	0 – 5s	5 – 10s	10 – 15s	15 – 20s	20 – 25s	25 – 30s	30 – 35s
Right inferior parietal	8	HHb	t (35) = 1.232, p = .226, d = .205	t (35) = 1.879, p = .069, d = .313	t (35) = 1.594, p = .120, d = .266	**t (35) = 2.328, p = .026, d = .046**	**t (35) = 2.030, p = .050, d = .338**	t (35) = 1.495, p = .144, d = .249	**t (35) = 2.410, p = .021, d = .402**
Right IFG	20	HHb	**t (41) = 3.199, p = .003*, d = .494**	t (41) = 2.000, p = .052, d = .309	t (41) = 1.079, p = .287, d = .166	t (41) = 1.632, p = .110, d = .252	t (41) = 1.139, p = .261, d = 176	t (41) = 1.309, p = .198, d = .202	t (41) = 1.702, p = .096, d = .263
Right IFG, orbital	31	HHb	**t (42) = 3.143, p = .003*, d = .479**	**t (42) = 2.881, p = .006*, d = .439**	**t (42) = 2.450, p = .019*, d = .374**	**t (42) = 3.512, p = .001*, d = .546**	**t (42) = 2.957, p = .005*, d = .451**	**t (42) = 2.541, p = .015*, d = 387**	**t (42) = 3.177, p = .003*, d = .485**

Note. Statistically significant results are highlighted in bold. * = significant after correcting the FDR (7 comparisons). IFG = inferior frontal gyrus.

5.5. Exploratory Longitudinal Brain Associations from 10- to 16-months

It was stated in the pre-registered analysis plan that preliminary exploratory analyses would be conducted on the longitudinal fNIRS data to examine changes in brain activation across assessment points. It is important to acknowledge that these analyses are limited in their statistical power due to the attrition at the 16-month assessment point resulting from the COVID-19 pandemic. A total of 102 data points were included in the analyses (N = 59 from the 10-month assessment point, N = 43 from the 16-month assessment point), although only 18 participants contributed valid fNIRS data to both assessment points.

5.5.1. Channels Showing Significant Block Type Effects at 16-months

Separate linear mixed models (restricted maximum likelihood estimation) were conducted on the nine channels showing a significant block-type effect at 16-months (dependent variable), with assessment point (10-months, 16-months) as a fixed factor and participants as a random factor. The models were conducted to investigate the change in activation from the 10-month assessment point to the 16-month assessment point (note that Channel 26 (HbO_2) and Channel 33 (HHb) showed significant block type effects at both assessment points). The results are reported in **Table 17** below, and estimated marginal means are reported in **Table 18**. Results indicated that activation (HHb difference) in Channels 8 (right inferior parietal), 28 (left DLPFC) and 31 (right IFG, orbital) increased significantly from 10- to 16-months; see **Figure 5**. The results of this exploratory analysis did not survive the correction for the FDR.

Table 17. Chapter 5. Exploratory Longitudinal Brain Changes in Channels with a Significant Block Type Effect at 16-months.

Location	Channel	Signal	Test Statistic	*p*	Effect size (Cohen's *f*)
L superior parietal	6	HHb	F (1, 87.116) = 1.286	.260	.057
R inferior parietal	8	HHb	F (1, 88.693) = 4.068	**.047**	.184
R IFG	20	HHb	F (1, 92.062) = 1.670	.199	.084
R IFG	23	HHb	F (1, 86.591) = 2.078	.153	.110
L DLPFC	28	HHb	F (1, 92.284) = 4.096	**.046**	.181
R DLPFC	26	HbO_2	F (1, 79.220) = .007	.934	.000
R IFG, orbital	31	HHb	F (1, 97.660) = 5.127	**.026**	.203
L OFC	29	HHb	F (1, 97.256) = 1.213	.274	.047
R OFC	33	HHb	F (1, 91.008) = .358	.551	.000

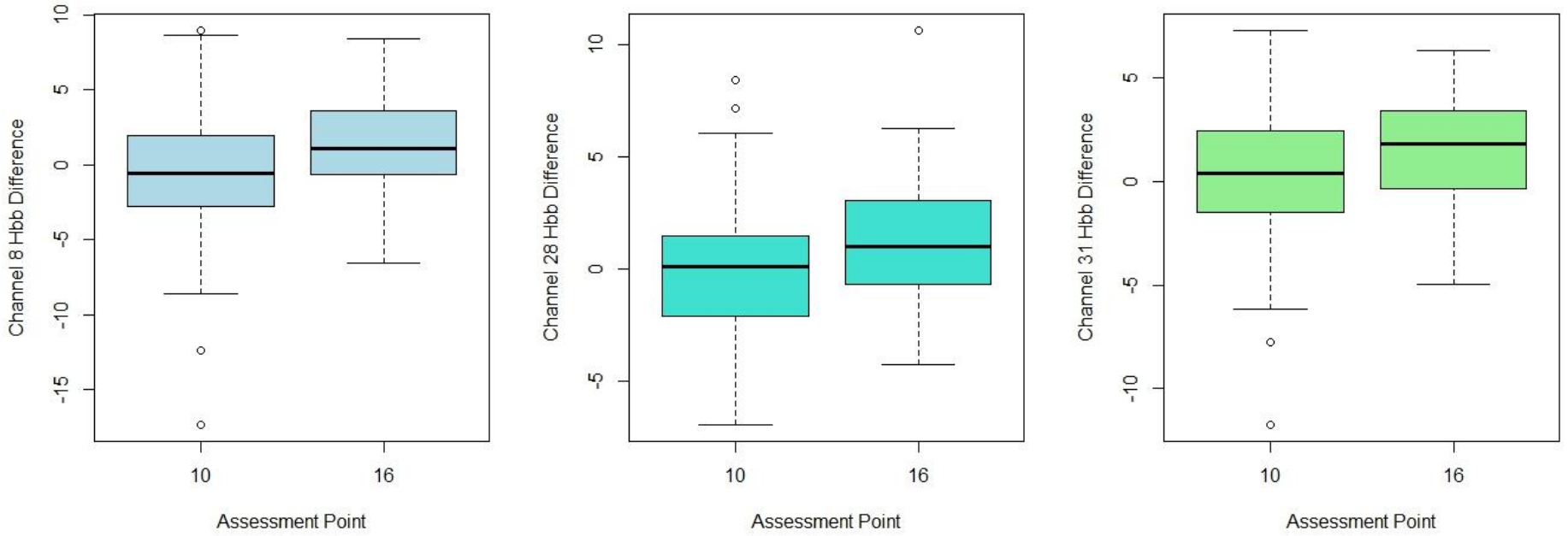
Note. Statistically significant results are highlighted in bold. None of the effects survived the procedure for controlling the FDR (N = 9 comparisons).
L = left, R = right. IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

Table 18. Chapter 5. Exploratory Longitudinal Brain Changes; Estimated Marginal Means (channels with a significant block type effect at 16-months).

Location	Channel	Assessment Point	Estimated marginal mean	Standard error	df	Confidence interval
L superior parietal gyrus (HHb)	6	10-months	.333	.495	51	-.661, 1.327
		16-months	1.127	.495	38	.125, 2.129
R inferior parietal (HHb)	**8**	10-months	-.452	.608	56	-1.670, .765
		16-months	1.220	.564	35	.075, -2.366
R IFG (HHb)	20	10-months	.199	.446	56	-.694, 1.092
		16-months	1.046	.480	41	.076, 2.016
R IFG (HHb)	23	10-months	.097	.376	58	-.655, .849
		16-months	.969	.474	42	.012, 1.926
L DLPFC (HHb)	**28**	10-months	.043	.410	57	-.778, .863
		16-months	1.267	.445	41	.368, 2.165
R DLPFC (HbO_2)	26	10-months	1.011	.949	56	-.889, 2.912
		16-months	1.135	1.132	36	-1.161, 3.431
R IFG, orbital (HHb)	**31**	10-months	.216	.434	57	-.654, 1.085
		16-months	1.581	.419	42	.736, 2.426
L OFC (HHb)	29	10-months	.142	.399	57	-.657, .941
		16-months	.741	.369	41	-.005, 1.487
R OFC (HHb)	33	10-months	.684	.458	58	-.233, 1.601
		16-months	1.105	.523	42	.029, 2.180

Note. Bolded channels showed significant change from 10- to 16-months. L = left, R = right. IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

Figure 5. Chapter 5. Exploratory Longitudinal Brain Changes (Channels Showing Significant Increase in Activation from 10- to 16-months).



Note. This figure illustrates the increase in activation from the 10-month assessment point to the 16-month assessment point in channels showing a significant effect of assessment point (i.e., a significant change over time): Channel 8 (right inferior parietal cortex), Channel 28 (left dorsolateral prefrontal cortex), Channel 31 (right inferior frontal gyrus, orbital). Note that all three channels showed a significant block type effect at 16-months, but not at 10-months. The variables on the y-axis refer to the HHb difference score (calculated as HHb in control blocks minus HHb in experimental blocks) across the block time course.
10 = 10-months, 16 = 16-months. HHb = Deoxygenated haemoglobin.

5.5.2. Channels Showing Significant Block Type Effects at 10-months

Six additional linear mixed models were separately conducted to investigate the change in activation across assessment points in channels showing significant block-type effects at 10-months, but not at 16-months. The results are reported in **Table 19** below, and estimated marginal means are reported in **Table 20**. Results indicated that activation (HbO_2 difference) in Channel 25 decreased significantly from 10- to 16-months, and no longer showed a significant effect of block type at 16-months; see **Figure 6**. The results of this exploratory analysis did not survive the correction for the FDR and so should be considered cautiously.

Table 19. Chapter 5. Exploratory Longitudinal Changes in Channels with a Significant Block Type Effect at 10-months.

Location	Channel	Signal	Test Statistic	*p*	Effect size (Cohen's *f*)
R inferior parietal	10	HbO_2	F (1, 75.167) = .272	.603	.000
R superior parietal	12	HbO_2	F (1, 75.753) = .229	.634	.000
R DLPFC	25	HbO_2	F (1, 94.017) = 4.377	**.039**	.188
	25	HHb	F (1, 81.980) = .490	.486	.000
R OFC	32	HbO_2	F (1, 75.985) = .056	.814	.000
	32	HHb	F (1, 77.131) = .001	.976	.000

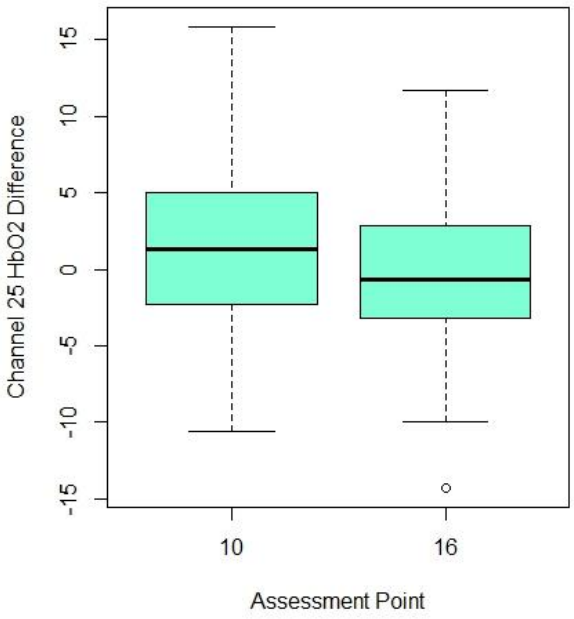
Note. Statistically significant results are highlighted in bold. The significant effect in Channel 25 (HbO_2) did not survive the procedure for controlling the FDR (N = 6 comparisons). L = left, R = Right. DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

Table 20. Chapter 5. Exploratory Longitudinal Brain Changes; Estimated Marginal Means (Change from 10-months).

Location	Channel	Assessment Point	Estimated marginal mean	Standard error	df	Confidence interval
R inferior parietal (**HbO_2**)	10	10-months	2.215	.877	51	.454, 3.976
		16-months	1.590	.814	28	-.076, 3.257
R superior parietal (**HbO_2**)	12	10-months	1.955	.865	50	.218, 3.692
		16-months	1.416	.724	27	-.069, 2.901
R DLPFC (**HbO_2**)	**25**	10-months	1.652	.812	55	.025, 3.278
		16-months	-.748	.870	41	-2.384, .888
R DLPFC (HHb)	25	10-months	1.223	.398	55	.426, 2.020
		16-months	.764	.521	41	-.287, 1.816
R OFC (**HbO_2**)	32	10-months	.160	.721	56	-1.283, 1.604
		16-months	.468	10.88	42	-1.727, 2.663
R OFC (HHb)	32	10-months	1.222	.432	56	.359, 2.85
		16-months	1.245	.637	42	-.040, 2.530

Note. Bolded channels showed significant change from 10- to 16-months. L = left, R = Right. IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

Figure 6. Chapter 5. Exploratory Longitudinal Brain Change (Significant Block Type Effects at 10-months but not at 16-months).



Note. This figure illustrates the decrease in activation from the 10-month to the 16-month assessment point in Channel 25 (HbO_2), which showed significant change over time. Note that Channel 25 showed a significant block type effect at 10-months, but not at 16-months The y-axis refers to the HbO_2 difference score (calculated as HbO_2 in experimental blocks minus HbO_2 in control blocks) across the block time course. Channel 25 covers the right dorsolateral prefrontal cortex. 10 = 10-months, 16 = 16-months.

6. Discussion

The aim of the pre-registered study presented in this chapter was to identify the neural correlates of response inhibition across the transition to toddlerhood. This study was a methodological replication of the study with 10-month-old participants (presented in Chapter 4) since the experimental paradigm and analysis methods remained the same but with the additional strength of contributing longitudinal data from the same sample of participants (now at 16-months of age). This enables the study of developmental change at both the behavioural and neural levels across the transition from late infancy to early toddlerhood. This section will begin with a summary of the key findings of the current study, before discussing the implications of the behavioural results and then interpreting the fNIRS results. Limitations of the current study will also be discussed, and the strengths and implications will be highlighted.

6.1. Summary of Key Findings

The behavioural results from the ECITT provided robust evidence for the predicted trial type effect whereby 16-month-old toddlers were significantly more accurate on prepotent trials than on inhibitory-demanding trials, as was found at 10-months (Chapter 4; Fiske et al., 2022). It was also found that toddlers responded significantly faster on correct prepotent trials than on correct inhibitory trials, again attesting to the task's inhibitory demand. Longitudinal analysis revealed that, despite acceptable 1-week test-retest reliability, there was no significant association between accuracy at 10-months and 16-months and no main effect of age on accuracy. These results were consistent with previous research in this age group (Hendry et al., 2021), and so supported the study hypotheses.

Results of the fNIRS analyses revealed some overlap in channels showing block type effects at 16-months as found at 10-months (Chapter 4; Fiske et al., 2022). At both age points, Channel 26 (HbO_2; right DLPFC) and Channel 33 (HHb; right OFC) were significantly more active when inhibition was required, which may suggest that regions of the right DLPFC and right OFC continue to be involved in response inhibition across the transition to toddlerhood. Although note the caveats about the effect observed in Channel 26 at 16-months, as such this effect should be interpreted with caution. Additionally, at 16-months, channels overlying the left superior parietal cortex, right IFG, left DLPFC, and left OFC were identified as being more active during inhibitory-demanding blocks. Exploratory longitudinal analyses revealed a significant increase in activation (HHb difference) in Channels 8 (right inferior parietal), 28 (left DLPFC), and 31 (right IFG, orbital) from 10- to 16-months, suggesting increasing recruitment of these cortical regions when inhibition is required across this developmental period. Similarly, there was a significant decrease in activation (HbO_2 difference) in Channel

25 (right DLPFC) from 10- to 16-months, suggesting that this channel is no longer significantly recruited when inhibition is required at 16-months.

In summary, whilst behavioural response inhibition does not appear to develop from 10- to 16-months of age, this fNIRS evidence demonstrates that the functional neural substrates that support response inhibition are changing. It could be that these functional neural mechanisms mature *in advance of* any improvement in behavioural response inhibition in the second year of life.

6.2. The ECITT as an Index of Response Inhibition in the Transition to the Toddlerhood

The ECITT was designed to measure response inhibition in infancy and early childhood and has already been used successfully as an index of response inhibition in 10-month-old infants (Hendry et al., 2021, Fiske et al., 2022; as in Chapter 4) and 16-month-old toddlers (Hendry et al., 2021). Replicating this previous work, 16-month-olds in the current study were significantly more accurate, and significantly faster at responding on prepotent trials (no inhibitory demand) than on inhibitory trials. This finding provides further support for the validity of the ECITT as a measure of infant and toddler response inhibition.

Additionally, performance on the ECITT showed significant test re-test reliability across sessions at 16-months for the mean inhibitory accuracy, the accuracy inhibitory score and the median prepotent reaction time variables. However, contrary to expectations, this was not true for the median inhibitory reaction time and mean prepotent accuracy variables. It is possible that the mean prepotent accuracy variable was not found to be reliable across sessions is due to the very high performance observed on prepotent trials (>.920 on average), which could suggest a ceiling effect. There is also less variability in accuracy on prepotent trials (~.082) compared to on inhibitory trials (~.324) so reliability assessments are less likely to be significant (Byers-Heinlein et al., 2022; Holmboe et al., 2021). Nonetheless, it was expected that performance on prepotent trials on the ECITT would be high such that a robust prepotency can be developed, and that a valid inhibitory demand can be imposed during inhibitory trials. The lack of stability in the median inhibitory reaction time variable across sessions is not surprising, since it is well established that reaction time is not the most reliable measure of performance in infants and toddlers (i.e., due to the ‘messy’ nature of responses and the general distractibility of this population; Holmboe et al., 2021).

Examinations of between-session consistency suggested that toddlers were significantly more accurate and responded significantly faster overall in Session 2 (blocked ECITT) than in Session 1 (behavioural ECITT). Interestingly at 10-months (Chapter 4), it was also found

that prepotent accuracy was significantly higher in Session 2 than in Session 1. This result could be due to practice effects, as the participants completed the two versions of the task within approximately one week of each other. However, it may also be that differences in task structure could impact the way the task was completed by the toddlers. For example, responding to six trials at a time with a short break between trials (baseline period) in the blocked ECITT may be less fatiguing and place fewer cognitive demands on the toddler than when they are required to continuously respond to a string of trials without a break (albeit with different animations each time to keep the toddler engaged) in the behavioural ECITT.

Another difference between the two versions of the ECITT was that there was a larger amount of attrition due to poor prepotent accuracy (< 60%) in Session 1 (*N* = 19) compared to Session 2 (*N* = 4). It may be the case that the discrepancy between the two sessions in participants being excluded based on this criterion is also related to these inherent structural differences between the two task versions. However, there is evidence to suggest that this attrition may be due to the existence of a side bias. As discussed by Hendry et al. (2021), previous research with infants has demonstrated a right-handed bias (Ferre et al., 2010) and a preference to reach for objects on the same side as their reaching hand (Begum Ali et al., 2020). When looking at the side allocations in the participants excluded from the behavioural ECITT dataset (Session 1), it was found that most were allocated to the left prepotent side (*N* = 14), and as such would be required to respond to the left-hand side of the screen on most trials (with potential interference from a pre-existing right-side response bias). Interestingly, of the four participants who were excluded because they scored less than 60% on prepotent trials on the blocked ECITT (Session 2), three were also excluded for this reason in Session 1. The potential influence of a pre-existing side bias on task performance in the ECITT (and other tasks that rely on location-based stimuli) may have important implications for infant and toddler researchers when choosing tasks or interpreting data and thus warrants closer investigation in future research.

Results from the current study confirmed that there were no significant group differences in accuracy between those with, and without, valid fNIRS data (in line with the hypothesis based on findings from the 10-month dataset in Chapter 4; Fiske et al., 2022). However, contrary to predictions, it was found that participants with valid fNIRS data responded significantly faster overall than those without valid fNIRS data. Previous research has found links between processing speed differences and performance on inhibition tasks (Friedman & Young, 2008), and it has been argued that processing speed is a building block of early executive function ability (Hendry et al., 2016), therefore this result might reflect differences in overall processing speed between the sub-samples. However, it is unlikely that this difference in response time/processing speed would be reflected at the neural level. This is

because there were many exclusion criteria (e.g., task refusal, cap placement, signal quality metrics) that were applied to assess the validity of the fNIRS data, that are unlikely to be related to processing speed. Further, there was no significant difference in inhibitory performance between the two sub-samples, suggesting that the groups do not differ in their inhibitory control abilities. Whilst this result was not anticipated, future research will continue to examine whether there are any confounding differences inherent to performance (rather than external factors to do with the experiment) which may impact results, and if found, will address these differences when interpreting results.

6.3. Development of Response Inhibition from 10- to 16-months

Longitudinal data from the studies presented in the current chapter and Chapter 4 of this thesis (Fiske et al., 2022) enabled the examination of age-related changes in response inhibition performance from the first (10-months) to the second (16-months) year of life. In line with findings from Hendry et al. (2021) and as hypothesised, there was no significant change in, and no significant association between, accuracy on the ECITT from 10- to 16-months. This lack of age-related improvement and individual stability in response inhibition is likely because response inhibition at both age points is still poor (around chance), and so it may be expected that performance would become more stable further into the second year as response inhibition improves (Hendry et al., 2016). Indeed, Holmboe et al. (2021) observed significant stability in individual differences in accuracy on the ECITT from 18 – 21-months, and from 21 – 24-months, and similar longitudinal research has shown that executive function skills stabilise from around 24-months (Broomell & Bell, 2022). Since the ECITT is easily scalable for use across the lifespan (i.e., by increasing the proportion of prepotent trials and/or decreasing the length of the animations between trials), future research should use this task across the second and third years of life to examine how behavioural response inhibition changes across this fundamental early developmental period.

In line with the hypotheses and replicating previous research, the results of Chapters 4 and 5 suggest that 10- and 16-month-old infants can successfully develop a prepotent motor response to a high degree of accuracy but only successfully inhibit at the level of chance. These findings expand the existing literature on response inhibition in infancy by providing evidence from an active task that requires a motoric response, and thus more closely mimics the demands of response inhibition tasks used with older children and adults. As such, the results of this study are more comparable to the broader response inhibition literature and allow us to understand the emergence of response inhibition already in the first years of life.

6.4. The Neural Correlates of Response Inhibition in the Transition to Toddlerhood

Results of the pre-registered analyses identified that channels overlying the left superior parietal gyrus, the right IFG, the bilateral DLPFC and the bilateral OFC were more active in blocks where response inhibition was required than when no inhibition was required. Interestingly two channels overlying the right DLPFC and right OFC that were found to show significant block type effects at 10-months also showed these effects at 16-months, suggesting consistency in the recruitment of these regions during inhibitory-demanding blocks of the ECITT across this age period. Results of exploratory longitudinal analyses revealed that indeed there was no significant change in the recruitment of Channel 26 (right DLPFC) and Channel 33 (right OFC) from 10- to 16-months. Again, it must be acknowledged that effects observed in Channel 26 at 16-months should be considered preliminary and interpreted with caution. Unlike at 10-months, no significant brain-behaviour associations were found between the accuracy inhibitory score on the ECITT and neural activation at 16-months. However, this may be due to the smaller sample size and limited statistical power at this assessment point. Questions surrounding individual differences in brain-behaviour associations warrant further investigation in studies with larger samples.

Considering the results from both the 10- and 16-month datasets alongside results from existing literature, it is possible to begin to construct a picture of the neural basis of inhibitory control development from infancy and into childhood. Previous research has consistently pointed to the involvement of the right PFC in tasks of response inhibition across the lifespan: in early childhood (Moriguchi et al., 2018; Moriguchi & Shinohara, 2019; X. Zhou et al., 2022), adolescence (Tamm et al., 2002), and adulthood (Aron et al., 2014). As evidenced by the longitudinal results of the current study, the activation of frontal regions in the right hemisphere appears to expand from the DLPFC to also include the IFG across this developmental period. Exploratory longitudinal analyses revealed a significant increase in activation in Channel 31 (overlying the right IFG, orbital) from 10- to 16-months. This parallels substantial evidence in the literature that highlights the right IFG as a key neural substrate in response inhibition in adults (for review, see; Aron et al., 2004, 2014) and that demonstrates the increasing importance of the right IFG with age (Rubia et al., 2007).

Similarly, the recruitment of prefrontal regions in the left hemisphere (alongside right prefrontal regions) appears to become increasingly important as response inhibition abilities mature from 10- to 16-months. The involvement of the bilateral parietal and prefrontal cortices has been evidenced in similar fNIRS studies examining inhibitory control in toddlers (Kerr-German et al., 2022), pre-schoolers (Li et al., 2017), and young children (Mehnert et al., 2013a; X. Zhou et al., 2022). For example, in the study with the closest aged participants

to the current study, Kerr-German et al. (2022) found that stronger fNIRS functional connectivity between channels covering the left and right parietal cortex, and between channels covering the left PFC and left parietal cortex, was associated with better inhibitory control performance in 2½-year-old toddlers. This evidence demonstrates the involvement of both hemispheres during a 'hot' inhibitory control task in toddlerhood and suggests that functional connectivity between bilateral frontal and parietal regions may support the exertion of 'hot' inhibitory control (it is not yet well understood if 'hot' and 'cool' inhibitory control share the same neural substrates). Moving to early childhood, Li et al. (2017) found associations between activation in the left DLPFC and inhibitory performance in 3 – 5-year-old children. In their fNIRS study with children aged 4 – 10 years, Zhou et al. (2022) found that independent of age, children recruited the right PFC when inhibition was required, but that the difference in activation in the left OFC between inhibitory and control conditions increased with age. Similarly, an fMRI study by Cope et al. (2020) involving 7 – 13-year-olds found increasing activation in bilateral regions of the OFC and IFG with age during a response inhibition task.

The emergence of response inhibition in the first year of life is supported by right-lateralised regions of prefrontal and parietal cortices (i.e., Chapter 4; Fiske et al., 2022), but during the transition to toddlerhood, this current study found that prefrontal and parietal regions of the left hemisphere are recruited alongside these right-lateralised regions to support the development of response inhibition. Further, this study demonstrates that the recruitment of right prefrontal regions expanded from 10- to 16-months to now include the right IFG, a key neural substrate of mature response inhibition (Aron et al., 2004; 2014). Future research (Chapter 6) will examine the developmental trajectory of response inhibition and the associated neural substrates in early childhood to better understand whether the same neural mechanisms support the improvement of response inhibition in this fundamental developmental period.

6.5. The Toddlerhood Transition: Brain Development and Response Inhibition Performance

Evidence from this research (presented in the current chapter and Chapter 4 of this thesis) suggests that whilst the functional neural correlates of response inhibition become more widespread from 10- to 16-months (with the additional recruitment of the left hemisphere and of the right IFG), these neural advances are not paralleled by behavioural response inhibition performance. This result is interesting, as it suggests that whilst there is no change in behavioural response inhibition across the toddlerhood transition, this is an important period of developmental change at the neural level. It could be that the functional and structural

maturation of the PFC (and regions of the parietal cortex) needs to be in place *first*, to act as a scaffold to support the improvement in cognitive performance. Potential evidence for this delay is reflected in EEG work by Bell & Fox (1992) who found that infants who tolerated greater delays (better inhibitory control) at 12-months of age showed a greater increase in EEG power in bilateral frontal electrodes from 9 – 10 months than those with poorer inhibitory control. Whereas those infants with poorer inhibitory control at 12-months of age did not show an increase in frontal power until 10 – 11 months of age, and only in the right hemisphere. Therefore, it may be that it is not until the necessary functional maturation of the frontal cortex has occurred, that improvements in behavioural performance become evident.

Indeed, a body of research exists that suggests that the structural and functional maturation of the PFC from infancy and throughout childhood appears to parallel advances in EFs observed across this developmental period (Diamond, 2002; Fiske & Holmboe, 2019a). Neuroscientific research into early childhood structural brain development has evidenced that the early years of life are a fundamental time for cortical maturation (Croteau-Chonka et al., 2016; Remer et al., 2017). Studies in the first year of life have identified that, from 7 – 10 months, significant structural and metabolically demanding maturation processes occur in the PFC with the end goal of increased synaptic plasticity and dendritic growth (Herschkowitz, 2000; Koenderink et al., 1994). During the period from 9 – 12 months of age, the functional frontoparietal network undergoes a period of particularly fast development (Gao et al., 2015). It is interesting to note that during the last half of the first year, these structural changes in the PFC appear to coincide with a period of rapid improvement in cognitive tasks such as the A-not-B task (Diamond, 1985; Diamond & Doar, 1989; Diamond & Goldman-Rakic, 1985; Fiske & Holmboe, 2019). Across the transition into the second year of life, synaptic density and intra-hemisphere connectivity within the PFC increases (Herschkowitz, 2000). By the end of the second year of life, the basic structural and functional maturation of the brain is mostly complete, although the reorganisation of existing networks continues into adolescence (Diamond, 2002; Gilmore et al., 2018).

Since no previous research has investigated the combined neural and behavioural changes in response inhibition across this important developmental transition into toddlerhood, the novel findings from the current study, uniquely using fNIRS, provide preliminary evidence for what could be a period of reorganisation within the PFC that lays the foundations for improvements in inhibitory control abilities. Future research that focuses on this key transitional period into toddlerhood is warranted. This would enable us to better understand the neural changes and mechanisms that occur early in the second year of life that may support improvements in cognitive development later in toddlerhood.

6.6. Variability of the Haemodynamic Response in Infants and Toddlers

The results of this pair of studies (Chapters 4 and 5) demonstrated considerable differences in the shape of the HRF observed at 10- and 16-months of age. The haemodynamic response arises due to a process called neurovascular coupling; whereby local neural activity can influence the vascular system that controls blood flow. Since the neurovascular system undergoes significant development in infancy and early childhood, it is likely that neurovascular coupling does not function in the same way as in adult brains (Kozberg & Hillman, 2016; Siddiqui et al., 2017). Although the shape and time course of the haemodynamic response in infancy is less well understood (de Roever et al., 2018), it is widely reported that there is significant variability in the infant haemodynamic response, and there is evidence to suggest that this variability can be influenced by the age of the infant, as well as experimental factors (Issard & Gervain, 2018). Similarly, it is not uncommon for infant fNIRS studies to observe non-canonical response functions in that both HbO_2 and HHb concentrations change in the same direction, or an inverted haemodynamic response function whereby the HbO_2 concentration decreases and the HHb concentration increases (Issard & Gervain, 2018), as was found in some channels in the 16-month study.

An interesting feature of the HRF at 16-months was that, in some channels, significant block type effects were found in the HHb signal already during the first time bin (0 – 5 seconds). One explanation for this early effect is that it is a result of anticipatory neural activation. Although the baseline used in this research was jittered (12 – 17 s) to minimise any anticipatory effects, there was a small delay (~400 ms) between the offset of the baseline and the onset of the task block. As such, it could be that the blank screen (as well as the experimenter moving the iPad towards the participant during this time) acts as a cue for the participant that the task block is about to start, and so the early activation observed may be in anticipation or preparation of a response, or in response to the transition from baseline (passive) to block (active). It is likely that 16-month-olds are more aware of these cues than 10-month-old infants (where this effect is not present), who were often more distracted by the end of the baseline blocks and less prepared for the task onset.

Since very little is understood about the development of the HRF and the physiological neurovascular coupling mechanisms in infancy and toddlerhood, more fNIRS research is needed in this field before we can fully understand the variable responses to the same task design observed in this study. The results of this study contribute to the sparse literature, highlighting that even from 10- to 16-months of age there is considerable change and progression in the temporal dynamics and shape of the HRF (during the same task, and even across channels), which will be of great interest to the infant and toddler fNIRS community and warrants further investigation in the future.

6.7. Limitations and Future Directions

A major limitation of the current study is the significant level of participant attrition that occurred due to lab closures as a result of the COVID-19 pandemic. As such, many participants who had been recruited as part of the study (and participated in sessions at 10-months) were unable to return for test sessions at 16-months. This resulted in the sample size at 16-months being much smaller than originally intended, and as a consequence, the statistical power of this study to identify small or medium effects was limited. Additionally, there was a substantial amount of data attrition (~50%) in the fNIRS data, which further limited the sample size and statistical power. This was particularly true for the individual differences analyses, which were unable to robustly assess brain-behaviour associations because of insufficient statistical power. Typically, individual difference analyses need large samples of over 100 participants (Dubois & Adolphs, 2016) to reliably investigate individual differences in brain-behaviour associations (de Haas, 2018). As such, it was not possible to detect brain-behaviour associations in the current sample (N = 43), particularly as these associations (if present) are likely to be of a small effect size. It must be acknowledged that many of the significant effects reported in this current study did not survive the procedure for controlling the FDR (Benjamini & Hochberg, 1995). As well as the limited sample size and statistical power, the large number of comparisons in this study (mostly linked to the fNIRS analyses and relating to the number of channels in the fNIRS probe) meant that the results did not remain significant. As such, the results of this study must be considered preliminary and interpreted with caution until they have been replicated in larger samples. Future research is already in process that aims to replicate the results of the current study with 16-month-old toddlers (and our previous work with 10-month-old infants; Fiske et al., 2022) in a larger longitudinal sample of ~200 participants.

To address the attrition of fNIRS data in future research, attempts should be made to reduce session-specific attrition (e.g., poor fNIRS cap placement). Indeed, according to a recent meta-analysis (Baek et al., 2023), variables such as participant age, study design, hardware design, and signal quality can impact the average attrition rate in infant and toddler fNIRS studies. One of the largest problems in the current study was data loss due to poor cap placement, which is a factor that can be improved with practice and training. The second reason was due to the strict inclusion criteria and data quality criteria that were imposed on the fNIRS dataset. This was done for the reason of improving the signal-to-noise ratio (which is already poor due to the nature of infant and toddler brain responses and motion artefacts) but could be re-evaluated in future such that a better balance is achieved between signal quality and data attrition. Although not uncommon in infant and toddler neuroimaging research, it should be acknowledged that the level of fNIRS attrition in the current study may

have biased our sample in some unknown way. Since our behavioural results revealed that toddlers who did not have valid fNIRS data performed very similarly to toddlers who did have valid NIRS data, it could be suggested that our fNIRS sample was not too biased. However, caution is still warranted.

A further limitation of this work is the use of a 12-month head model (Shi et al., 2011) to localise channel positions at 16-months. Whilst an alternative approach would have been to use a more closely age-matched head model to ensure a potentially more accurate localisation process, we decided that it would be more advantageous to use the 12-month model that we had used previously to retain consistency when comparing the fNIRS data from both the 10- and 16-month assessment points. Ideally, future research would use subject-specific structural MRI data from the cohort of participants in this study to develop the head model, although this is not always appropriate or feasible with infant and toddler research. Further, the use of precise optode position recording devices such as the Polhemus digitizer, photogrammetry and video-based methods (e.g., Erel et al., 2021; Xia et al., 2023) are becoming increasingly feasible for use with infant and toddler participants and produce more accurate optode registrations.

This study aimed to identify the functional neural correlates of response inhibition in infancy using fNIRS and to chart their potential changes over the transition from the first to the second year of life. To do so, activation (changes in haemoglobin concentration) in channels across the PFC and parietal cortex was compared between control blocks (no inhibition required), and blocks where inhibition was required (experimental blocks). However, the current study (and the study presented in Chapter 4) did not examine functional connectivity between regions measured by the fNIRS probe as it was beyond the scope of the methodological aims. Indeed, research points to the importance of functional connections between frontal and parietal regions in supporting the development of executive functions in toddlers (Kerr-German et al., 2022) and young children (Buss et al., 2014; Buss & Spencer, 2014; Mehnert et al., 2013a). Future research is planned to investigate functional connectivity in the 10- and 16-month datasets. It is also likely that regions of the cortex (i.e., motor regions) that were not measured with the fNIRS probe used in the current study may have played a role in task performance. However, since the fNIRS probe used in this current study did not contain channels that covered the whole head, it is not possible to assess the role of other regions that may have been involved during the task. Future research should investigate the involvement of functional cortical connections in the infant brain to develop a clearer understanding of how the development and strengthening of functional connections may support response inhibition performance in this population.

6.8. Strengths and Implications

In using the same methodological paradigm (same task, same fNIRS probe) with the same sample of participants at both 10- and 16-months of age, the results of the current study add valuable knowledge to our limited existing understanding of developmental change in inhibitory control over this key transitional period. Through this relatively large longitudinal infant and toddler dataset, it has been possible not just to examine the differences between infants' performance and associated neural activation from 10- to 16-months, but to consider both behavioural and neural *changes*, across the transition to toddlerhood. The longitudinal findings of the current study demonstrate that although there is no behavioural development from 10- to 16-months of age, there appears to be more widespread recruitment of brain regions within the PFC and parietal cortex when inhibition is required at 16-months (i.e., more bilateral recruitment, and involvement of broader areas of the right frontal cortex). These results are exciting because they shed new light on the functional maturation of the PFC across the transition from infancy to toddlerhood, in the context of response inhibition performance, and will be of great interest to the field of developmental cognitive neuroscience.

From a behavioural perspective, this study is also unique in that it uses the same task (that requires a manual response) at both assessment points in infancy. Usually, within the literature, researchers have used different tasks (to ensure age-appropriateness) at each assessment point to assess the same construct. This can lead to difficulties in interpreting results since it is unclear whether changes in performance are due to an age-related improvement in the construct, or instead due to task-specific differences. Although no age-related performance improvements were observed in the current study, we can be confident that this lack of an effect is not due to different task demands. The task showed excellent test-retest reliability, suggesting that the ECITT is a robust measure of individual differences in response inhibition in 16-month-old toddlers. Additionally, as this task requires a motor response to a touchscreen, it more closely mimics the response style required in 'gold-standard' response inhibition tasks commonly used with older children and adults. In demonstrating that the ECITT can be used reliably alongside fNIRS at 10- and 16-months of age, it is now possible for researchers to begin to utilise this task across the lifespan to plot the developmental trajectories of behavioural response inhibition and the associated functional neural correlates.

From a neuroimaging perspective, the field of infant and toddler fNIRS research is still relatively young and there is much still to be understood. However, this study has lowered the age boundary for which it is possible to use fNIRS to functionally localise neural activation during a response inhibition task, even in toddlers who are 16-months of age and

squarely belong to the age group that is so challenging to assess at the transition from infancy to early childhood (hence the toddler 'data desert'; Kerr-German et al., 2023). Equally, by demonstrating that a response-based task can be accessed by infants and toddlers alike, in this understudied age and parallel to the fNIRS measurement, this study will hopefully enable the field to move forward by encouraging more research that makes use of active tasks with this early developmental population.

7. Conclusion

The work presented in this chapter has contributed new knowledge about the neural correlates of response inhibition at 10- and 16-months of age, where previously very little was understood. In doing so, this research has started to fill the gap in the literature regarding the development of response inhibition in infancy and across the transition into toddlerhood. Additionally, with this valuable longitudinal data that utilised the same experimental paradigm, with the same cohort of participants at two age points in infancy, it has been possible to examine the longitudinal development of response inhibition and the underlying functional neural correlates for the first time.

8. Interim Summary: The Neural Correlates of Response Inhibition in the Transition to Toddlerhood

Chapters 4 and 5 of this thesis presented the results from two studies that aimed to examine the functional neural substrates of response inhibition using fNIRS in the first (10-months) and second (16-months) years of life. Until now, no previous studies have used fNIRS alongside a response inhibition task that requires a motor response in children under two years of age. Behavioural results indicate that infants are significantly more accurate (10- and 16-months) and respond significantly faster (16-months) on trials with no inhibitory demand than on trials where response inhibition is needed. The fNIRS results suggested that regions of the DLPFC, OFC and parietal cortex (right-lateralised at 10-months, with additional left hemisphere and right IFG activation at 16-months) are more active when inhibition is required. Results from longitudinal analyses suggest that whilst there is no change in response inhibition performance from 10- to 16-months, more widespread, bilateral regions of the PFC and parietal cortices are recruited at 16-months when response inhibition is required. Thus, highlighting that the transition from infancy to toddlerhood may reflect an important developmental period for the reorganisation or specialisation of the PFC. As such, the results of these studies provide new knowledge about the emergence of inhibitory control in infancy – both behaviourally, and functionally in the cortex of the brain.

Chapter 6

Behavioural and Neural Indices of Inhibitory Control Development from Infancy to Early Childhood

This chapter marks the final study in a trio of studies that have used fNIRS to longitudinally investigate the functional neural correlates of response inhibition across the first years of life. The study presented in Chapter 4 of this thesis identified that regions within the right prefrontal and parietal cortices were more active when infants in the first year of life (10-months of age) were required to exert response inhibition – specifically, the right DLPFC, right OFC, and right parietal cortex. Moving into the second year of life (16-month-olds), the study described in Chapter 5 demonstrated that whilst behavioural response inhibition performance did not significantly improve from 10- to 16-months of age, infants recruited more widespread regions of the prefrontal and parietal cortices (bilateral, and now also including the right inferior frontal cortex) when response inhibition was required. This could suggest that the transition from late infancy into toddlerhood represents a fundamental period of reorganisation in the PFC that then functions as a scaffold to support the improvement of behavioural response inhibition into early childhood. The data presented in the current chapter were collected from the same sample of participants as in Chapters 4 and 5, now at 3½ years of age, and follow the same methodological approach as used previously (with some minor exceptions). Overall, the study described in the current chapter aimed to identify the brain regions that support response inhibition in early childhood, and to longitudinally examine developmental change in both behavioural and neural indices of response inhibition across the first four years of life.

This study was pre-registered on the Open Science Framework before analysis. The reader will be directed to the pre-registration for more details where necessary throughout the chapter. The co-authors of this pre-registration have permitted the content to be used in this thesis chapter (an author contribution statement is included in Appendix D1). At present, the pre-registration is embargoed so that unpublished results from previous studies are not made publicly available. For this thesis, the pre-registration and associated documents can be found here and should be treated as confidential.

1. Background

The fourth year of life brings many significant developmental changes that support the transition into early childhood. A child in their fourth year now has a more sophisticated grasp of language, their motor skills are becoming more coordinated, and their emotional regulation and social skills are quickly advancing. The development of these skills often coincides with an important life transition as many children begin to regularly attend preschool settings. Overall, there is a much greater need for the employment of control (be it inhibitory control, socio-emotional control, or behavioural control) at the start of the early childhood period, yet little is understood about the maturational processes in the brain that may support this increased demand for control.

Recently, neuroimaging studies have begun to examine the neural underpinnings of the executive processes central to the development of inhibitory control in early childhood. An important question of interest is whether prefrontal and parietal activation during inhibitory control tasks will be right-lateralised (as is often found in adult studies of inhibitory control; e.g., Aron et al. 2014), or whether activation will be found in both hemispheres, as is more typical in studies with early developmental populations. For example, an MRI study found that regions of the mature cognitive control network (including bilateral PFC and inferior parietal regions) were associated with inhibitory control performance in 3 – 4-year-old children (Berger et al., 2022), and a recent fNIRS study demonstrated that resting state activation over the bilateral PFC in 4- and 5-year old children was positively associated with performance on both an executive function (EF) task and parent-reported measures of EF (Eng et al., 2022). Similarly, McKay et al. (2022) found that 4½-year-olds activated the right middle frontal gyrus, right IFG, and bilateral supramarginal gyrus during a Go / No-Go task. Another study using the Go / No-Go task with 4 – 10-year-olds found that channels overlying the right DLPFC and right IFG showed differential activation between trial types (Zhou et al., 2022). Finally, a study that used the Stroop task to assess cognitive flexibility (but required inhibition of a prepotent response) in 4-year-olds found an increase in activation in the bilateral DLPFC when inhibition was required (Li et al., 2017).

The overarching aim of the current study is to examine the developmental trajectory of response inhibition and the associated neural correlates across the first four years of life. Based on the results described in the previous paragraph, and the results of my previous work, it is predicted that activation in bilateral regions of the PFC and parietal cortex would be found during the ECITT with 3½-year-old children. The current study is the final longitudinal follow-up of the same cohort of participants who have completed the ECITT alongside fNIRS in infancy (10-months) and toddlerhood (16-months). No previous study has used the same task to assess response inhibition alongside fNIRS across infancy,

toddlerhood, and early childhood in the same cohort of participants. As such, this study will contribute new knowledge about the change in the recruitment of regions of the PFC and parietal cortex and examine the development of response inhibition across the early years of life.

2. Method

2.1. Participants and Exclusions

Full demographic information for the sample of 3½-year-old participants is available in Chapter 2 of this thesis. Note that this sample includes data from 22 pilot participants at 3½ years (administration procedure identical to that used in the longitudinal sample). Following sample-level exclusions, 125 children contributed behavioural ECITT data (Session 1), and 121 children contributed blocked ECITT (Session 2) data to this study. Following exclusions (**Table 1**), the final sample of behavioural ECITT data consisted of 119 participants, and the blocked ECITT sample consisted of 100 participants. A total of 96 participants had valid ECITT data from both sessions. fNIRS data from the 100 participants who contributed valid blocked ECITT data were assessed against inclusion criteria to determine the validity of the fNIRS data collected whilst the ECITT was completed (**Table 1**). The final sample of participants with valid fNIRS data was 61. Of the 61 participants with valid fNIRS and blocked ECITT data, 60 also contributed valid behavioural ECITT data.

Table 2 provides an overview of the number of participants with valid longitudinal data across the three assessment points. Note that there was significant attrition at the 16-month assessment point due to lab closures during the COVID-19 pandemic.

Table 1. Chapter 6. 3½ year Data Exclusions.

Session 1 (behavioural ECITT)	***N***
Experimenter administration error	3
Did not complete the full task	2
Software failure: data did not save	1
Total Excluded	**6**
Percentage Excluded	**4.8%**
Total Included	**119**
Session 2 (blocked ECITT)	***N***
Less than 2 blocks of each condition completed	2
Completed an earlier version of the task	19
Total Excluded	21
Percentage Excluded	**17.36%**
Total Included	**100**
fNIRS Data	***N***
Data file was lost	1
Refused to wear fNIRS cap	10
The fNIRS cap was removed before the minimum number of blocks had been completed	2
fNIRS cap placement was invalid	5
No longer had the minimum number of blocks following exclusion of invalid or extra-long blocks	8
Poor signal quality in > 30 channels	13
Total Excluded	39
Percentage Excluded	**39.0%**
Total Included	**61**

Table 2. Chapter 6. Sample Sizes for Longitudinal Data.

Data	**Assessment Points**	**N**
Behavioural ECITT (Session 1)	All	39
	10-months and 3½ years	84
	16-months and 3½ years	45
Blocked ECITT (Session 2)	All	38
	10-months and 3½ years	78
	16-months and 3½ years	44
fNIRS	All	9
	10-months and 3½ years	25
	16-months and 3½ years	16

2.2. Apparatus and Stimuli

The same fNIRS apparatus (Gowerlabs NTS fNIRS system) and stimuli (ECITT; Holmboe et al., 2021) as was used in the 10-month study (Chapter 4) and the 16-month study (Chapter 5) were used in the current study. Please see the equivalent section of Chapter 4.

Some minor modifications were made to both versions of the ECITT (behavioural version and blocked version) to ensure age-appropriateness for the 3½-year-old participants in the current study. Note that these changes were only deemed necessary at this assessment point, and not at the 16-month assessment point, because previous research had shown that

the original version of the ECITT was developmentally suitable and provided a reliable and valid measure of inhibitory control still at 16-months and even up to 30-months of age (Hendry et al., 2021; Holmboe et al., 2021). However, since no previous research had used the ECITT at 42-months, I piloted the original version of the task and it was clear that the task was too easy for this age group, as participants became disengaged due to the slow pace of trials. As such, some minor modifications were made (described below) to ensure the same task could be used to measure response inhibition also at 42-months.

In the behavioural ECITT administered in Session 1, infant and toddler participants (10- and 16-months) completed 32 trials, whereas 3½-year-old participants completed 64 trials (two consecutive blocks of 32 trials). For the blocked ECITT administered in Session 2, the number of trials per block increased from six (as at 10- and 16-months) to eight trials. That is, control blocks now consisted of eight prepotent trials and experimental blocks consisted of four prepotent and four inhibitory trials. In both versions of the task, the allocation of prepotent trials (75%) and inhibitory trials (25%) remained the same, as did the constraints on trial order described in Chapter 4. Additionally, the duration of the animations after each trial was decreased from ~ 4 s to ~ 1 s to create a faster pace (and thereby higher difficulty level) and keep the interest of the older children.

The number of blocks completed by participants with valid fNIRS data ranged from 3 – 6 of each block type (Control: *M* = 4.34, Experimental: *M* = 4.31), with a mean duration of 18.5 s (*SD* = 2.8 s) for control blocks and 19.3 s (*SD* = 2.5 s) for experimental blocks. Overall, participants with valid fNIRS data completed between 6 – 12 blocks of trials (*M* = 8.66), which is equivalent to 48 – 96 individual trials. Note that whilst in infancy (10- and 16-months) there was no stopping point on the task, for the 3½-year-old participants the task was stopped by the experimenter once the participant had completed at least four blocks of each type (eight blocks total). Although in some cases (i.e., if children were distracted during a block) the experimenter would continue administering the task (to a maximum of six blocks of each type). This decision was made to ensure that sufficient valid data was collected, but that the participant was not too fatigued to complete the several other remaining tasks during the session.

2.3. Procedure

The administration procedure was largely identical to that described for both the 10- and 16-month assessment points (Chapters 4 and 5), although some modifications were made for the 3½-year-old participants. Please see the equivalent section of Chapter 4 of this thesis for a description of the study procedure. Changes made to the administration procedure for the

3½-year-old participants are as follows. Whilst the cap was being fitted, children watched a child-friendly cartoon on a laptop to keep them entertained during the setup process and to ensure their head was straight and as still as possible during fitting. Before the task and fNIRS recording were started, the cartoon was paused, and the laptop was moved out of sight and reach of the child. Once the task was complete and the fNIRS recording had stopped, the cartoon was resumed. This allowed time for the experimenter to collect optode localisation geometric data using the Polhemus digitizer (~ 3 minutes). This information was collected to support the accurate localisation of the optodes on the participant's specific head measurements during the head modelling process. Unfortunately, due to technical problems with the setup of the device, it was not possible to use the Polhemus data for optode localisation as was intended.

3. Data Processing

The data processing procedures were near-identical as those described for the 10- and 16-month assessment points, although deviations are noted below. Please see the equivalent section of Chapter 4 for full details about data processing and preparation.

3.1. Behavioural Data Processing

In the previous studies (Chapters 4 and 5), behavioural data from the ECITT were coded offline from videos taken during the session. Coding happened at the trial level to manually assess the accuracy and validity of each trial (and reaction time correction at 16-months), which was deemed necessary due to the 'messy' nature of motor responses in infancy. At 3½ years, intentional motor responses to the task were clearer and generally less noisy. However, to ensure that the accuracy and reaction time data recorded by the ECITT app were consistent with the manual coding of 3½ year data, a sample of 21 videos was manually coded using the same coding scheme as for the previous datasets. Excellent inter-coder reliability (between a human coder and the data recorded by the app) was obtained for accuracy (Cohen's kappa = .960) and reaction time correction (correct, valid trials only; Cohen's kappa = .996). Note that it was only necessary to correct the reaction time on eight trials (out of 1314 trials) and this was for eight different participants. As such, it was decided that the automated iPad-recorded accuracy and reaction time values were as reliable as the manual coding of motor responses at 3½ years. The validity of the trials at 3½ years was also assessed by the coder during manual video coding. However, only one reason for invalidity was identified across all 21 videos, which was that the first trial was cued by the experimenter (as part of the protocol). Since this is consistent across participants, and the

first trial is always excluded from analyses, it was decided that it was not necessary to manually code the validity of the trials in the ECITT.

3.2. fNIRS Data Processing

Trial blocks were invalid (and excluded) if the duration was longer than the mean duration + 2 SD for each block type (Control = 26.5 s, Experimental = 31.5 s). Participants with more than 2/3 of channels excluded following the pruning of poor-quality channels were not included in further analysis (*N* = 13 excluded, 61 valid data files remaining). Channels were excluded if less than 50% of participants with valid fNIRS data contributed good-quality data. Note that the change from the 70% criteria used in previous chapters reflects the larger sample size, better overall quality of the fNIRS data, and a larger number of valid trials (particularly inhibitory trials) collected at 3½ years compared to 10- or 16-months. Oxygenated haemoglobin (HbO_2) and deoxygenated haemoglobin (HHb) concentration change data from each channel were block averaged over 22 seconds (containing two seconds of data from valid baseline blocks and 20 seconds of data from valid task blocks). Baseline concentration change data (two seconds) were subtracted from the average haemoglobin concentrations in the 20-second experimental window and the baseline-corrected data were divided into five four-second time bins.

4. Study Hypotheses and Analysis Approach

The hypotheses, variables, and analysis plans were defined and pre-registered before analysis and are described in brief here. Since this study is largely a methodological replication of the research presented in Chapters 4 and 5, knowledge about the results from these studies was used to form pre-registered hypotheses about the current dataset. Similarly, since data from the behavioural ECITT (Session 1) at 3½ years was analysed for Chapter 7 of this thesis, it was possible to use this to form pre-registered hypotheses about the blocked ECITT performance at 3½ years. For full details, including justifications for the hypotheses, please see here.

Data collected from the behavioural ECITT (Session 1) at 10- and 16-months have already been analysed and are reported in Chapters 4 and 5 of the current thesis. Behavioural ECITT data (Session 1) at 3½ years will be reported in Chapter 7 of this thesis (results from Session 1 data were known before the pre-registration relating to the current chapter was written). Therefore, the behavioural ECITT (Session 1) data will only be included in the current chapter in relation to the examination of between-session consistency and test re-test reliability where data from both versions of the ECITT are used. As such, when

behavioural data are mentioned in the current chapter, this refers to the blocked ECITT during the fNIRS session (Session 2), unless otherwise explicitly stated.

4.1. Pre-registered Behavioural Hypotheses and Analysis Plans

4.1.1. ECITT Condition Effects

H1 and H2: To test the hypotheses (based on previous findings e.g., Hendry et al., 2021; Holmboe et al., 2021, and Chapters 4 and 5 of this thesis) that participants are significantly more accurate on prepotent than inhibitory trials (H1), and that participants respond significantly faster on correct prepotent than correct inhibitory trials (H2), two paired samples *t*-tests will be conducted with the mean accuracy variables (inhibitory, prepotent) (H1), and the median reaction time variables (inhibitory, prepotent) (H2).

4.1.2. Group Performance Differences

H3: Participants will be divided into two groups depending on whether they contributed both valid ECITT data and valid fNIRS data (N = 61) or whether they only contributed valid ECITT data (N = 39). Two 2 × 2 mixed ANOVAs will be conducted to examine whether there are any performance differences between groups. The first ANOVA will have mean accuracy as the dependent variable, trial type as the within-subjects factor (inhibitory, prepotent) and sub-sample (fNIRS data, no fNIRS data) as the between-subjects factor. The second will have median reaction time on correct trials as the dependent variable, trial type (inhibitory, prepotent) as the within-subjects factor and sub-sample as the between-subjects factor.

Based on the results of Chapters 4 and 5, it was predicted that there would be no significant difference in accuracy (H3a) between groups, but that participants who contributed both valid ECITT and fNIRS data would have significantly faster median reaction time on both correct prepotent and inhibitory trials than participants who only contributed valid ECITT data (H3b).

4.1.3. Between-Session Consistency and Test Re-Test Reliability

Since participants completed two versions of the ECITT as part of this study, analyses will be conducted to investigate the group-level stability and the test re-test reliability of performance across the two sessions. Hypotheses are based on the results of previous findings reported in Chapters 4 and 5 of this thesis.

H4: It was predicted that participants would be significantly more accurate on inhibitory trials, and respond significantly faster on both trial types, on the blocked ECITT in Session 2 than on the behavioural ECITT in Session 1. There are no specific predictions about interaction effects. It was also predicted that the accuracy inhibitory score on the blocked ECITT (Session 2) would be significantly greater than the accuracy inhibitory score from the behavioural ECITT (Session 1). To investigate the group-level stability of accuracy and reaction time across sessions, two separate 2 × 2 repeated measures ANOVAs will be conducted. The ANOVAs will have trial type (prepotent, inhibitory) and session (behavioural ECITT in Session 1, blocked ECITT in Session 2) as within-subjects factors. A paired *t*-test will also be conducted with the accuracy inhibitory score as the dependent variable to investigate the group-level stability in inhibitory performance across the sessions.

H5: To establish test re-test reliability, five confirmatory correlational analyses will be conducted on data from the behavioural ECITT (Session 1) and the blocked ECITT (Session 2). Correlations will be conducted separately for the following variables: accuracy inhibitory score, mean prepotent accuracy, mean inhibitory accuracy, median prepotent reaction time, and median inhibitory reaction time. It was predicted that there would be a significant correlation of at least a medium effect size ($r \geq .3$) in performance between sessions for all variables.

4.1.4. Behavioural Development from Infancy to Early Childhood (ECITT)

H6a: To investigate whether accuracy improves from 10-months to 3½ years, a 2 × 2 linear mixed model will be conducted with trial type (prepotent, inhibitory) and age (10-months and 3½ years) as within-subjects factors. This hypothesis is based on similar work by Holmboe et al. (2021). A paired *t*-test will be conducted to investigate whether the accuracy inhibitory score is significantly different between 10-months and 3½ years. Again, based on previous work by Holmboe et al. (2021), it was predicted that participants would be significantly more accurate on both trial types and would have significantly better response inhibition performance at 3½ years than at 10-months. It was also predicted that there would be a significant main effect of trial type (greater accuracy on prepotent compared to inhibitory trials), a significant main effect of age (greater accuracy at 3½ years than at 10-months), and a significant interaction (larger improvement in inhibitory accuracy than in prepotent accuracy between 10 months and 3½ years). Note that these predictions were made despite the preschool version of the ECITT being faster paced (i.e., harder) than the infant version.

H6b: To investigate whether accuracy and reaction time improve from 16-months to 3½ years, two separate 2 × 2 linear mixed models will be conducted. One model will have mean accuracy data as the dependent variable, and the other will have median reaction time (on correct trials) data as the dependent variable. Both models will have trial type (prepotent, inhibitory) and age (16-months and 3½ years) as within-subjects factors. A paired *t*-test will also be conducted to investigate whether the accuracy inhibitory score is significantly different between 16-months and 3½ years. As before, the following predictions are based on similar work by Holmboe et al., 2021).

Accuracy: It was predicted that participants would be significantly more accurate on both trial types and would have significantly better response inhibition performance at 3½ years than at 16-months. It was also predicted that there would be a significant main effect of trial type (greater accuracy on prepotent compared to inhibitory trials), a significant main effect of age (greater accuracy at 3½ years than at 16-months), and a significant interaction (larger improvement in inhibitory accuracy than in prepotent accuracy between 16-months and 3½ years). These predictions were made despite the preschool version of the ECITT being faster paced (i.e., harder) than the infant version.

Reaction time: It was predicted that there would be no significant difference in median reaction times on both trial types (correct prepotent, correct inhibitory) between 16-months and 3½ years. It was also predicted that there would be a significant main effect of trial type (faster responses on correct prepotent compared to on correct inhibitory trials). Finally, it was predicted that there would be no significant main effect of age, and no significant interaction.

H7: Two separate correlational analyses will be conducted to examine whether there is a significant association between performance (accuracy inhibitory score) on the blocked ECITT at 10-months and 3½ years (H7a), or at 16-months and 3½ years (H7b). It was predicted that performance would not be significantly correlated at 10-months and 3½ years, or 16-months and 3½ years. Two further correlational analyses will be conducted to examine whether there is a significant association between reaction time (median prepotent, median inhibitory) at 16-months and 3½ years. It was predicted that there would be no significant correlation between the median inhibitory reaction time on the blocked ECITT at 16-months and 3½ years, but it was predicted that there would be a significant correlation between median prepotent reaction time at 16-months and 3½ years.

4.2. Pre-registered fNIRS Hypotheses and Analysis Plans

Following pre-processing and block averaging of the fNIRS data, average haemoglobin concentration data were available for each: individual (N = 61), chromophore (HbO_2, HHb), channel (N = 46), condition (control, experimental, difference (control – experimental), and time bin (N = 5).

4.2.1. Identifying Channels Showing Significant Block Type Effects

H8a (Confirmatory): Based on findings from the 16-month dataset (Chapter 5), it was predicted that the haemodynamic response in nine channels overlying regions of the PFC and parietal cortex will be differentiated by block type (i.e., 'experimental' blocks requiring inhibition vs. 'control' blocks with no inhibitory requirement). These channels were: Channel 6 (left superior parietal), Channel 8 (right inferior parietal), Channels 20 and 23 (right inferior frontal gyrus (IFG)), Channel 26 (right DLPFC), Channel 28 (left DLPFC), Channel 29 (left OFC), Channel 31 (right IFG, orbital), and Channel 33 (right OFC). To investigate whether these nine channels are showing significant block type effects or a time × block type interaction, data will be divided into five 4-second time bins (0 – 20 seconds of the block time course). Repeated measures ANOVAs will be conducted for each channel and each chromophore (HbO_2 and HHb) with time bin (5 levels) and block type (2 levels) as within-subjects factors. Channels showing a significant main effect of block type, or a significant time × block type interaction in either chromophore will be considered as showing a significant block type effect (i.e., haemoglobin concentration is differentiated by block type).

H8b (Exploratory): Once H8a has been tested, exploratory repeated measures ANOVAs (as described above) will be conducted on the remaining channels in the probe to investigate whether any other channels are showing significant block type effects.

H8a and H8b: As in previous work (Chapters 4 and 5), if channels show significant block type effects, two-tailed paired *t*-tests will be conducted to investigate the time course of the significant effect.

4.2.2. Individual Differences (Brain-Behaviour): Exploratory Analysis

H9: Once channels displaying significant block type effects have been identified (H8), two-tailed correlational analyses will be conducted to investigate whether individual differences in neural activation in these channels (across the time bins showing significant effects) are associated with individual differences in the accuracy inhibitory score. Since findings from the 10-month dataset relating to potential associations between individual performance

differences and inhibition-specific brain activation were weak and did not survive correction for multiple comparisons (Chapter 4), and there were no significant associations in the 16-month dataset (Chapter 5), no specific predictions were made about whether there would be significant brain-behaviour associations at 3½ years.

4.2.3. Neural Development from Infancy to Early Childhood: Exploratory Analysis

H10: Once H8 has been tested, exploratory linear mixed model analyses will be conducted with the haemoglobin difference measure as the dependent variable to investigate the change in activation from the 10-month assessment point to the 3½ year assessment point (RQ10a), and from the 16-month assessment point to the 3½ year assessment point (RQ10b). These analyses will be conducted on channels showing significant block type effects at the 10-month and/or 16-month assessment points, as well as any new channels identified at 3½ years. Two separate linear mixed models (restricted maximum likelihood estimation) will be conducted on the channels showing a significant block type effect (dependent variable) at one of the assessment points in each model. Assessment point (Model 1: 10-months, 3½ years, Model 2: 16-months, 3½ years) will be entered into the model as a fixed factor and participants as a random factor. These analyses will be conducted to investigate the change in activation in each channel across assessment points.

4.2.4. A Note on Optode Registration

Before submitting the pre-registration, the anatomical labels of brain regions covered by channels in the probe at 3½ years were generated by Dr Liam Collins-Jones to support the predictions of channels and brain regions. Please see Appendix D2 for the anatomical labels of all channels in the probe. Again, the 12-month-old atlas was used (Shi et al., 2011) as in the previous studies presented in Chapters 4 and 5. Whilst we recognise that there is a substantial change in head size from 12-months to 3½ years, we feel that the consistency gained from keeping the atlas the same throughout the three studies is still advantageous and will make developmental comparisons more straightforward. This approach means that the channel localisation remains relatively consistent across studies, making it easier to investigate changes in activation over time in this longitudinal dataset. Further, we have struggled to find an atlas that has suitable parcellation for 3½-year-olds, and we deem that it would not be ideal to use an adult atlas with this young population, as a preliminary assessment based on our probe and an adult atlas (AAL2; Rolls et al., 2015) indicated that a large proportion of channels would be located in different cortical areas. Upon careful

inspection of these adult-based locations and images of our probe placement, we felt that they did not represent the channel locations accurately.

4.3. Statistical Analysis

All statistical analyses were conducted in SPSS version 29. All variables were tested against the parametric test assumptions, and when violated, appropriate non-parametric equivalents were used. Greenhouse-Geisser corrected degrees of freedom and significance values were used because the channel-level fNIRS data did not meet the sphericity assumption required for repeated measures ANOVA. The procedure for controlling the FDR (Benjamini & Hochberg, 1995) was used where multiple tests were conducted. CIs (95%) were calculated on 1000 bootstrap samples. Please see Appendix D3 for details of how the data were tested against the parametric test assumptions and the results of any equivalent non-parametric tests that were conducted.

5. Results

5.1. Behavioural Results

Descriptive statistics for the behavioural variables (blocked ECITT) are presented in **Table 3**.

Table 3. Chapter 6. Descriptive Statistics for the ECITT.

Variable	N	Mean (SD)
Mean inhibitory accuracy	100	.810 (.199)
Mean prepotent accuracy	100	.991 (.039)
Accuracy inhibitory score	100	.817 (.194)
Median inhibitory reaction time (ms)	100	1389 (328)
Median prepotent reaction time (ms)	100	1024 (280)

5.1.1. ECITT Condition Effects

As predicted (H1 & H2), the results of paired samples *t*-tests revealed that participants were significantly more accurate on prepotent than on inhibitory trials: t (99) = -9.404, $p < .001$, d = -.940, and were significantly quicker at responding on correct prepotent trials than on correct inhibitory trials: t (99) = 15.729, $p < .001$, d = 1.573.

5.1.2. Behavioural Development from Infancy to Early Childhood

Descriptive statistics for the five ECITT performance variables on the blocked ECITT at 10-months, 16-months and 3½ years are reported in **Table 4** below.

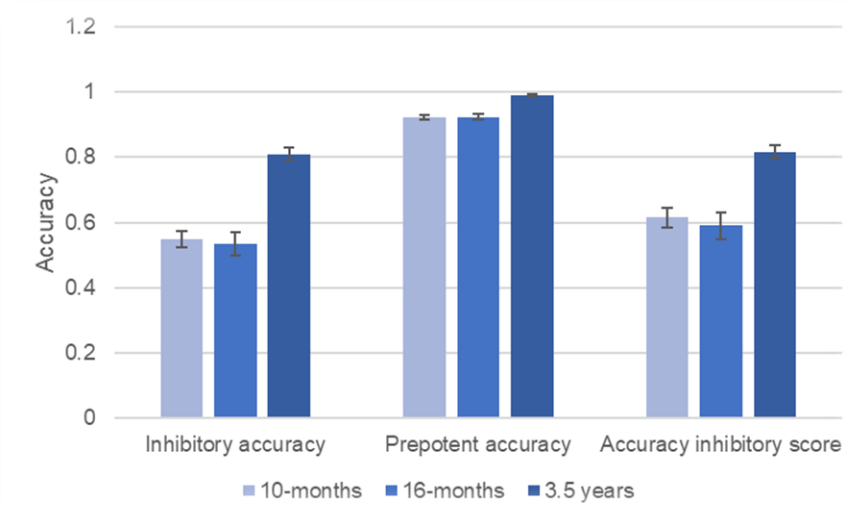
Table 4. Chapter 6. Descriptive Statistics for Longitudinal ECITT Performance.

	10-months		16-months		3½ years	
	N	Mean (SD)	N	Mean (SD)	N	Mean (SD)
Mean inhibitory accuracy	128	.549 (.292)	81	.536 (.324)	100	.810 (.199)
Mean prepotent accuracy	128	.922 (.085)	81	.924 (.088)	100	.991 (.039)
Accuracy inhibitory score	128	.615 (.337)	81	.590 (.369)	100	.817 (.194)
Median inhibitory reaction time (ms)	-	-	77	1454 (418)	100	1389 (328)
Median prepotent reaction time (ms)	-	-	77	1280 (217)	100	1024 (280)

To investigate whether overall accuracy on the ECITT improved from 10 months to 3½ years (H6a: Model 1), and from 16-months to 3½ years (H6b: Model 2), two separate 2 x 2 linear mixed models (restricted maximum likelihood estimation) were conducted with trial type and age as within-subjects factors. Results are reported in **Table 5** below and see **Table 6** for estimated marginal means. Both models revealed a significant main effect of age, such that participants were significantly more accurate at 3½ years than at 10-months of age (Model 1) or 16-months of age (Model 2). Similarly, as predicted, a significant main effect of trial type was found in both models whereby participants were significantly more accurate on prepotent trials than on inhibitory trials. A significant interaction effect was observed in both models, such that there was a larger improvement in inhibitory accuracy than in prepotent accuracy between 10 months and 3½ years (Model 1) and between 16-months and 3½ years (Model 2). Results of two paired samples *t*-tests revealed that there was a significant improvement in inhibitory performance on the ECITT (accuracy inhibitory score) between 10-months and 3½ years: t (77) = -4.246, $p < .001$. d = -.481, and between 16-months and 3½ years: t (43) = -2.817, p = .004, d = -.425.

To establish a full picture of accuracy development across infancy and early childhood, an additional exploratory 3 × 2 linear mixed model was conducted with the accuracy data across all assessment points. Results are presented in Appendix D3 and support the results of the models reported here. See **Figure 1** for an illustration of the accuracy change over time.

Figure 1. Chapter 6. Accuracy Change on the ECITT from Infancy to Early Childhood.



Note. Error bars represent standard error.

Table 5. Chapter 6. Results of Linear Mixed Models: Accuracy on the ECITT from Infancy to Early Childhood.

Model 1: (10-months and 3½ years)	**Test Statistic**	***p***	**Effect size (Cohen's *f*)**
Trial type	*F* (1, 247.289) = 265.532	**<.001**	1.03
Age	*F* (1, 247.289) = 94.454	**<.001**	0.366
Interaction	*F* (1, 247.289) = 32.007	**<.001**	0.353
Model 2: (16-months and 3½ years)	**Test Statistic**	***p***	**Effect size (Cohen's *f*)**
Trial type	*F* (1, 143.137) = 179.597	**<.001**	1.11
Age	*F* (1, 143.137) = 64.598	**<.001**	0.662
Interaction	*F* (1, 143.137) = 23.837	**<.001**	0.397

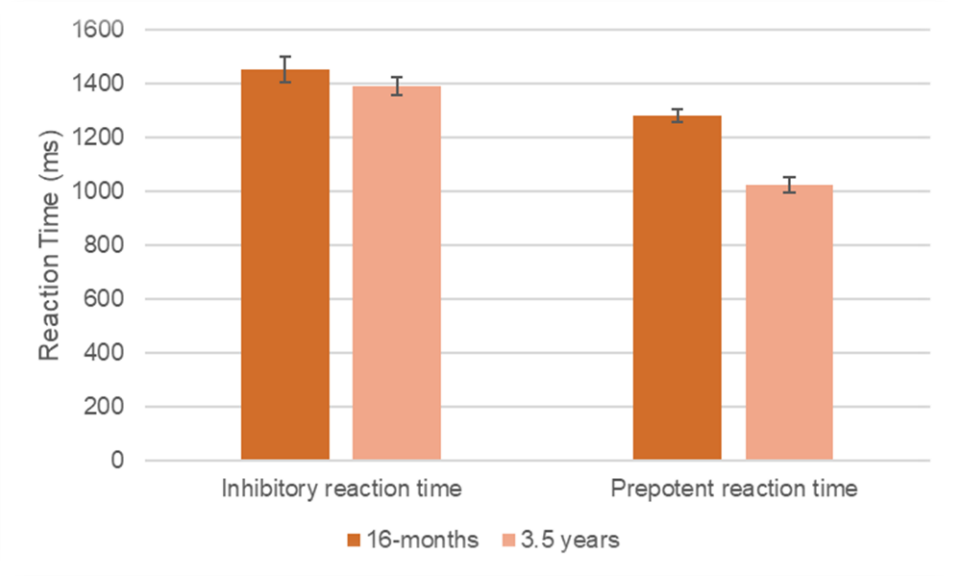
Note. Statistically significant results are highlighted in bold.

Table 6. Chapter 6. Estimated Marginal Means: Accuracy Improvement from Infancy to Early Childhood

Model 1: (10-months and 3½ years)		Estimated marginal mean	Standard error	Degrees of Freedom	Confidence interval
Trial Type	Inhibitory	.680	.016	217.670	.647, .712
	Prepotent	.956	.004	182.178	.948, .965
Age	10-months	.735	.014	145.171	.709, .762
	3½ years	.901	.010	106.763	.880, .921
Interaction	Inhibitory 10-months	.549	.026	124	.497, .601
	Prepotent 10-months	.922	.008	124	.907, .937
	Inhibitory 3½ years	.810	.020	99	.771, .850
	Prepotent 3½ years	.991	.004	99	.983, .999
Model 2: (16-months and 3½ years)		**Estimated marginal mean**	**Standard error**	**Degrees of Freedom**	**Confidence interval**
Trial Type	Inhibitory	.673	.021	126.793	.633, .714
	Prepotent	.957	.005	106.103	.947, .968
Age	16-months	.730	.019	91.636	.693, .767
	3½ years	.901	.010	106.763	.880, .921
Interaction	Inhibitory 16-months	.536	.039	80	.465, .608
	Prepotent 16-months	.924	.010	80	.905, .943
	Inhibitory 3½ years	.810	.020	99	.771, .850
	Prepotent 3½ years	.991	.004	99	.983, .999

To investigate whether overall reaction time on the ECITT improved from 16-months to 3½ years (H6b: Model 3), a 2 × 2 linear mixed model (restricted maximum likelihood estimation) was conducted with trial type and age as within-subjects factors. Results are reported in **Table 7** below and see **Table 8** for estimated marginal means. A significant main effect of age was found, such that participants responded significantly faster at 3½ years than at 16-months. Similarly, a significant main effect of trial type was found whereby participants responded significantly faster on prepotent trials than on inhibitory trials. A significant interaction effect was observed, such that there was a larger reaction time improvement in prepotent reaction time between 16-months and 3½ years than in inhibitory reaction time. See **Figure 2** for an illustration of the reaction time change from 16-months to 3½ years.

Figure 2. Chapter 6. Reaction Time Change on the ECITT From Infancy to Early Childhood.



Note. Error bars represent standard error.

Table 7. Chapter 6. Results of Linear Mixed Models: Reaction Time on the ECITT from Infancy to Early Childhood.

Reaction time	**Test Statistic**	***p***	**Effect size (Cohen's *f*)**
Trial type	*F* (1, 248.311) = 21.615	**<.001**	0.287
Age	*F* (1, 248.311) = 61.126	**<.001**	0.490
Interaction	*F* (1, 248.311) = 7.751	**.006**	0.164

Note. Statistically significant results are highlighted in bold.

Table 8. Chapter 6. Estimated Marginal Means: Reaction Time Improvement from Infancy to Early Childhood

Reaction Time (ms)		**Estimated marginal mean**	**Standard error**	**Degrees of Freedom**	**Confidence interval**
Trial Type	Inhibitory	1421	29	140.990	1364, 1479
	Prepotent	1152	19	174.997	1116, 1189
Age	16-months	1367	27	114.063	1314, 1420
	3½ years	1207	22	193.271	1164, 1250
Interaction	Inhibitory 16-months	1454	48	76	1358, 1549
	Prepotent 16-months	1280	25	76	1231, 1330
	Inhibitory 3½ years	1389	33	99	1324, 1455
	Prepotent 3½ years	1024	28	99	969, 1080

Four separate Pearson's correlational analyses were conducted to examine whether there was a significant association between performance on the blocked ECITT at 10-months and 3½ years (H7a) and at 16-months and 3½ years (H7b). As predicted, there were no significant associations between performance on the ECITT in infancy and early childhood. Results are reported in **Table 9**.

Table 9. Chapter 6. Performance on the ECITT: Longitudinal Associations.

	Statistic
Accuracy Inhibitory Score (10-months and 3½ years)	*r* (76) = -.069, *p* = .274, *CI* = -.290, .167
Accuracy Inhibitory Score (16-months and 3½ years)	*r* (40) = -.238, *p* = .067, *CI* = -.482, .064
Median Prepotent RT (16-months and 3½ years)	*r* (40) = .224, *p* = .085, *CI* = -.187, .538
Median Inhibitory RT (16-months and 3½ years)	*r* (40) = .108, *p* = .256, *CI* = -.110, .402

5.1.3. Between-Session Consistency and Test Re-Test Reliability

Accuracy: As hypothesised (H4), results of the 2 × 2 mixed ANOVA demonstrated a significant main effect of session, whereby participants were significantly more accurate in Session 2 (blocked ECITT) than in Session 1 (behavioural ECITT): F (1, 95) = 5.812, p = .025, ηp^2 = .058, Cohen's f = 0.22. The trial type × session interaction was not significant: F (1, 95) = .429, p = .514, ηp^2 = .004, Cohen's f = .000. Estimated marginal means are reported in **Table 10**. Contrary to predictions, there was no significant difference between the accuracy inhibitory score in Session 1 and Session 2: t (95) = -.885, p = .189, Cohen's d = -.090.

Reaction Time: As hypothesised (H4), there was a significant main effect of session whereby participants responded significantly faster in Session 2 than in Session 1: F (1, 95) = 137.172, p < .001, ηp^2 = .591, Cohen's f = 1.18. There was also a significant type × session interaction, whereby the difference in reaction time between trial types (faster on prepotent trials than on inhibitory trials) was larger in Session 2 than in Session 1: F (1, 95) = 9.796, p = .002, ηp^2 = .093, Cohen's f = 0.30. Estimated marginal means are reported in **Table 10**.

Table 10. Chapter 6. Estimated marginal means for mixed ANOVAs (Group-Level Between Session Consistency).

Accuracy		Estimated marginal mean	Standard error	Confidence interval
Trial type	Inhibitory	.806	.015	.776, .837
	Prepotent	.983	.003	.977, .988
Session	1	.883	.009	.865, .901
	2	.906	.011	.885, .927
Interaction	Inhibitory S1	.791	.016	.759, .824
	Inhibitory S2	.821	.020	.782, .861
	Prepotent S1	.974	.003	.967, .981
	Prepotent S2	.991	.004	.983, .999
Reaction Time (ms)		**Estimated marginal mean**	**Standard error**	**Confidence interval**
Trial type	Inhibitory	1581	37	1508, 1653
	Prepotent	1281	34	1213, 1349
Session	1	1647	45	1558, 1736
	2	1215	29	1157, 1273
Interaction	Inhibitory S1	1766	51	1665, 1867
	Inhibitory S2	1395	34	1328, 1463
	Prepotent S1	1528	47	1435, 1621
	Prepotent S2	1034	29	977, 1091

To establish test re-test reliability, five confirmatory correlational analyses were conducted on data from the behavioural ECITT (Session 1) and the blocked ECITT (Session 2), results are reported in **Table 11** below. Performance (as measured by the mean inhibitory accuracy variable, the accuracy inhibitory score and the median inhibitory reaction time variable) was consistent across sessions.

Table 11. Chapter 6. ECITT Test Re-Test Reliability.

	Pearson's correlation coefficient	*p*	Confidence interval
Mean inhibitory accuracy	r (94) = .446	**<.001**	.270, .595
Mean prepotent accuracy	r (94) = .164	.054	.044, .505
Accuracy inhibitory	r (94) = .424	**<.001**	.266, .585
Median inhibitory reaction time	r (94) = .464	**<.001**	.285, .639
Median prepotent reaction time	r (94) = .060	.278	.001, .235

Note. Statistically significant results are highlighted in bold. All results remained significant following the procedure for controlling the FDR (N = 5 comparisons).

5.1.4. Group Performance Differences

Two 2 × 2 mixed ANOVAs were conducted to examine whether there were any significant performance differences between those participants who contributed valid fNIRS data and valid ECITT data (*N* = 61) and those who only contributed valid ECITT data (*N* = 39). Estimated marginal means are reported in **Table 12**.

Accuracy: As hypothesised (H3a), results demonstrated a significant main effect of trial type, whereby participants were significantly more accurate on prepotent trials than on inhibitory trials: F (1, 98) = 81.484, $p < .001$, $\eta p^2 = .454$, Cohen's $f = 0.897$. Again, as predicted, there was no significant main effect of sub-sample: F (1, 98) = .008, $p = .927$, $\eta p^2 = .000$, Cohen's $f = .000$, and no significant trial type × sub-sample interaction: F (1, 98) = .259, $p = .612$, $\eta p^2 = .003$, Cohen's $f = .000$.

Reaction Time: In line with predictions (H3b), results demonstrated a significant main effect of trial type, whereby participants responded significantly faster on correct prepotent trials than on correct inhibitory trials: F (1, 98) = 274.803, $p < .001$, $\eta p^2 = .737$, Cohen's $f = 1.655$. There was also a significant main effect of sub-sample, whereby participants who contributed both valid ECITT and fNIRS data responded significantly faster than those who only contributed valid ECITT data: F (1, 98) = 5.203, $p = .025$, $\eta p^2 = .050$, Cohen's $f = 0.21$. The trial type × sub-sample interaction was also significant, whereby participants who contributed valid fNIRS data were significantly faster on inhibitory trials than those who did not contribute valid fNIRS data: F (1, 98) = 8.694, $p = .004$, $\eta p^2 = .081$, Cohen's $f = 0.277$.

Table 12. Chapter 6. Estimated Marginal Means for Mixed ANOVAs (Group Performance Differences).

Accuracy		**Estimated marginal mean**	**Standard error**	**Confidence interval**
Trial type	Inhibitory	.811	.020	.770, .852
	Prepotent	.990	.004	.982, .998
Sub-sample	Behavioural only	.899	.017	.865, .933
	fNIRS + Behavioural data	.901	.014	.874, .929
Interaction	Behavioural only - Inhibitory	.815	.032	.752, .879
	Behavioural only - Prepotent	.984	.006	.971, .996
	fNIRS + Behavioural Data - Inhibitory	.807	.026	.756, .858
	fNIRS + Behavioural Data Prepotent	.996	.005	.986, 1.00
Reaction time (ms)		**Estimated marginal mean**	**Standard error**	**Confidence interval**
Trial type	Inhibitory	1411	32	1347, 1475
	Prepotent	1031	29	974, 1088

Sub-sample	Behavioural only	1286	44	1198, 1374
	fNIRS + Behavioural data	1157	35	1086, 1227
Interaction	Behavioural only - Inhibitory	1510	51	1409, 1610
	Behavioural only - Prepotent	1062	45	973, 1151
	fNIRS + Behavioural Data - Inhibitory	1313	40	1233, 1393
	fNIRS + Behavioural Data Prepotent	1000	36	929, 1072

5.2. fNIRS Group-Level Results

Confirmatory analyses: In the pre-registration, it was hypothesised that nine channels (found to be showing significant block type effects at 16-months) would also show significant block type effects at 3½ years. These channels were: Channel 6 (left superior parietal), Channel 8 (right inferior parietal), Channels 20 and 23 (right inferior frontal gyrus (IFG)), Channel 26 (right dorsolateral prefrontal cortex (DLPFC)), Channel 28 (left DLPFC), Channel 29 (left OFC), Channel 31 (right IFG, orbital), and Channel 33 (right OFC). Following pre-processing, Channel 6 (left superior parietal) was excluded from the confirmatory group-level analysis because less than 50% of participants contributed data to this channel. As such, repeated measures ANOVAs were conducted on data from the remaining eight channels.

The results of the repeated measures ANOVA revealed that seven channels demonstrated a significant main effect of time (i.e., the haemoglobin concentration changed over time from baseline; see Appendix D4). Following the procedure for controlling the FDR, all channels retained significance for the main effect of time. Three channels were found to show significant block type or time × block type interaction effects, namely, Channel 8 (right inferior parietal), Channel 29 (left OFC) and Channel 31 (right IFG), see **Table 13** below, and see **Figure 5** below for HRF plots.

Exploratory analyses: In line with the pre-registered analysis plan, exploratory repeated measures analyses were conducted on the remaining channels in the fNIRS probe to examine whether any additional channels were showing significant block type effects or interactions. It was found during pre-processing that there were 10 channels for which less than 50% of participants contributed data and so these channels were excluded from the analysis. These channels were located in the bilateral parietal cortex (Channels 2, 3, 5, 9, 10, 11 and 12) and the bilateral middle frontal gyrus (Channels 15, 22 and 24) (see Appendix D4 for a figure that illustrates the locations of these channels on the fNIRS probe). These channels likely had poor optode coupling due to the position on the curve of the head and/or because of hair in these areas. Additionally, the two short separation channels (Channels 30 and 34) were excluded from the analysis because they were showing

significant block type effects and so were not functioning as short channels (see Chapter 3 for discussion).

Of the 25 channels included in the exploratory repeated measures analyses, a total of 24 channels demonstrated a significant main effect of time in the HbO_2 and/or the HHb signal (Appendix D4). Following correction for the FDR (50 comparisons; 25 channels × two chromophores), there were only three channels for which the main effect of time was no longer significant. Four channels were found to show a significant block type effect or a significant time × block type interaction effect, namely, Channel 7 (right inferior parietal), Channels 18 and 43 (left DLPFC), and Channel 45 (right DLPFC).

A *t*-statistic image of significant haemoglobin concentration differences between conditions is shown in **Figure 3** and **Figure 4** for visualisation purposes. See also **Table 13** below and see **Figure 5** for HRF plots.

Table 13. Chapter 6. Significant HbO_2 and HHb Concentration Change Differences Between Block Types.

Location	Hemisphere	Channel	Signal	Statistic
Inferior parietal	Right	7	HHb	F (1.656, 57.964 = 4.219, p = .026, ηp^2 = .108, Cohen's f = .297
		8*	HHb	F (1.600, 51.189 = 3.954,p = .034, ηp^2 = .109, Cohen's f = .296
IFG	Right	31*	HbO_2	F (1, 51) = 4.554, p = .038, ηp^2 = .082, Cohen's f = .259
			HHb	F (1, 51) = 5.423, p = .024, ηp^2 = .096, Cohen's f = .289
DLPFC	Left	18	HbO_2	F (1, 49) = 6.400, p = .015, ηp^2 = .116, Cohen's f = .325
		43	HHb	F (1, 40) = 5.859, p = .020, ηp^2 = .128, Cohen's f = .340
	Right	45	HbO_2	F (1, 46) = 5.999, p = .018, ηp^2 = .115, Cohen's f = .323
OFC	Left	29*	HHb	F (2.159, 120.920) = 3.142, p = .043, ηp^2 = .053, Cohen's f = .193

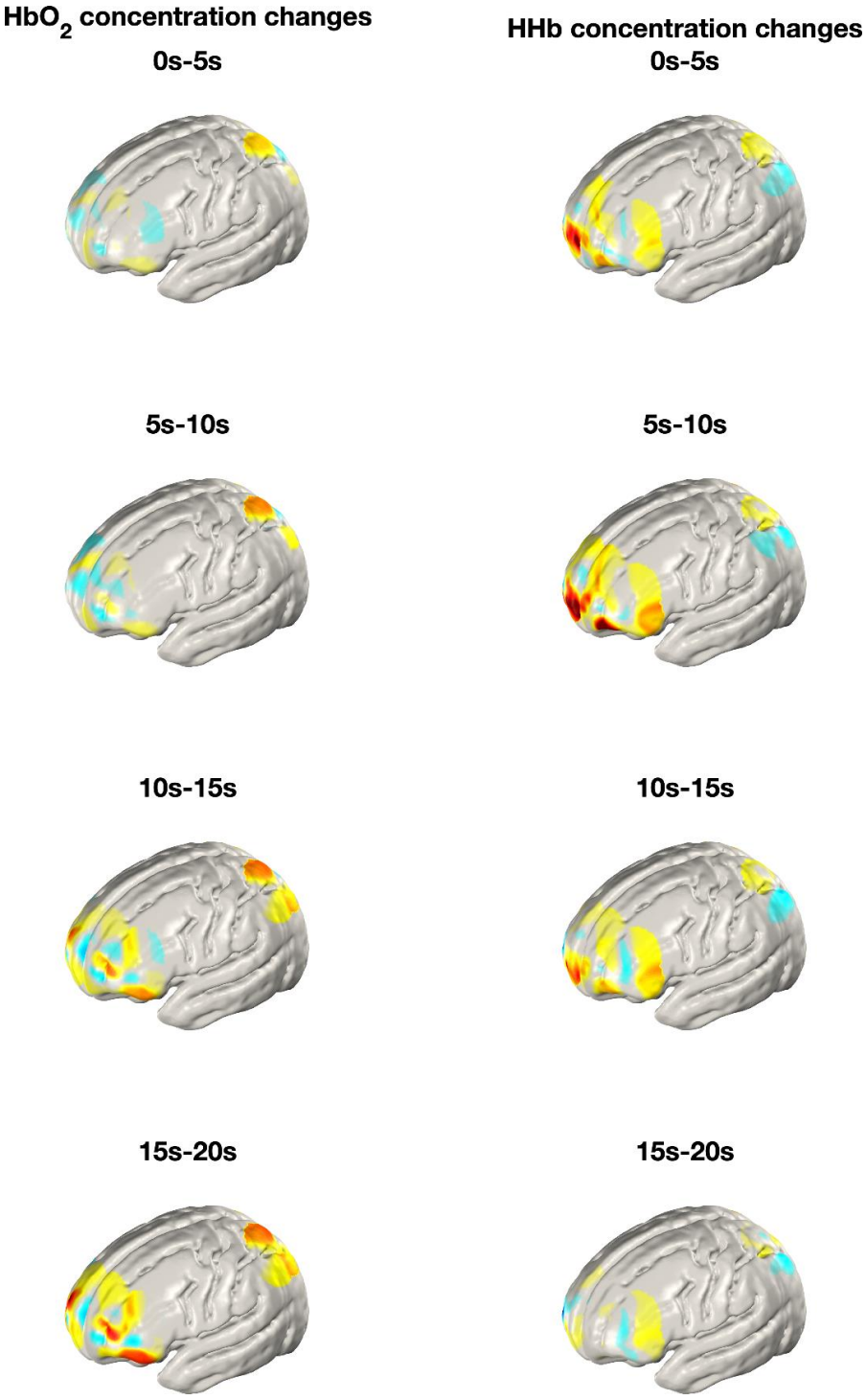
Note. * = Channels were pre-registered in the confirmatory analyses (and also showed significant effects at 16-months). None of the effects survived the procedure for controlling the FDR. IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

5.2.1. fNIRS Time Course Analyses

To examine the time course of the significant effects, paired *t*-tests were conducted on the seven channels identified in the primary analyses as showing significant block-type effects; results are reported in **Table 14**. See also **Figure 5**, where the time bins showing significant block-type effects are highlighted in each channel with either a blue (HHb) or red (HbO_2) bar.

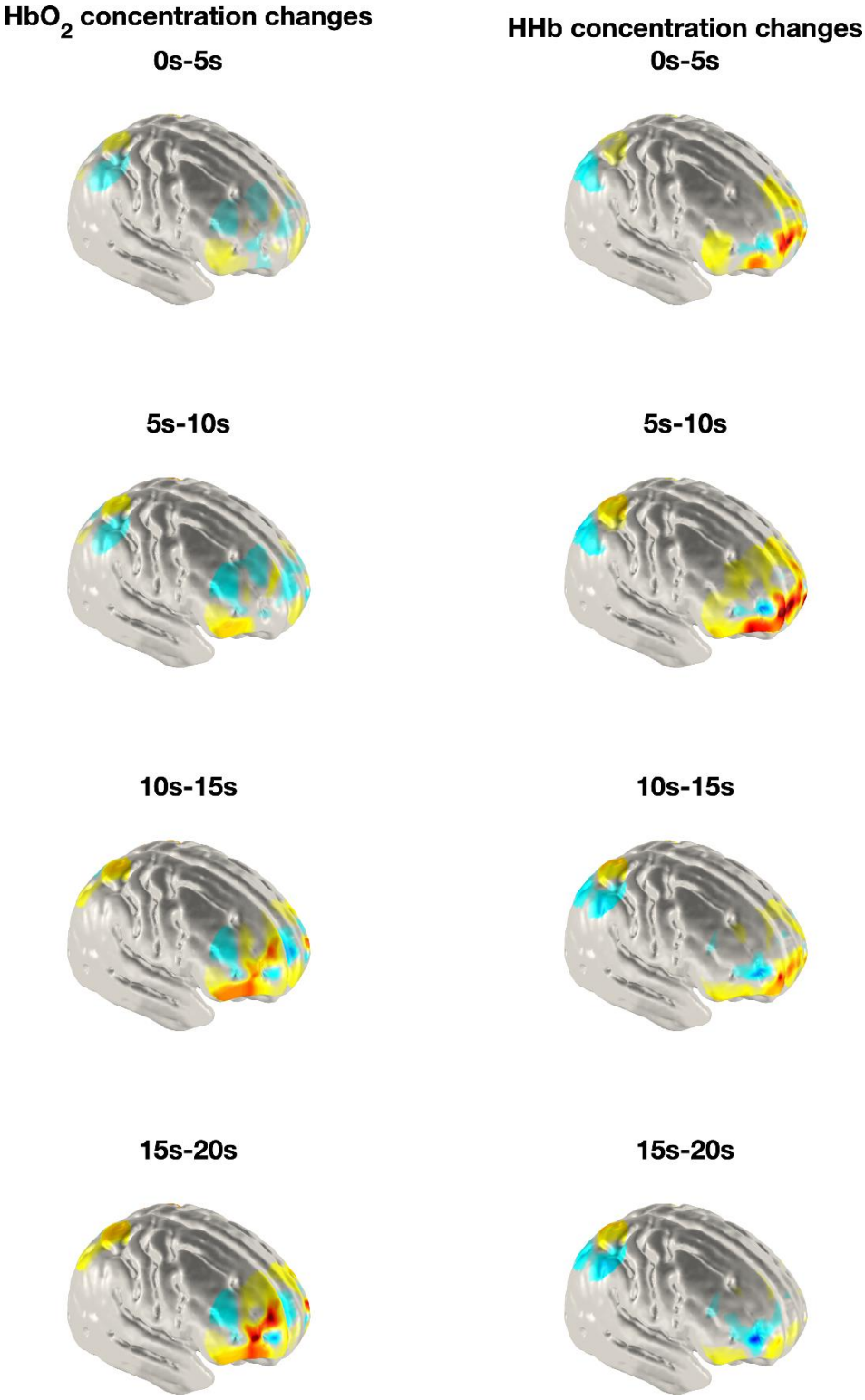
It is worth noting that for Channel 7 (right inferior parietal) and Channel 29 (left OFC) there were no significant HHb concentration differences between block types within any of the five time bins. This is because the paired *t*-tests were conducted on an exploratory basis using the two-tailed *p*-values. As such, no further analyses will be conducted with data from these channels.

Figure 3. Chapter 6. Group-level *T*-Statistic Image of the Contrast in Haemoglobin Concentration Changes Between Block Types in the Left Hemisphere.



Note. Group-level T-statistic images of the contrast in concentration changes of each chromophore (HbO_2 on the left and HHb on the right) between experimental and control blocks (experimental – control) in the left hemisphere. Images are displayed in the space of a cortical surface derived from averaged structural MRI data of a 12-month-old cohort of infants (Shi et al., 2011). Using this approach, all displayed T-statistic values are significantly different across block types (paired t-test) at the alpha level of $p < .01$. **Image produced by Dr Liam Collins-Jones.**

Figure 4. Chapter 6. Group-Level *T*-Statistic Image of the Contrast in Haemoglobin Concentration Changes Between Block Types in the Right Hemisphere.



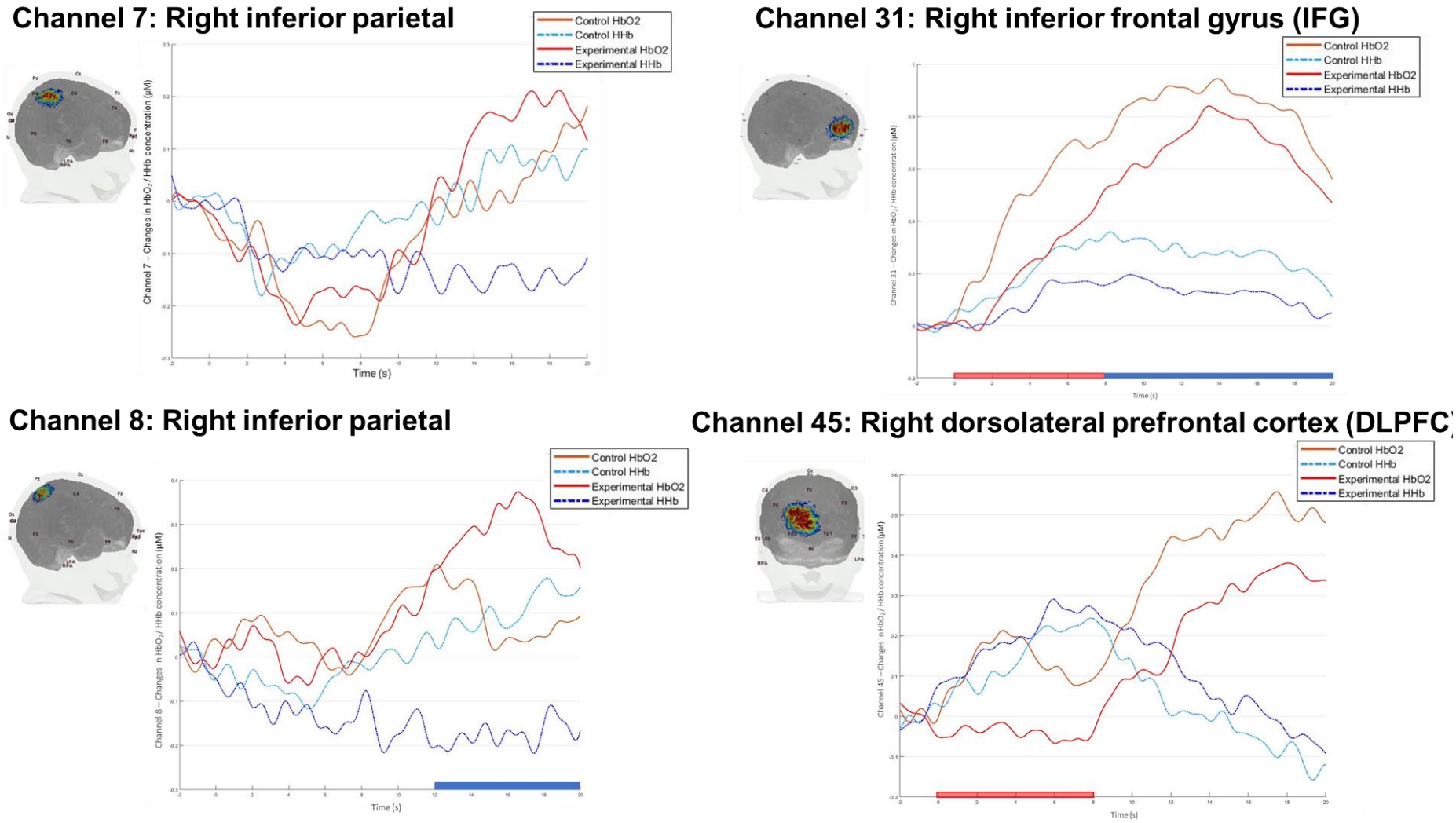
Note. Group-level T-statistic images of the contrast in concentration changes of each chromophore (HbO2 on the left and HHb on the right) between experimental and control blocks (experimental – control) in the right hemisphere. Images are displayed in the space of a cortical surface derived from averaged structural MRI data of a 12-month-old cohort of infants (Shi et al., 2011). Using this approach, all displayed T-statistic values are significantly different across block types (paired t-test) at the alpha level of $p < .01$. **Image produced by Dr Liam Collins-Jones.**

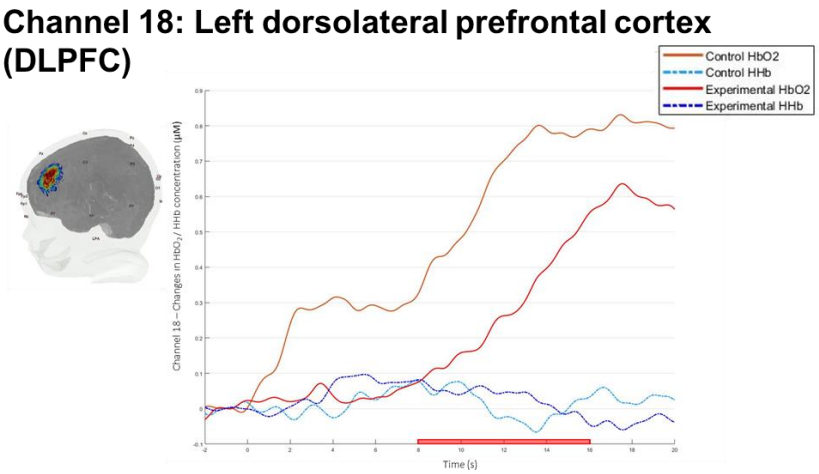
Table 14. Chapter 6. Time Course of the Significant HbO_2 or HHb Block Type Effects.

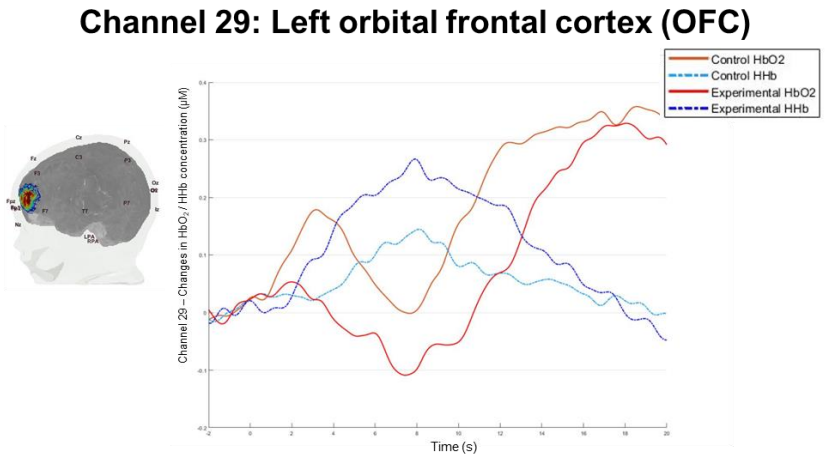
Location	Channel	Signal	0 – 4s	4 – 8s	8 – 12s	12 – 16s	16 – 20s
Right inferior parietal	7	HHb	*t* (35) = -.308, *p* = .760, *d* = .051	*t* (35) = .207, *p* = .837, *d* = .034	*t* (35) = 1.076, *p* = .289, *d* = .179	*t* (35) = 1.682, *p* = .102, *d* = .280	*t* (35) = 1.946, *p* = .060, *d* = .324
	8*	HHb	*t* (32) = 1.035, *p* = .308, *d* = .180	*t* (32) = 1.005, *p* = .322, *d* = .175	*t* (32) = 1.347, *p* = .187, *d* = .235	***t* (32) = 2.089, *p* = .045, *d* = .364**	***t* (32) = 2.245, *p* = .032, *d* = .391**
Right IFG	31*	HbO_2	**t (51) = 2.826, p = .007#, d = .392**	**t (51) = 2.403, p = .020#, d = .333**	t (51) = 1.823, p = .074, d = .253	t (51) = 1.478, p = .146, d = .205	t (51) = 1.594, p = .117, d = .221
		HHb	*t* (51) = 1.594, *p* = .117, *d* = .221	*t* (51) = 1.656, *p* = .104, *d* = 230	***t* (51) = 2.214, *p* = .031, *d* = .307**	***t* (51) = 2.152, *p* = .036, *d* = .298**	***t* (51) = 2.082, *p* = .042, *d* = .289**
Left DLPFC	18	HbO_2	*t* (49) = .749, *p* = .458, *d* = .106	*t* (49) = 2.005, *p* = .051, *d* = .284	***t* (49) = 2.460, *p* = .017, *d* = .348**	***t* (49) = 2.365, *p* = .022, *d* = .334**	*t* (49) = 1.889, *p* = .065, *d* = .267
	43	HHb	***t* (40) = -2.488, *p* = .017#, *d* = .389**	***t* (40) = -2.499, *p* = .017#, *d* = .390**	***t* (40) = -2.788, *p* = .008#, *d* = .435**	*t* (40) = -2.002, *p* = .052, *d* = .313	*t* (40) = -1.384, *p* = .174, *d* = .216
Right DLPFC	45	HbO_2	***t* (46) = 3.082, *p* = .003#, *d* = .450**	***t* (46) = 2.206, *p* = .032, *d* = .322**	*t* (46) = 1.978, *p* = .054, *d* = .289	*t* (46) = 1.893, *p* = .065, *d* = .276	*t* (46) = 1.337, *p* = .188, *d* = .195
Left OFC	29*	HHb	*t* (56) = -.399, *p* = .691, *d* = .053	*t* (56) = -1.752, *p* = .085, *d* = .232	*t* (56) = -1.614, *p* = .112, *d* = .214	*t* (56) = -.760, *p* = .450, *d* = .101	*t* (56) = .113, *p* = .910, *d* = .015

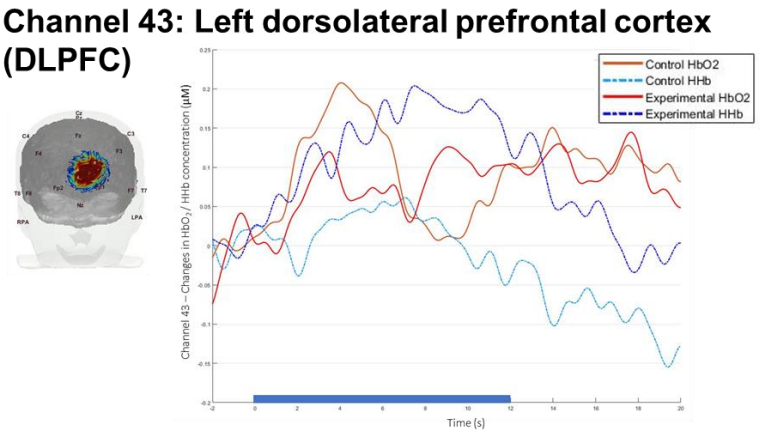
Note. * = Channels were pre-registered in the confirmatory analyses (and also showed significant effects at 16-months). Statistically significant results are highlighted in bold. # = significant after correcting the FDR (5 comparisons). The significant effects in Channel 31 (HbO_2), Channel 18, Channel 43, Channel 45 and Channel 29 are in the opposite direction than expected. IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

Figure 5. Chapter 6. Haemodynamic Response Function for Channels Showing Significant Block Type Effects.









Note. This figure illustrates the average haemodynamic response function from -2 seconds (baseline) to 20 seconds of the block time course for channels showing significant block type effects. The change in concentration in HbO2 and HHb (μM) for each channel are plotted on the y-axis, time bin is plotted on the x-axis. Bars (blue = HHb, red = HbO2) on the x-axis indicate the time-bins where there is a significant block-type effect (note that these time-bin effects did not survive the correction for the FDR (5 comparisons) but are added here for illustrative purposes). Sensitivity profiles illustrate the position of each channel on the cortex and the channel sensitivity (heat map: red = more sensitive, blue = less sensitive).

5.2.2. Description of the Significant Block Type Effects

As seen in **Table 13**, a significant time × block type interaction was found in the HHb signal for Channel 7 and Channel 8 (right inferior parietal), suggesting that there was a significantly greater decrease in HHb concentration in experimental blocks compared to in control blocks, and that the HHb difference between conditions was dependent on the time bin. A significant main effect of block type was observed in the HHb signal for Channel 31 (right IFG orbital), such that there was a significantly greater HHb decrease in experimental blocks than in control blocks. These effects suggest that there is a significantly greater HHb decrease in the right inferior parietal cortex (Channels 7 and 8) and the right IFG (Channel 31) when inhibition is required.

Additionally, a significant HbO_2 block type effect was observed for Channel 18 (left DLPFC), Channel 31 (right IFG orbital) and Channel 45 (right DLPFC). However, the effects were in the opposite direction than predicted, as HbO_2 concentration showed a significantly greater increase in control blocks than in experimental blocks. Similarly, a significant HHb block type effect was observed for Channel 43 (left DLPFC), and a significant HHb time × block type interaction effect was observed for Channel 29 (left OFC), but again these effects were not in the predicted direction as there was a significantly greater HHb decrease in control blocks compared to experimental blocks.

As can be seen in **Figure 5**, Channel 7 (right inferior parietal) and Channel 29 (left OFC) show an inverted HRF response. In Channel 7, there is an overall decrease in both HbO_2 and HHb from baseline, whereby the HbO_2 concentration (in both block types) is lower than the HHb concentration. After approximately 10 s of the block time course, the response appears to correct such that there is an increase in HbO_2 (in both block types), however, the HHb signal appears to remain fairly steady until around 16 s of the block time course where the HHb in control blocks increases and there is a significant (one-tailed) HHb difference between block types (from 16 – 20 s). Overall, the effects found in Channel 7 suggest that there was a larger HHb decrease in the experimental compared to control blocks, as expected. In Channel 29, the inversion occurs early in the block time course until around 12s where the HbO_2 signal (in both block types) begins to increase, and from around 8s the HHb signal (in both block types) begins to decrease. The significant interaction found in Channel 29 occurs from 4 – 8s of the block time course (one-tailed). Overall, the effects found in Channel 29 suggest that there was a larger increase in HHb concentration in experimental blocks than in control blocks. Not only is the HHb signal increasing from baseline when the significant effect is observed (when it is expected to decrease from baseline), but it is also the case that there was a larger increase in experimental compared to control blocks (where it would be expected that there was a *lower* HHb concentration in experimental blocks).

5.3. Individual Differences Analyses

Exploratory correlational analyses were conducted to investigate whether individual differences in neural activation (in channels showing significant block type effects across the identified time bins) were associated with individual performance differences in the accuracy inhibitory score. Results of Pearson's correlational analyses (**Table 15**) revealed that there were no significant associations between performance on the ECITT (accuracy inhibitory score) and the haemoglobin difference variables.

Table 15. Chapter 6. Individual Differences Analyses.

Location	Hemisphere	Channel	Signal	Time Bins	Statistic
Inferior parietal	Right	8*****	HHb	4 – 5	*r* (32) = -.143, *p* = .427, *CI* = -.439, .168
IFG	Right	31*****	HbO_2	1 – 2	*r* (51) = -.043, *p* = .760, *CI* = -.334, .266
			HHb	3 – 5	*r* (51) = .090, *p* = .527, *CI* = -.196, .382
DLPFC	Left	18	HbO_2	3 – 4	*r* (49) = -.007, *p* = .962, *CI* = -.341, .359
		43	HHb	1 – 3	*r* (40) = -.087, *p* = .590, *CI* = -.378, .241
	Right	45	HbO_2	1 – 2	*r* (46) = -.162, *p* = .276, *CI* = -.429, .140

Note. * = Channels were pre-registered in the confirmatory analyses (and also showed significant effects at 16-months). IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

5.4. Longitudinal Development of the Neural Correlates of Response Inhibition from Infancy to Early Childhood

It was stated in the pre-registration that exploratory linear mixed model analyses would be conducted to investigate the change in activation from the 10-month assessment point to the 3½-year assessment point (RQ10a), and from the 16-month assessment point to the 3½-year assessment point (RQ10b). However, it was decided that the analyses examining change from 10-months to 3½ years (RQ10a) would not be conducted because no channels were showing significant block type effects at both 10-months and 3½ years.

5.4.1. Channels Showing Significant Block Type Effects at 3½ years

Separate linear mixed models (restricted maximum likelihood estimation) were conducted on the four channels showing a significant block type effect at 3½ years (dependent variable),

with assessment point (16-months, 3½ years) as a fixed factor and participants as a random factor. A total of five models were conducted as Channel 31 showed significant block type effects in both HbO_2 and HHb signals. Note that data from Channel 7 (right inferior parietal) and Channel 29 (left OFC) were not included in these analyses. The models were conducted to investigate the change in activation from the 16-month assessment point to the 3½ year assessment point. The results are reported in **Table 16** below, and estimated marginal means are reported in **Table 17**.

Results indicated that the HbO_2 difference in Channel 18 (left DLPFC) significantly increased from 16-months to 3½ years, such that there was a larger HbO_2 difference at 3½ years compared to 16-months. In other words, whilst there was no significant difference in HbO_2 concentration between block types at 16-months, there was a significant difference at 3½ years, such that the HbO_2 concentration was significantly higher in control conditions than in experimental conditions (note that this is in the opposite direction than expected, hence the negative estimated marginal mean at 3½ years). As such, the change appears negative (**Figure 6**) due to the way that the HbO_2 difference measure is calculated (HbO_2 concentration in experimental conditions *minus* HbO_2 concentration in control conditions), but reflects a larger difference between block types at 3½ years (in the opposite direction than expected) compared to no significant difference between block types at 16-months.

Table 16. Chapter 6. Exploratory Longitudinal Brain Changes (from 16-months) in Channels with a Significant Block Type Effect at 3½ years.

Location	Hemisphere	Channel	Signal	Statistic	*P*	Effect Size (Cohen's f)
Inferior parietal	Right	8*****	HHb	*F* (1, 53.291) = .180	.673	.000
IFG	Right	31*****	HbO_2	*F* (1, 86.571) = 1.930	.168	.102
			HHb	*F* (1, 85.014) = .013	.909	.000
DLPFC	Left	**18**	HbO_2	*F* (1, 71.844) = 5.235	**.025**	.239
		43	HHb	*F* (1, 69.984) = 3.466	.067	.185
	Right	45	HbO_2	*F* (1, 69.881) = 1.704	.196	.099

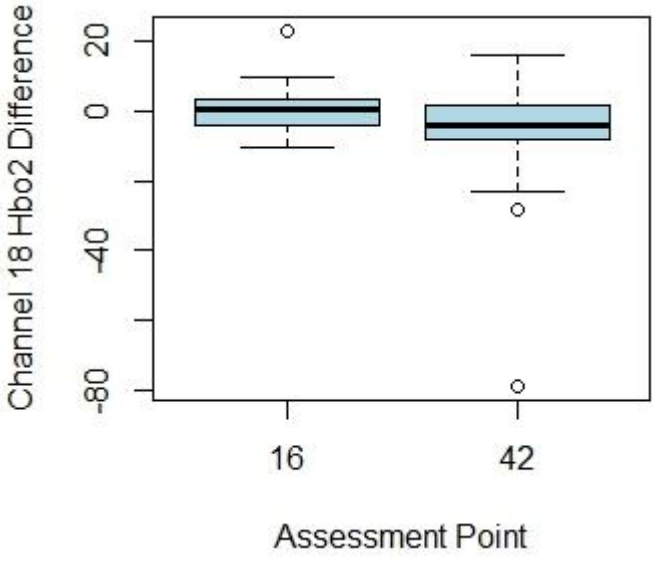
Note. * = Channels also showed significant effects in the 16-month study (Chapter 5). The statistically significant result is highlighted in bold, although this effect did not survive the procedure for controlling the FDR. IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex.

Table 17. Chapter 6. Exploratory Longitudinal Brain Changes from 16-months; Estimated Marginal Means (channels with a significant block type effect at 3½ years).

Location	Channel	Assessment Point	Estimated marginal mean	Standard error	df	Confidence interval
Right inferior parietal	8 (HHb)	16-months	1.221	.564	35	.075, 2.367
		3½ years	1.683	.931	32	-.213, 3.579
Right IFG	31 (HbO_2)	16-months	-.621	.929	42	-2.496, 1.254
		3½ years	-2.917	1.367	51	-5.661, -.173
	31 (HHb)	16-months	1.581	.419	42	.736, 2.426
		3½ years	1.493	.641	51	.206, 2.780
Left DLPFC	**18 (HbO_2)**	16-months	.069	.967	41	-1.888, 2.027
		3½ years	-4.826	1.908	49	-8.660, -.993
	43 (HHb)	16-months	.282	.655	35	-1.048, 1.613
		3½ years	-1.291	.533	40	-2.368, -.213
Right DLPFC	45 (HbO_2)	16-months	-.147	.987	37	-2.147, 1.854
		3½ years	-1.731	707	46	-3.154, -.309

Note. Estimated marginal mean refers to the mean haemoglobin concentration difference between experimental and control blocks in each channel across the block time course. IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex.

Figure 6. Chapter 6. Exploratory Longitudinal Brain Changes (Channels Showing Significant Change from 16-months to 3½ years).



Note. This figure illustrates the change in activation from the 16-month assessment point to the 3½ year (42-month) assessment point in Channel 18 (HbO_2; left DLPFC), which showed a significant effect of assessment point (i.e., a significant change over time). Note that Channel 18 showed a significant block type effect at 3½ years (in the opposite direction to what was expected), but not at 16-months. The variable on the y-axis refers to the HbO_2 difference score (calculated as HbO_2 in experimental blocks minus HbO_2 in control blocks) across the block time course. 16 = 16-months, 42 = 42-months (3½ years). HbO_2 = Oxygenated haemoglobin.

5.4.2. Channels Showing Significant Block Type Effects at 16-months

Six additional linear mixed models were separately conducted to investigate the change in activation across assessment points in channels showing significant block-type effects at 16-months, but not at 3½ years. The results are reported in **Table 18** below, and estimated marginal means are reported in **Table 19**. Results indicated that the HHb difference in Channel 28 significantly decreased from 16-months to 3½ years (**Figure 7**), such that there was a significantly larger HHb difference at 16-months (where a significant block type effect was found) compared to at 3½ years (where no significant block type effect was found).

Table 18. Chapter 6. Exploratory Longitudinal Brain Changes (at 3½ years) in Channels with a Significant Block Type Effect at 16-months.

Location	Channel	Signal	Test Statistic	*p*	Effect size (Cohen's *f*)
Left superior parietal	6	HHb	F (1, 32.262) = .162	.690	.000
Right IFG	20	HHb	F (1, 65.680) = .828	.366	.000
Right IFG	23	HHb	F (1, 80.699) = .674	.414	.000
Left DLPFC	**28**	HHb	F (1, 90.869) = 5.097	**.026**	.210
Right DLPFC	26	HbO_2	F (1, 74.297) = 1.291	.260	.062
Right OFC	33	HHb	F (1, 96.949) = 2.437	.122	.121

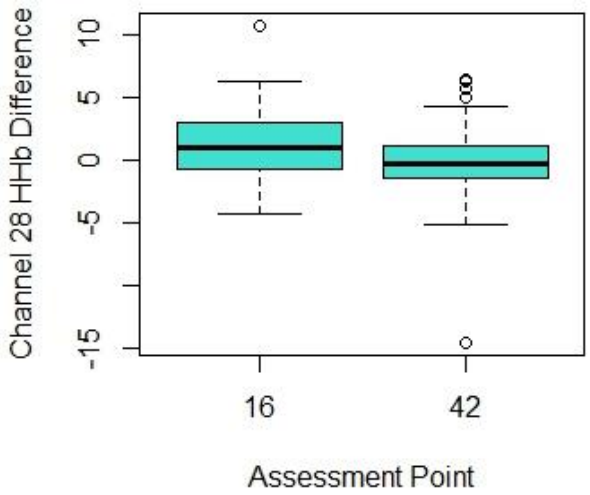
Note. The statistically significant result is highlighted in bold, however, the effect did not survive the procedure for controlling the FDR (N = 6 comparisons). IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

Table 19. Chapter 6. Exploratory Longitudinal Brain Changes; Estimated Marginal Means (channels with a significant block type effect at 16-months).

Location	Channel	Assessment Point	Estimated marginal mean	Standard error	df	Confidence interval
L superior parietal gyrus (HHb)	6	16-months	1.127	.495	38	.125, 2.129
		3½ years	.537	1.112	23	-1.663, 2.936
R IFG (HHb)	20	16-months	1.046	.480	41	.076, 2.016
		3½ years	-.034	1.086	48	-2.217, 2.149
R IFG (HHb)	23	16-months	.970	.474	42	.013, 1.927
		3½ years	.238	.754	49	-1.277, 1.754
L DLPFC (HHb)	**28**	16-months	1.268	.445	41	.369, 2.166
		3½ years	-.198	.473	50	-1.149, .752
R DLPFC (HbO_2)	26	16-months	1.136	1.132	36	-1.160, 3.432
		3½ years	-.903	1.392	40	-3.716, 1.911
R OFC (HHb)	33	16-months	1.104	.533	42	.028, 2.180
		3½ years	-.078	.537	57	-1.154, .998

Note. Estimated marginal mean refers to the mean haemoglobin concentration difference between experimental and control blocks in each channel across the block time course.
L = left, R = Right. IFG = inferior frontal gyrus, DLPFC = dorsolateral prefrontal cortex, OFC = orbital frontal cortex.

Figure 7. Chapter 6. Exploratory Longitudinal Brain Change (Significant Block Type Effects at 16-months but not at 3½ years).



Note. This figure illustrates the decrease in activation from the 16-month assessment point to the 3½ year (42-month) assessment point in Channel 28 (HHb; left DLPFC), which showed a significant effect of assessment point (i.e., a significant change over time). Note that Channel 28 showed a significant block type effect at 16-months, but not at 3½ years. The variable on the y-axis refers to the HHb difference score (calculated as HHb in control blocks minus HHb in experimental blocks) across the block time course. 16 = 16-months, 42 = 42-months (3½ years). HHb = Deoxygenated haemoglobin.

6. Discussion

6.1. Summary of Key Findings

With longitudinal data collected from the same cohort of participants under the same experimental paradigm at three time points in infancy and early childhood, the current study was able to examine the development of response inhibition and the associated neural correlates across the first four years of life. Replicating previous findings (Fiske et al., 2022; Hendry et al., 2021; Holmboe et al., 2021), results showed that 3½-year-olds were significantly more accurate and responded significantly faster on prepotent trials than on inhibitory trials, suggesting that the ECITT still represents an inhibitory challenge for 3½-year-olds. However, performance is much improved from infancy (10-months) and early toddlerhood (16-months), as 3½-year-olds were significantly more accurate, responded significantly faster, and showed better response inhibition performance (accuracy inhibitory score) than at previous assessment points. Results indicated a larger improvement in accuracy on inhibitory trials compared to prepotent trials, reflecting children's improving response inhibition skills from infancy to early childhood. There was a larger improvement in reaction time on prepotent trials compared to inhibitory trials, suggesting an overall increase in children's processing speed, that is hindered by the inhibitory demand. This improvement in inhibitory performance was evident despite the difficulty of the ECITT being increased (faster stimulus presentation) between 16-months and 3½ years. As predicted, there were no significant longitudinal associations between performance in infancy and toddlerhood and performance at 3½ years.

Regarding the fNIRS analyses, it was found that channels covering the right inferior parietal cortex and the right IFG were significantly more active when inhibition was required. Additional channels (covering the bilateral DLPFC and the left OFC) were identified as showing significant block type effects in the opposite direction than expected such that activation was greater in control conditions (where there is no inhibitory demand) than in experimental (inhibitory demanding) conditions. Overall, the neural substrates of response inhibition appear to transition from right-localised regions of the DLPFC, OFC and parietal cortex at 10-months, to more widespread bilateral activation across prefrontal regions at 16-months. In early childhood, the neural correlates overlap with regions identified at 16-months, with two channels covering the right inferior parietal cortex and the right IFG being recruited when inhibition was required at both 16-months and 3½ years. This could be evidence for further maturation of the response inhibition network between toddlerhood and preschool age. However, more dorsal areas of the left and right DLPFC (and possibly midline) were also activated at 3½ years, although this activation appears not to be

associated with the response inhibition demands of the task and needs to be explored further.

6.2. Response Inhibition Development from Infancy to Early Childhood

Previous work with 10-month-old infants (Chapter 4; Fiske et al., 2022; Hendry et al., 2021), 16-month-old infants (Chapter 5; and Hendry et al., 2021), and 18-, 24- and 30-month-old toddlers (Holmboe et al., 2021) has established that the ECITT is a reliable measure of response inhibition for use in infancy and early childhood. The results of the current study replicated the condition effects found in this previous research, which shows that 3½-year-olds are significantly more accurate and respond significantly faster on prepotent trials than on inhibitory trials. This demonstrates that the preschool version of the ECITT (more difficult task due to faster trial presentation) still provides an inhibitory demand for 3½-year-olds, and as such, is an appropriate response inhibition task for this age group.

When investigating performance differences between the behavioural and blocked versions of the ECITT, it was found that participants were significantly more accurate and responded significantly faster on the blocked ECITT (Session 2) than on the behavioural ECITT (Session 1). There was also a larger difference in reaction time between trial types (faster on prepotent trials than on inhibitory trials) on the blocked ECITT than on the behavioural ECITT. This could be because of differences in the task design between the two versions. For example, in control blocks of the blocked ECITT, 3½-year-olds learn that they can respond very quickly (without an accuracy penalty) since these blocks only contain prepotent trials – as such, responses on prepotent trials are faster. Whereas, in experimental blocks (mixed prepotent and inhibitory trials) and in the behavioural ECITT (where trial types are presented pseudorandomly), children needed to respond more slowly on both trial types to keep making accurate responses. Additionally, performance differences between sub-samples (those with and without valid fNIRS data) were examined. It was found that whilst there were no accuracy differences between groups, participants who contributed valid fNIRS data responded significantly faster than those who did not. Specifically, participants who contributed valid fNIRS data were significantly faster on inhibitory trials, which could suggest that participants who contributed valid fNIRS data had better inhibitory performance (as measured by reaction time). However, this is the first time in this series of studies (Chapters 4 – 6) whereby potential differences in inhibitory performance between groups have emerged.

Additionally, performance changes from infancy (10-months, 16-months) to early childhood (3½ years) were examined. Results showed that whilst accuracy in both trial types did not significantly improve across the transition to toddlerhood, there was a significant

improvement from infancy and toddlerhood to 3½ years on both inhibitory and prepotent trials. Of note, there was a larger accuracy improvement on inhibitory trials (compared to prepotent trials), suggesting that, whilst young children are generally more accurate on prepotent trials than infants and toddlers, there is a larger improvement in their inhibitory skills across this early developmental period (as also found by Holmboe et al., 2021).

Regarding reaction time change from 16-months to 3½ years, results indicated that 3½-year-olds made significantly faster responses than at 16-months, and again there was a larger reaction time improvement on inhibitory trials. This suggests that 3½-year-olds were significantly more accurate and responded significantly faster than at any other assessment point and that there was a larger improvement in accuracy on inhibitory trials but a larger improvement in reaction time on prepotent trials. This could be reflective of a speed-accuracy trade-off at 3½ years, where children are better able to slow down their responses on inhibitory trials to avoid errors, whereas 16-month-olds are still responding more impulsively. This finding aligns with research by Wiebe et al. (2012) with 3 – 5 year-olds who found that better performance on the Fish & Sharks (Go / No-Go) task was related to slower responding in younger children, but with faster responding later in this developmental period. Based on this finding, it could be predicted that future research with 3 – 5-year-olds would observe improved response time on inhibitory trials of the ECITT across this period of early childhood. However, it is worth considering that the current study did not examine associations related to individual differences in reaction time performance (only accuracy), and that reaction time measures may contain important information about processing speed that may relate to individual differences in inhibitory control (Hendry et al., 2016). Future research should examine associations between inhibitory reaction time (or a reaction time difference measure) on the ECITT and performance on the other inhibitory control tasks at 3½ years to further investigate the interplay between speed and accuracy.

This study also examined stability in individual performance differences from infancy (10-months, 16-months), however, no significant associations were found. Since few studies have found evidence of stability before 18-months (Holmboe et al., 2021) and most evidence supports stability in individual performance differences has previously from around 24-months (Broomell & Bell, 2022), it was not expected that performance would be significantly correlated from infancy to early childhood.

Overall, it can be seen from the data presented in this chapter, and also in Chapters 4 and 5 of the current thesis, that the ECITT is a useful tool for the measurement of response inhibition from its emergence in infancy and as it develops across early childhood. The results of the current study have begun to demonstrate the developmental trajectory of

response inhibition across this period, with improvements in accuracy and reaction time from 16-months of age. Future research is already planned that will use the ECITT with another cohort of participants at 24- and 30-months of age such that changes in response inhibition performance can be examined in the toddler years, from which point performance stability would be expected.

6.3. The Neural Correlates of Response Inhibition from Infancy to Early Childhood

Until now, there has been a significant gap in the literature where very little is known about the neural correlates of response inhibition in the first years of life. Much of the existing knowledge was contributed by electroencephalography (EEG) studies that highlighted the important role of the PFC, particularly the DLPF(Bell et al., 2007; Bell & Fox, 1992; Cuevas, Swingler, et al., 2012; Fox & Bell, 1990)et al., 2012; Fox & Bell, 1990). The fNIRS findings from Chapter 4 of this thesis (Fiske et al., 2022) contributed new knowledge that pinpointed right lateralised regions of the PFC (specifically the right DLPFC and OFC) and parietal cortex as key neural substrates of response inhibition already in the first year of life.

Less is known about the neural correlates of response inhibition in toddlerhood (the second and third years of life). However, fNIRS research by Kerr-German et al. (2022) using a 'hot' inhibitory control task (inhibition in an affective context) with 2½-year-olds found an association between better task performance and stronger functional connectivity between the left frontal and left parietal cortex, as well as between the bilateral parietal cortex. It could be that functional interactions between brain regions play a key role in the maturation of the neural substrates of inhibitory control in the early years. Planned connectivity analyses using the data presented in this current study (and in Chapters 4 and 5) will extend our current understanding of what maturation means in the context of brain regions underpinning early inhibitory control development. The research presented in Chapter 5 of this thesis similarly demonstrated the increased involvement of the left hemisphere alongside the recruitment of the right hemisphere when inhibition was required. Specifically, results highlighted the involvement of channels overlying the left superior parietal gyrus, the right IFG, the bilateral DLPFC and the bilateral OFC when there was an inhibitory demand. Importantly, there was some consistency in the recruitment of two channels covering the right DLPFC and right OFC at both 10- and 16-months, suggesting that these regions of the PFC continue to play an important role in response inhibition across the transition to toddlerhood. Overall, the involvement of bilateral regions of the frontal and parietal cortices appears to be an important developmental milestone in the maturation of inhibitory control in the second year

of life, however, it remains a key priority for future research to continue to investigate the neural correlates of inhibitory control in toddlerhood before this can be confirmed.

In early childhood, some fNIRS evidence exists that continues to highlight the important role of the left hemisphere, particularly the left DLPFC in inhibitory control performance in 3- to 5-year-olds (Li et al., 2017). Moreover, there is evidence that suggests that the continued maturation of the bilateral frontal-parietal brain network is fundamental for the development of improved response inhibition performance from 4- to 6 years (Mehnert et al., 2013). Similarly, in slightly older children (6 – 10 years), fMRI research by Durston et al. (2002) found increased activation in the bilateral OFC, the right parietal cortex and the right DLPFC during inhibitory demanding trials, but importantly noted that activation in these areas was greater for children than for adults. The evidence presented in the current chapter demonstrated that 3½-year-old children recruited the right inferior parietal cortex and the right IFG when inhibition was required on the ECITT. Whilst there were no specific channels that were consistently activated at both 10-months and 3½ years, there was consistency in the recruitment of the right IFG and the right parietal cortex (although note that at 10-months activation was localised to slightly more dorsal regions). The specific channels identified at 3½ years were more closely overlapping with specific channels identified at 16-months, with Channel 8 (right inferior parietal) and Channel 31 (right IFG) being recruited when inhibition was required at both 16-months and 3½ years and the addition of Channel 7 (right inferior parietal cortex; adjacent to Channel 8) also being recruited at 3½ years. The consistent recruitment of these right-lateralised brain regions across infancy and early childhood may be indicative of the maturation of the neural system that underpins early response inhibition.

Finally, in their review of the literature across the lifespan, Kang et al. (2022) propose that a reconceptualization of inhibitory control is necessary such that future research efforts consider the role of key frontal-parietal networks as underpinning inhibitory control development, rather than focusing on identifying the development in individual brain regions. As such, it is clear that future research is needed that adopts functional connectivity approaches to better understand the formation and strengthening of brain networks in frontal and parietal cortices that support the maturation of inhibitory control from infancy and into adulthood. Until then, the current thesis contributes new knowledge in highlighting the longitudinal change in the recruitment of regions of prefrontal and parietal cortices when inhibition is required on the same task from infancy to early childhood, providing an important foundation from which future research can be conducted with early developmental populations.

6.3.1. Unexpected Findings at 3½ years

In this current study, there were also some unexpected findings related to neural activation in brain regions that were *not* associated with inhibitory processes. For example, Channel 29 (overlaying the left OFC) was found to be more active (compared to baseline) in blocks where there was no inhibitory demand, therefore showing the opposite effect than expected. This channel also showed an inverted HRF, such that the HHb signal showed an increase from baseline whereas the HbO_2 signal showed a decrease from baseline. As such, it is very challenging to interpret this activation. In the Discussion section of Chapter 4 of this thesis, I proposed that the involvement of the OFC may be linked to perseveration (i.e., the failure to inhibit), and hypothesised that, if this was the case, there would be a reduction in the recruitment of the OFC as inhibitory skills improve with age. At 10-months, activation was found in the right OFC when inhibition was required, and at 16-months, activation was found in the bilateral OFC when inhibition was required. Just as there was no significant change in inhibitory performance from 10- to 16-months, there was also no change in recruitment of significant channels covering the OFC from 10- to 16-months. As such, it is possible that this consistent OFC recruitment during experimental blocks of the ECITT in infancy and toddlerhood reflects perseveration. Although it may be that the OFC activation in infancy and toddlerhood is related to perseveration, it appears that the role of the OFC in the ECITT changes by 3½ years. Since there was no recruitment of the right OFC and activation in the left OFC was larger in control blocks, it is clear that left OFC activation at 3½ years is not related to perseveration (unlikely in control blocks where participants have very high accuracy on average), or to the response inhibition demand of the ECITT since there is no inhibitory demand in control blocks. Nonetheless, it is important that this finding is replicated in future studies before OFC activation can be properly understood in relation to the ECITT.

Additionally, Channels 18, 43 and 45 overlaying the bilateral DLPFC were also found to be more active (compared to baseline) in blocks where there was *no inhibitory demand*. The DLPFC has been commonly accepted as a neural substrate of response(Bunge et al., 2002; Diamond & Goldman-Rakic, 1989; Durston et al., 2002, 2006; Rubia et al., 2006)2002, 2006; Rubia et al., 2006a), and indeed the results presented in this thesis also found that the DLPFC was recruited by 10-month (right DLPFC) and 16-month-old infants (bilateral DLPFC) when there was an inhibitory demand. However, at 3½ years it appears that the bilateral DLPFC still plays an important role during the ECITT, but this role may not be related to the inhibition of a prepotent response. I will now discuss some potential explanations for these unexpected findings in the left OFC and bilateral DLPFC at 3½ years.

The first possible theory is that, unlike infants and toddlers, 3½-year-old children are exerting proactive control during control blocks (where there is no inhibitory demand). According to

Braver (2012), top-down proactive control supports the maintenance of task goals in preparation for upcoming task requirements which have a higher cognitive demand (such as the need to inhibit responses in the experimental blocks of the ECITT). The DLPFC has been evidenced to be a key neural substrate in proactive control (Aron, 2011; Hwang et al., 2014, 2016). This is opposed to reactive control, which is bottom-up control prompted by the presence of stimuli to be inhibited. Although reactive control still involves the DLPFC, the involvement is more transient and less robust as wider brain regions are additionally recruited in support of reactive control (e.g., the anterior cingulate cortex and parietal regions) (Braver, 2012). As such, it may be there is a larger involvement of the DLPFC for 3½ year-olds (but not infants and toddlers) because they are engaging in other cognitive processes (e.g., working memory, monitoring) to support them in maintaining task rules in control blocks in preparation for the more challenging experimental blocks (Chatham et al., 2012). This theory is supported in a review by Chevalier (2015) which proposes that the development of EF in children comes with the increased recruitment of proactive control processes to effectively meet task demands (see also, Chevalier, Bailey Martis et al., 2015). Constantinidis & Luna (2019) propose that a key process in the development of inhibitory control from adolescence into adulthood is the neural activation that occurs in the DLPFC ahead of the inhibitory stimulus. As such, it may be that 3½ year-olds are already engaging in rudimentary proactive control processes that represent a pivotal milestone in the development of mature inhibitory control.

A second potential explanation could be that 3½-year-olds actually have to inhibit *more* during control blocks than experimental blocks. This is because, by 3½ years, the cognitive and motor demands required during control blocks are minimal. As such, it may be that young children are actually having to work harder to inhibit distraction and maintain engagement on the task to respond repeatedly to the same type of trial (prepotent) than when they are required to inhibit a prepotent response in experimental blocks. Therefore, this inhibitory process to ignore distractors may be activating the bilateral DLPFC and left OFC more during control blocks, compared to experimental blocks where children are inhibiting a prepotent response, as their response inhibition skills are now much improved (compared to infancy). This could be a further indication of proactive control processes that young children are engaging in during this task to maintain focus on the task requirements. Whilst research into pre-school aged children's task engagement in laboratory settings is limited, a study by Halliday et al. (2018) found evidence for six factors that underpin task engagement in preschool children, many of which could be argued to require executive processes. This includes attention to instructions, on-task behaviour, persistence, and monitoring progress / strategy use (Halliday et al., 2018). It would be difficult to examine

within the current data whether children were engaging in these inhibitory processes to maintain engagement in the control conditions, but future research that examines the link between task engagement (particularly when task demands are low) and inhibitory control would help shed light on this potential explanation for the increased DLPFC and OFC activation during control conditions at 3½ years.

Relatedly, it could be that the low cognitive and motor demands of the control block allows more mental capacity for the engagement of other cognitive processes that may engage the DLPFC, such as episodic memory. Specifically, it could be that the animations after every correct trial might elicit memories or relevant prior knowledge in the child's mind. For example, seeing the animation of a flower may trigger an episodic memory related to being in the garden with Grandma planting flowers, or the animation of an elephant may elicit a memory of seeing an elephant at the zoo at the weekend. Research has pointed to the DLPFC as having a key role in integrating episodic memory into working memory (Balconi, 2013; Brand & Markowitsch, 2008), and so it is plausible that DLPFC activation during control condition could be reflective of interactions between episodic and working memory. Although very little evidence exists that examines the neural correlates of episodic memory in preschool aged children, there is behavioural evidence that suggests that the pre-school years are an important period for the development of episodic memory retention (Scarf et al., 2013), and even some evidence to suggest the emergence of episodic-like memory skills already in toddlerhood (Newcombe et al., 2014).

It is also worth considering how 'distraction' plays a role in both of the above explanations of the DLPFC and OFC activation in control conditions. Firstly, it is clear that to maintain focus on the task during "easy" control conditions, young children must exert inhibitory control to ignore distractors in the environment. Secondly, if the minimal task demands mean there is more capacity for episodic memories to be triggered and brought forward into working memory, there is also the requirement to use inhibitory control in attempt to suppress these memories. Perhaps these additional executive or meta-cognitive processes (that are not involved in infancy due to the more challenging nature of the task for that age-group, and their limited language skills) are related to the switch from reactive to proactive control that occurs in early childhood (Chevalier et al., 2015), as discussed above.

Finally, it could be that the DLPFC activation in control blocks at 3½ years is related to "off-task" thought. Research by Turnbull et al. (2019) investigated the context regulation hypothesis, which proposes that there is a control process that both exerts control when task demands are high (e.g., to reduce goal-irrelevant thought, minimise interference from distractors, and maintain focus on the goal), and that allows off-task thoughts when there is

no clear task goal, or the task is non-demanding. The results of this fMRI study with adult participants demonstrated that DLPFC activation is high during both on-task (demanding) conditions and off-task (non-demanding) conditions (Turnbull et al., 2019). However, research is limited as to whether young children engage in “off-task” thought. Not only is this difficult to measure, but young children are also often unreliable when it comes to reporting what they had been thinking. Whilst some research exists into private speech in pre-schoolers (e.g., observing children’s self-talk during activities in the preschool classroom; (Winsler et al., 2003)), there appears to be limited evidence about internalised speech or thoughts in early childhood. Although, a recent study by (C et al., 2024) investigated mind-wandering (or off-task thought) in 4 – 6 year olds and found evidence to suggest links between mind wandering and sustained attention, processing speed, cognitive flexibility, and inhibition. As such, it may be that there are important links between EFs and mind-wandering / off-task thought in young children, however, it is not possible to test this in the current study. Until such time that reliable measures of mind-wandering can be evaluated with children under 4 years of age, it is not possible to know whether mind-wandering could be the cause of the DLPFC and OFC activation found in the current study.

Overall, these post-hoc theories offer potential explanations for the larger DLPFC and OFC activation found in control blocks of the ECITT, as these blocks have very minimal demands, no time limitations, and are generally very easy for 3½-year-olds, and so allows more time and space for ‘off-task’ thought and the engagement of other cognitive processes. To test these theories, future research using the ECITT with 3½-year-olds should impose a time demand on trials by asking participants to “respond as quickly as possible and try not to make any mistakes” (although this can be risky with young children who may interpret this as an invitation to tap the screen quickly and repeatedly without much thought). Also, the presentation order of blocks could be randomised, such that they cannot be predicted. In this way, it would be expected that the activation seen in the DLPFC in the current study may not be found if the block order was randomised. This is because the child cannot predict whether the next block is a control or experimental block, so the need for proactive control would be the same across all blocks. As such, the task demands in control blocks would increase, leaving less space for ‘off-task’ thought. Nonetheless, more research is needed to examine the functional neural substrates of proactive and reactive control processes in early childhood to support our understanding of specific facets of control and the underlying brain regions supporting the exertion of inhibitory control.

6.4. Limitations and Future Directions

A major limitation of the current study (as in the previous experimental chapters) is that many of the significant effects reported in the fNIRS analyses did not survive the procedure for controlling the FDR (Benjamini & Hochberg, 1995), and so should only be considered as preliminary until they can be replicated in future research. Similarly, there was a lack of statistical power for the longitudinal analyses due to the large amount of attrition at the 16-month assessment point (due to necessary lab closures during the pandemic) and the sample size at 3½ years being smaller than intended likely due to the (unplanned) length of time between assessment points. Nonetheless, rigorous protocols were put in place to ensure that transparent scientific procedure was followed in this study, such as pre-registering the hypotheses and analysis plans in great detail and taking a stringent multiple comparisons correction approach to minimise the risk of Type I errors. Future research is needed that replicates these results in larger samples before firm conclusions can be drawn about the implications of the current findings.

A second limitation is the use of the same head model for optode localisation and image reconstruction purposes at 3½ years as was used previously at 10- and 16-months. Whilst it cannot be ignored that significant changes in head size and structural brain development occur from infancy to early childhood, it was decided that the use of the same head model (12-month AAL atlas; Shi et al., 2011) would be beneficial to enable consistency between assessment points such that more reliable developmental comparisons could be made as the channel localisation remains relatively consistent across studies. However, it is worth noting that some of the subtle changes in which channels are activated (such as activation moving to a neighbouring channel) could be due to the changes in head size at 3½ years. Further, it was difficult to find an atlas with suitable parcellation for 3½-year-olds that could achieve a similar parcellation to that with the infant atlas, so it was not possible to choose an age-matched atlas. Though structural MRI scans from our sample would have been the ideal choice for the most accurate optode localisation, this was not something that had been planned within the current study as it was not feasible due to the high cost of MRI. Following a preliminary assessment using an adult atlas (AAL2; Rolls et al., 2015), it was found that a large proportion of channels were located in different cortical areas (compared to infancy) and whilst some change was expected, the change was considered too substantial. Further, upon careful inspection of the adult-based locations and images of the probe placement on an adult head model, it was collaboratively decided that the use of an adult atlas with this young population was not appropriate. Future research is needed both in the development of freely available MRI atlases with appropriate parcellation for developmental populations, and also to account for the change in head size and brain structure and anatomy in early

developmental longitudinal research (although note that a possible solution has recently been proposed by Magee et al., 2023).

The exclusion of several channels covering the parietal cortex, particularly at 3½ years but throughout all assessment points, means that this research may be missing important information about changes in the recruitment of the parietal cortex during inhibitory processes across early development. These exclusions occurred to ensure that fNIRS data were of high quality, and it is likely that the poor signal in these parietal channels is related to poor scalp-optode coupling as a result of the position of the optodes on the curve of the head and because of hair thickness in this area. Efforts should be made in future research to optimise the coupling of parietal optodes. Additionally, it is worth highlighting that although the study presented in the current chapter is longitudinal, there was a large amount of attrition between assessment points and significant data exclusion at each assessment point. As such, the number of participants who contributed valid behavioural and/or fNIRS data to at least two assessment points is fairly low. To look at true longitudinal stability and change over time, a much larger sample of participants who contributed valid fNIRS data to at least two assessment points would be needed. As such some of the longitudinal analyses presented in the current study, particularly where fNIRS data is involved, are in a way partially cross-sectional and should be replicated in future longitudinal studies.

Finally, whilst the current research begins to map out a developmental trajectory of response inhibition and the associated neural correlates from infancy and across early childhood, future research is needed to provide the full picture of development across the lifespan. For example, the crucial toddler years (e.g., the second and third years of life) were unfortunately missed from the current longitudinal study due to the onset of the pandemic. However, there is currently a significant gap in knowledge about how EF skills such as response inhibition develop across this period, and less is known about the recruitment of neural regions during this period. Similarly, whilst the data presented in this chapter describe the behavioural performance and neural correlates of response inhibition at the start of early childhood (3½ years), knowledge is lacking about what happens after this point as response inhibition skills continue to mature across childhood and adolescence. Research that uses the ECITT alongside fNIRS with adult participants would provide clear evidence of the neural correlates of mature response inhibition in adulthood and would enable us to better understand the developmental trajectory of response inhibition from infancy. With future research that provides these missing puzzle pieces, combined with the knowledge contributed from the research presented in this thesis from infancy and early childhood, it would be possible to establish a full developmental trajectory (at least for the ECITT) of response inhibition and the associated neural correlates across the lifespan.

6.5. Strengths and Implications

Despite the sample attrition discussed in the previous section, the longitudinal data presented from the three assessment points across infancy and early childhood is nonetheless a substantial and informative dataset that will be extremely valuable to the field. Not only has this dataset enabled the investigation of developmental change across this currently under-studied period of early life, but it has also contributed new knowledge about the neural correlates of response inhibition from its emergence in infancy and as it matures into early childhood. Whilst the fNIRS results presented here are preliminary and will require replication, the contributions of this new knowledge will provide a solid foundation from which future research studies into the neural correlates of early inhibitory control can be conducted.

An additional strength of this study was that the experimental paradigm and methodological approach remained the same across all assessment points, except for a simple necessary modification to the pace of the ECITT to be appropriate for the 3½-year-old children. Due to difficulties in finding inhibitory control tasks that are suitable for use with infants and young children, it is very rare for longitudinal studies to continue to use the same task across assessment points spanning infancy and early childhood. The research presented in this chapter (and Chapters 4 and 5 of this thesis) has demonstrated that the ECITT is an appropriate and reliable measure of response inhibition from as young as 10-months of age (Chapter 4; (Fiske et al., 2022; see also, Hendry et al., 2021), can continue to be used in early toddlerhood (Chapter 5) and, with minor modification, is also a reliable measure of response inhibition at 3½ years of age (Chapter 6). The benefit of maintaining task consistency across the assessment points was the increased confidence that the changes in response inhibition performance observed over infancy and early childhood were due to age-related developmental improvements, rather than a methodological artifact related to different task demands. For example, I am more confidently able to interpret the lack of significant association in performance across assessment points as being due to developmental change, rather than associations potentially being masked by changes in task or response modality between assessment points. Similarly, I can be confident that the changes observed at the neural level cannot be due to task-related factors, particularly between 10- and 16-months when the task was identical, and performance did not change. Finally, by also keeping the fNIRS methodology identical between assessment points (i.e., same cap, same processing pipeline, same head model for optode localisation), more reliable comparisons of change in neural activation can be made across assessment points, something that has rarely been done (particularly with the same cohort of participants and the same manual response task) in the early developmental fNIRS literature. As such, the research presented in Chapters 4 – 6 of this thesis has provided new knowledge about the

developmental trajectory of response inhibition and the associated neural correlates in the first four years of life.

7. Conclusion

The current study presents novel longitudinal data on the age-related changes in neural correlates of response inhibition from infancy and across early childhood. Whilst response inhibition in late infancy appears to be supported by right-lateralised regions of the prefrontal and parietal cortices, the transition to toddlerhood sees the recruitment of bilateral prefrontal regions and of the left parietal cortex to support response inhibition, despite there being no behavioural improvements in response inhibition across this period. At the start of early childhood, a clear improvement in response inhibition performance is observed yet there are some brain regions consistently recruited by infants and young children alike, specifically the right inferior parietal cortex and the right IFG. This consistent recruitment suggests that these brain regions are fundamental neural indices of inhibitory control, even from infancy when inhibitory skills are emerging. Overall, whilst results are preliminary and require replication, the findings from the current study contribute exciting new knowledge about the neural correlates of response inhibition across the early years of life and begin to piece out the trajectory from the emergence of rudimentary skills in infancy to a mature process in adulthood.

Chapter 7

'Hot' and 'Cool' Inhibitory Control in Infancy and Early Childhood: Longitudinal Associations and Contributions to Pre-Academic Outcomes

The study presented in the current chapter reports on data collected in the final wave of the OEEF longitudinal study when children were 3½ years of age. This study aims to examine both within-age and longitudinal associations between 'hot' and 'cool' inhibitory control tasks in infancy (at 10- and 16-months) and early childhood (3½ years). Additionally, this study aims to examine the concurrent associations between early childhood inhibitory control and pre-academic outcomes at 3½ years and the potential longitudinal associations between infant inhibitory control and pre-academic skills.

The research questions, hypotheses, key variables, and analysis plans associated with the current study were pre-registered on the Open Science Framework before analysis. The co-author of this pre-registration has permitted the content to be used in the context of the current thesis.

1. Background

As discussed in previous chapters, researchers have been relatively limited by the availability of suitable tasks for the assessment of both 'hot' and 'cool' inhibitory control in infancy. In this way, the longitudinal examination of inhibitory control from infancy to early childhood has been hindered by the need to use different measures with infants and young children (to ensure the task is a valid assessment of inhibitory control in that age group). As such, research that has examined longitudinal associations between 'hot' and 'cool' indices of inhibitory control in infancy and early childhood is limited (although studies exist that examine these associations at the same age (Di Norcia et al., 2015) or from early to middle childhood (Draperi et al., 2022)). As such, the study reported in this current chapter will investigate concurrent and longitudinal associations between measures of 'hot' and 'cool' inhibitory control measured in infancy (10- and 16-months) and early childhood (3½ years). Since the measures used in the current study were designed to be as structurally similar as possible at each assessment point, it is possible to examine change in, and associations

between, ‘hot’ and ‘cool’ inhibitory control performance whilst keeping the task demands as constant as possible when assessing the same construct.

Additionally, it is well-understood that EF skills such as inhibitory control have important links with a range of childhood outcomes, including school readiness (e.g., Blair & Raver, 2015; Mann et al., 2017) and academic achievement (e.g., Becker et al., 2014; Blair & Razza, 2007; Bull & Scerif, 2001). Research has identified that EFs measured at age 2 are strongly associated with early mathematics and literacy skills at 5 years of age (Mulder et al., 2017). However, since very little is known about the emergence of inhibitory control in infancy, no previous research exists that investigates the potential predictive association between infant inhibitory control and later childhood outcomes, such as early academic skills. As such, the current study aims to address this gap in the literature by contributing new knowledge about the relations between early inhibitory control and pre-academic outcomes in early childhood.

There has been a recent line of enquiry that has investigated the differential associations between ‘hot’ and ‘cool’ inhibitory control and early academic outcomes (Brock et al., 2009; Kim et al., 2013; Mulder et al., 2014; Willoughby et al., 2011). As a brief recap, ‘hot’ inhibitory control refers to affective control and regulation, often measured in early development using delay of gratification tasks (Kochanska et al., 2000; Mischel et al., 1989). In their influential study, Friedman et al. (2011) demonstrated that ‘hot’ inhibitory control measured using a delay of gratification task in toddlerhood (14 – 36 months) predicted individual differences in EF skills in adolescence. ‘Cool’ inhibitory control refers to more abstract recruitment of cognitive control abilities, often measured using age-appropriate response inhibition tasks such as the Go / No-Go task (Howard & Melhuish, 2017) and has shown considerable links with academic outcomes, particularly in the field of mathematics (Bull & Scerif, 2001; Cragg & Gilmore, 2014; Mulder et al., 2017). Research by Mulder et al. (2014) with two-year-olds has shown that measures of ‘cool’ EF were significantly associated with pre-academic skills one year later and that measures of ‘hot’ EF (delay of gratification) predicted behavioural problems, but not pre-academic skills. This result was also found in research by Kim et al. (2013), where children’s effortful control was measured in early childhood (38- and 52-months), and their behaviour problems and academic skills were rated by parents and teachers when the child was 5, 6, and 8 years of age. Results of this study found that whilst performance on ‘hot’ tasks predicted behaviour problems (but not academic skills), performance on ‘cool’ tasks predicted academic performance (but not behaviour problems).

The current pre-registered study will investigate the influence of ‘hot’ and ‘cool’ measures of inhibitory control – both in infancy and in early childhood – on the emergence of early language and mathematic skills assessed at 3½ years of age. This line of research may

have many important implications for researchers and practitioners in early childhood education, as well as those interested in supporting cognitive development in the early years of life. Research in the first years of life will pave the way for the possible early identification of children who may go on to have later academic difficulties *before* they enter the classroom.

2. Method

2.1. Participants

This study includes longitudinal data from the 10-month (*N* = 141), 16-month (*N* = 75), and 3½ year (*N* = 93) assessment points of the OEEF study. Full demographic information for the participant sample at each assessment point is available in Chapter 2 of this thesis. Five participants were excluded due to not meeting the longitudinal study inclusion criteria. Additional participants (who had not previously been involved in the study) took part in pilot test sessions at 3½ years (*N* = 30) and are included in the current 3½ year sample. As such, the 123 participants at the 3½ year assessment point were comprised of 93 longitudinal participants and 30 pilot participants. Pilot participants included in this sample completed the tasks under the same administration protocol as used in the longitudinal study. See 'Task-level Exclusions' below for details about exclusion criteria and the final number of participants that contributed valid data to each task.

Ahead of the 3½ year assessment point, participants who had previously taken part in piloting at 10-months and/or 16-months were invited back to participate in pilot test sessions. It was stated in the pre-registration that data collected from pilot participants at the 10-month assessment point (*N* = 7) and the 16-month assessment point (*N* = 6) would only be included in longitudinal analyses, as data from the pilot sample in infancy have already been analysed and published in Hendry et al. (2021). However, it was decided that since this was only a small sub-sample of overlapping data, these participants would be included in all analyses.

2.2. Tasks, Procedure, and Variables

2.2.1. Infant Hot Inhibitory Control Tasks

At the infant assessment points (10-months, 16-months) two 'hot' inhibitory control tasks were used to assess infants' ability to follow a prohibition. For both tasks, infants were seated on the lap of their caregiver at the side of a rectangular table adjacent to the

experimenter, who sat at the head of the table: see **Figure 1** below. For both tasks, latency to touch was the dependent variable (maximum of 30 seconds) which was calculated from offline video coding of the tasks. Information about inter-coder reliability is available in Hendry et al. (2021).

In the Toy Prohibition task (Friedman et al., 2011), the experimenter showed the infant an attractive toy (a light-up glitter wand) that had previously been out of sight, and said "[Child's name], don't touch it – no". The glitter wand was then immediately placed on the table in front of the child (within their reach) and the experimenter looked away from the infant and the toy. If the infant had not already touched the glitter wand, the experimenter would give prompts at 30 seconds ("It's ok, you can touch it now"), 35 seconds ("You can touch it"), and 40 seconds ("Let's see what happens when we touch it", then demonstrating by touching the toy). The task was stopped if the infant had still not touched the toy after 45 seconds. See here for a video of a 16-month-old infant completing the glitter wand task (caregiver consented).

The Touchscreen Prohibition task is similar to the Toy Prohibition task. However, the attractive object is an animated frog on a touchscreen device (Apple iPad; vertical configuration). The experimenter held the iPad (blank at first) in sight of the infant and once they had the infant's attention, pressed a button so that a brightly coloured animated frog 'hopped' to the centre of the screen. The experimenter pointed to the frog and said "[Child's name], don't touch it – no." and immediately put the iPad on the table in front of the infant and looked away from the infant and the touchscreen. Once the frog was touched, it made a "quack" sound and hopped to another location on the screen. If the infant had not already touched the frog, the experimenter gave prompts at 30 seconds ("It's ok, you can touch it now"), 35 seconds ("You can touch it", pointing at the frog), and 40 seconds ("Let's see what happens when we touch it", then demonstrating by tapping the frog). The task was stopped if the infant did not touch the frog after 60 seconds. Infants were considered to have broken the prohibition if they touched the frog on the screen, anywhere else on the iPad, or the iPad case. See here for a video of a 16-month-old completing this task (with caregiver consent).

2.2.2. Early Childhood Hot Inhibitory Control Tasks

At 3½ years, three 'hot' inhibitory control tasks were administered to examine children's ability to choose to delay gratification (Treasure Delay) and to follow a prohibition and delay gratification when told not to touch an attractive object (Gift Delay, Dinky Toys). For the Treasure Delay and Gift Delay tasks, children sat independently on an age-appropriate chair positioned at the side of a rectangular table. The experimenter sat on a chair directly

opposite the child. The caregiver was in the room, although positioned in a chair behind the child to be out of the child's sight. For the Dinky Toys task, children were sitting on their caregiver's lap positioned at a small table, adjacent to the experimenter. The caregiver was informed about the tasks ahead of the sessions and was instructed to try not to engage with the child during this time.

The Treasure Delay task is a novel task that I co-designed with an undergraduate intern (Alicia Mortimer). The task is based on the 'Less is More' task (Carlson et al., 2005) whereby children are required to choose between receiving a larger reward after a delay, or a smaller reward immediately. In the Treasure Delay task, children were told that to win the game, they must have the most treasure in their treasure chest. They were then required to choose between two trays of treasure – one with five pieces, and the other with two pieces of treasure. If the tray of five pieces was chosen, children had to wait for 30 seconds (measured using a sand timer) before they could put the treasure in their treasure chest. If the tray of two pieces was chosen, children could put the treasure in their treasure chest immediately, but they forfeit the five pieces of treasure to their pirate competitor (who does not have to wait). In this way, this task measures the ability of children to choose to delay gratification. Children's behaviour was scored on whether they chose the small tray (0) or large tray (1) on each trial (total possible score of 3). See Appendix E1 for a full description of the administration protocol and see **Figure 2** below for an image of the task administration. A video of a child completing a trial of this task (parental consent provided) is available here.

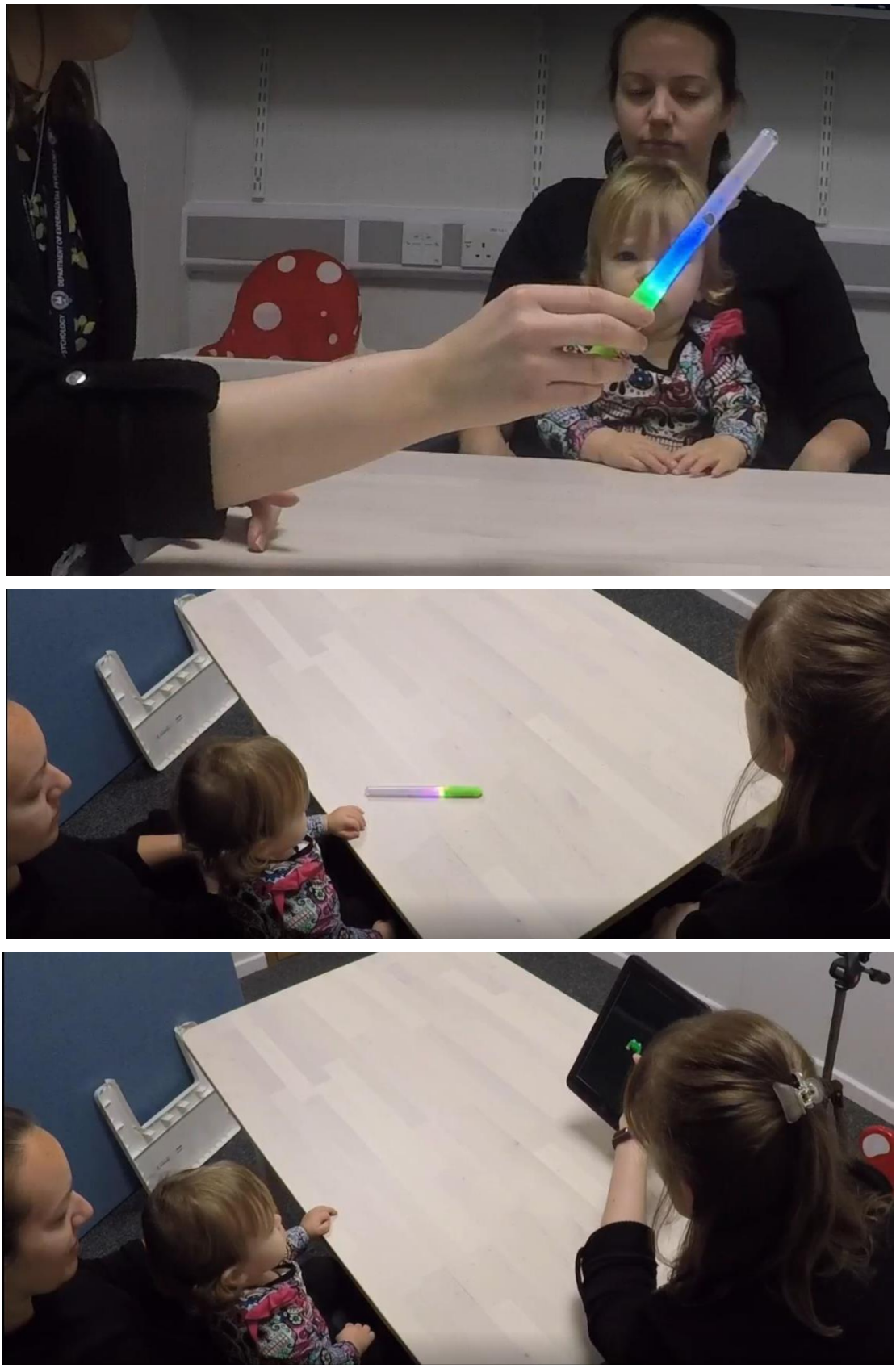
In the Gift Delay task ('Gift-in-bag' task; Kochanska et al., 2000), the experimenter showed the child a gold paper bag and explained that this was a gift for the child to "Thank [you] for playing all the games with me today". The experimenter then acted like they had forgotten something, and told the child "Oh no, I can't find the bow. I'll leave this here whilst I go and look for it". The experimenter placed the bag on the table in front of the child whilst at the same time instructing them "Try not to touch it until I come back with the bow". Note that the instruction not to touch was always given *before* the bag was placed on the table. The experimenter then left the room for 3 minutes. The child remained in the room with their caregiver and the second experimenter (who was behind a screen). Children's behaviour toward the gift bag was scored using the following criteria: did not touch the bag (5), peeked into the bag without touching it (4), touched or opened the bag to peek in (3), put hand into the bag (2), takes the gift from the bag (1), or takes the gift from the bag before the experimenter has left the room (0). If children showed multiple behaviours during the 3 minutes, the score given was based on the behaviour that scored lowest on the coding

scheme. See here for a video of the task set up and of the child completing the task (parental consent provided) and see **Figure 2** below for images from this video.

In the Dinky Toys task (Kochanska et al., 2000), the experimenter told the child that they could choose a special prize from the prize box. Children were instructed to place their hands on the table and were told “I’d like you to tell me which colour you would like, try not to touch”. The experimenter then opened the lid of the prize box and tilted the box so that the children could see inside. The box contained several small toys that were identical except in colour. Behaviour was scored using the following criteria: did not remove hands from the table (5), moves hands but on the table (4), removes hands from the table (3), points to toy (2), touches toy but does not take it out of the box (1), or takes the toy from the box (0). The task was coded as invalid if the parent interfered with the child’s behaviour (e.g., reminded them of the rule). A video of a child completing a trial of this task (parental consent provided) is available here.

Note that in both the Treasure Delay and Gift Delay tasks, children’s behaviour during the waiting period was manually coded (offline) to capture the rich range of behaviours children displayed. This information is not included in the current thesis but will form the basis of a manuscript that I hope to prepare after thesis submission, intending to investigate children’s strategy use whilst they are delaying gratification. To gain an idea of the kind of behaviours shown, see here for a video of a participant completing the Gift Delay task at 3½ years of age (with permission from the caregiver). To observe the progression in delay of gratification skills from infancy to early childhood, see here for a video of the **same participant** at 16 months old completing the Toy Prohibition task (caregiver consented).

Figure 1. Chapter 7. Infant Hot Inhibitory Control Tasks.



Note. This image shows the Toy Prohibition task (top and middle) and the Touchscreen Prohibition task (bottom) at 16-months. Images are used with caregiver consent.

Figure 2. Chapter 7. Early Childhood Hot Inhibitory Control Tasks.











Note. This image shows the Treasure Delay task (top) the Gift Delay task (middle), and the Dinky Toys task (bottom) administered at 3½ years. Images are used with caregiver consent.

2.2.3. Cool Inhibitory Control Tasks (Infancy and Early Childhood)

The Early Childhood Inhibitory Touchscreen Task (ECITT; Holmboe et al., 2021) was used to assess response inhibition ('cool' inhibitory control) at all three assessment points. This task has been described in previous chapters of the thesis. As explained in Chapter 6, the only differences between the task used at 3½ years from that used in infancy (10- and 16-months) was that the length of the animations after each trial was reduced, and 64 trials were completed instead of 32. The key variable from this task was the 'accuracy inhibitory score'.

At 3½ years of age, the Fish and Sharks task from the Early Years Toolbox (Howard & Melhuish, 2017) was also used to assess response inhibition. This task is a child-friendly version of the Go / No-Go task and requires children to touch the screen when they saw a fish, and not to touch the screen when they saw a shark. Note that the fish and sharks were animated (moved horizontally across the screen in 2500 ms), and children could press anywhere on the touchscreen for a response to be recorded (they did not have to 'catch' the moving target). Children completed two blocks of 32 trials (64 trials total), of which 75% were 'prepotent' trials (fish) and 25% were 'inhibitory' trials (shark). As such, the number of trials and proportion of prepotent and inhibitory trials is matched to the ECITT at 3½ years. The key variable for this task was the 'accuracy inhibitory score' (calculated using the 'Go accuracy' and 'No-Go accuracy' variables, like in the ECITT), such that there is a common measure to compare performance on the two 'cool' tasks.

2.2.4. Pre-Academic Skills (3½ years)

The Numbers task from the Early Years Toolbox (Howard et al., 2022) assessed preschool numerical ability. This child-friendly task was presented on an iPad (horizontal configuration) and covered a range of early mathematical skills, such as 'number sense', 'cardinality and counting', 'numerical operations', 'spatial measurement', and 'patterns'. The task started on the first trial and continued until the participant made five consecutive incorrect responses. The dependent variable was the number of correct trials across the task.

The Verbal Comprehension Index (VCI) from the standardised Weschler Preschool and Primary Scales of Intelligence, fourth UK edition (Weschler, 2013) was used as a measure of early language skills and included tests of receptive vocabulary and comprehension. The task started on the first trial and continued until the participant made three consecutive incorrect responses. The dependent variable was the 'VCI composite score' which is a standardised composite score (mean = 100, highest score possible = 160).

2.3. Task-level Exclusions

Table 1 contains details of the task-level data exclusion; note that these exclusions were pre-registered. Task inclusion criteria for the 'hot' inhibitory control tasks administered at 10- and 16-months were that data were only included if infants touched the touchscreen within 60 seconds (Touchscreen Prohibition) and if the infant was not distressed before administration (Toy Prohibition); see Hendry et al. (2021). For the Treasure Delay task at 3½ years, participants were excluded due to experimenter error (*N* = 1) or if they did not pass the post-task preference check (*N* = 10). For the Dinky Toys task at 3½ years, participants were excluded due to experimenter error (*N* = 3) or parental interference (*N* = 8). There were no exclusion criteria for the Gift Delay task. As previously discussed, the criteria for the ECITT (administered at all assessment points) was that participants must complete a minimum of 16 trials (including at least two valid inhibitory trials) and must have at least 60% accuracy on prepotent trials. Details of exclusions at 10- and 16-months are reported in Chapters 4 and 5 respectively. No exclusions were made at 3½ years as all participants met these criteria. Data were excluded from the Fish & Sharks (Go / No-Go) task at 3½ years if the data did not save (*N* = 2) or if participants did not have at least 60% accuracy on 'Go' trials (*N* = 13). The Numbers task did not have any exclusion criteria, and the only exclusion criteria for the VCI of the WPPSI was that participants needed to have completed all sub-tests that make up the VCI (*N* = 4 were excluded).

Table 1. Chapter 7. Final Sample Size Overview

Type	Task	***N*** **10-months**	***N*** **16-months**	***N*** **3½ years**
'Hot' Inhibitory Control	Touchscreen Prohibition	148	81	-
	Toy Prohibition	148	80	-
	Treasure Delay	-	-	84
	Gift Delay	-	-	122
	Dinky Toys	-	-	97
'Cool' Inhibitory Control	ECITT	128	61	119
	Fish and Sharks	-	-	103
Pre-Academic Skills	Numbers	-	-	123
	VCI	-	-	89

2.3.1. Longitudinal Data

Longitudinal ECITT data is available for 80 participants at both 10-months and 3½ years and 45 participants at both 16-months and 3½ years. A total of 36 participants contributed valid ECITT data at all assessment points. Longitudinal data from the 'hot' inhibitory control tasks administered in infancy is available at both 10- and 16-months for a total of 76 participants for the Toy Prohibition task, and a total of 77 participants for the Touchscreen Prohibition task.

3. Study Hypotheses and Analysis Approach

The research questions, hypotheses, and analysis plans were defined and pre-registered before analysis. A summary of the hypotheses and analysis plans are provided in the sections below, but for full details and justification, it is necessary to view the full pre-registration. Both confirmatory and exploratory research questions and hypotheses were registered, depending on the availability of previous evidence in the literature. Where directional hypotheses have been outlined, the evidence that was used to form the prediction is highlighted. For example, previous research by Hendry et al. (2021) used the same inhibitory control tasks in infancy (10-months, 16-months) and so some predictions were based on the findings of this study. Where it is stated that hypotheses and analyses will be exploratory (due to a lack of existing evidence and novel research questions being asked about longitudinal predictions from infancy to early childhood), the variables and measures that will be used to investigate these exploratory research questions have been clearly defined.

As a reminder, the 'cool' inhibitory control tasks used in this study were the ECITT (all assessment points), and the Go / No-Go task (3½ years). The 'hot' inhibitory control tasks used in this study were the Touchscreen Prohibition and Toy Prohibition tasks (infancy) and the Gift Delay, Treasure Delay, and Dinky Toys tasks (3½ years). In accordance with the pre-registration, if performance on the two 'hot' inhibitory control tasks is significantly correlated within-age at 10- and/or 16-months, and if performance on the three 'hot' inhibitory control tasks is significantly correlated within-age at 3½ years, the scores will be combined into a composite 'hot inhibitory control' measure for each assessment point where the correlation is significant.

3.1. Pre-registered Hypotheses

Please see the 'Hypotheses' section of the pre-registration for full justifications and explanations about the study hypotheses, which are summarised below in **Table 2** (within-

age inhibitory control associations), **Table 3** (longitudinal inhibitory control associations), **Table 4** (exploratory longitudinal inhibitory control associations), **Table 5** (within-age associations with early academic outcomes), and **Table 6** (exploratory longitudinal associations with early academic outcomes).

Table 2. Chapter 7. Hypotheses for Within-Age Inhibitory Control Associations.

Hypothesis	Explanation	Rationale / Background
H1: There will be a significant correlation between performance on the Touchscreen and Toy Prohibition tasks at both 10- and 16-months.	Hypotheses are based on the findings of Hendry et al. (2021)	I expect to replicate these findings in the current sample (same ages, same tasks)
H2: It is not expected that there will be a significant correlation (with effect size greater than $r = 0.30$) between performance on the ECITT and: a) the Touchscreen Prohibition task at either 10- or 16-months b) the Toy Prohibition task at 16-months*		
H3: Is there a significant correlation between performance on the ECITT and the Go / No-Go at 3½ years of age? [a]	Exploratory	See table note [a].
H4: There will be significant positive correlations between performance on the three 'hot' inhibitory control tasks at 3½ years of age.	Exploratory	All tasks were designed to measure same construct
H5: Are there significant correlations between performance on the two 'cool' inhibitory control tasks and performance on the three hot' inhibitory control tasks at 3½ years of age?	Exploratory	To examine whether 'hot' and 'cool' inhibitory control are unified in early childhood

Note. * The association between the ECITT and Toy Prohibition at 10-months of age in this sample of participants is already known ($r = 0.15$) and has been published by Lui et al. (2021).

[a] From a theoretical perspective, it would be expected that there would be a significant association between performance on the ECITT and the Go / No-Go task because they have been designed to measure the same construct and, as such, are structurally similar tasks. However, I had concerns regarding data quality stemming from participants' engagement with Fish & Sharks task (Howard & Melhuish, 2017) noted during task administration. Therefore, I am not confident in the quality of the Go / No-Go data to predict an association between the two tasks (as stated in the pre-registration).

Table 3. Chapter 7. Hypotheses for Longitudinal Associations (Inhibitory Control).

Hypothesis	Explanation	Rationale / Background
H6: It is not expected that there will be a significant correlation (with effect size greater than *r* = 0.30) between performance on the ECITT at 10-months and 3½ years of age.	Based on the findings of Hendry et al. (2021)	I expect to replicate these findings in the current sample (same ages, same tasks)
H7: It is predicted that performance on the ECITT at 16-months of age will be significantly associated with ECITT performance at 3½ years of age.	Based on the findings of Holmboe et al. (2021)	These previous findings demonstrated age-related performance improvements from 18 – 24 months, and from 24- 30 months.
H8: It is not expected that there will be a significant correlation (with effect size greater than *r* = 0.30) between performance on the 'hot' inhibitory control tasks 10-months and performance on the same 'hot' inhibitory control task at 16-months.	Based on the findings of Hendry et al. (2021)	I expect to replicate these findings in the current sample (same ages, same tasks)
H9: a) It is predicted that there will be a significant association between 'hot' inhibitory control performance at 16-months and 'hot' inhibitory control performance at 3½ years. b) It is not expected that there will be a significant correlation (with an effect size greater than *r* = 0.30) between 'hot' inhibitory control performance at 10-months and 'hot' inhibitory control performance at 3½ years.	Based on the findings of Friedman et al. (2011)	Friedman et al. (2011) found some stability in 'hot' inhibitory control (latency to touch attractive object) from 14- to 36-months, and that those with better performance at 14-months had better performance at 36-months.

Table 4. Chapter 7. Exploratory Longitudinal Associations (Inhibitory Control).

Exploratory Research Question	Explanation	Rationale / Background
H10: Is there a significant predictive association between ECITT performance at 10-months and 16-months, and Go / No-Go performance at 3½ years?	Exploratory	Stability in EF performance from ~24-months (e.g.,Broomell & Bell, 2022; Carlson et al., 2004), but it is uncertain whether there will be stability from 16-months as this has not previously been examined.
H11: Does performance on the ECITT at 10-months, and at 16-months, predict performance on 'hot' inhibitory control tasks at 3½ years?	Exploratory	
H12: Does performance on 'hot' inhibitory control tasks at 10-months, and at 16-months, predict performance on 'cool' inhibitory control tasks at 3½ years?	Exploratory	

Table 5. Chapter 7. Hypotheses for Within-Age Associations between Inhibitory Control and Early Academic Outcomes.

Hypothesis	Explanation	Rationale / Background
H13: a) It is not expected that there will be a significant correlation (with an effect size greater than *r* = 0.30) between children's 'hot' inhibitory control skills and their early numeracy ability at 3½ years. b) It is not expected that there will be a significant correlation (with an effect size greater than *r* = 0.30) between children's 'hot' inhibitory control skills and their early language skills at 3½ years.	Based on the findings of Kim et al. (2013) with 38- and 52-month-olds and Mulder et al. (2014) with 24-month-olds	'Hot' inhibitory control was not predictive of academic skills, whereas 'cool' inhibitory control predicted academic skills.
H14: a) There will be a significant positive association between children's 'cool' inhibitory control skills and their early numeracy ability at 3½ years.* b) There will be a significant positive association between children's 'cool' inhibitory control skills and their early language skills at 3½ years.		

*Note.** Based on previous literature, an association between children's 'cool' inhibitory control skills and their early numeracy ability would be expected. However, a colleague also using this dataset found no significant association between performance on the Go / No-Go task and performance on the Numbers task at 3½ years. I will be applying specific exclusion criteria and deriving a different index of response inhibition from the Fish & Sharks task, so I may find a different result. It should be noted that I do not have prior knowledge about the association between the ECITT and Numbers at 3½ years.

Table 6. Chapter 7. Exploratory Longitudinal Associations: Infant Inhibitory Control and Early Academic Outcomes

Exploratory Research Question	Explanation	Rationale / Background
H15: a) Does performance on the ECITT ('cool' inhibitory control) at 10- and 16-months predict children's early numeracy performance at 3½ years? b) Does performance on the ECITT ('cool' inhibitory control) at 10- and 16-months predict children's early language performance at 3½ years?	Exploratory	Relatively little is known about associations between inhibitory control measured in infancy and later academic outcomes
H16: a) Does performance on 'hot' inhibitory control tasks (Touchscreen and Toy Prohibition) at 10- and 16-months predict children's early numeracy performance at 3½ years? b) Does performance on 'hot' inhibitory control tasks (Touchscreen and Toy Prohibition) at 10- and 16-months predict children's early language performance at 3½ years?		

3.2. Pre-registered Analyses

Correlational analyses (one-tailed) will be conducted to test confirmatory hypotheses that make specific predictions about an association, whereas two-tailed correlational analyses will be conducted when testing exploratory hypotheses. Note that the number of confirmatory

correlational analyses may reduce if the Touchscreen and Toy Prohibition tasks are correlated at 10- or 16-months, or if the three 'hot' inhibitory control tasks are correlated at 3½ years. This is because an average 'hot inhibitory control' measure will be calculated for each assessment point where the correlation is significant.

If significant longitudinal associations are found between inhibitory control measures at 10-months and 3½ years, and 16-months and 3½ years (H10 – H12), these associations will be followed up with exploratory multiple linear regression analyses to further establish how multiple measures are related over time, and to identify which infant variables are significant predictors of inhibitory control at 3½ years. The same follow-up multiple linear regression analyses are planned if significant associations are found in H13 – H14 (within-age associations between inhibitory control and early academic outcomes), and H15 – H16 (longitudinal associations between infant inhibitory control and early academic outcomes).

3.3. Statistical Analysis

All statistical analyses were conducted in SPSS version 29. All variables were tested against the parametric test assumptions, and when violated, appropriate non-parametric equivalents were used. Pearson's correlational analysis (*r)* was used where both variables are continuous, and Spearman's correlational analysis (r_s) was used when variables were not normally distributed. Kendall's tau-b correlational analysis (r_b) was used where one variable is continuous and one is ordinal. All confirmatory statistical tests will be one-tailed, and all exploratory tests will be two-tailed. Where a test is exploratory and two-tailed, this is clearly stated in the text. The procedure for controlling the false discovery rate (FDR; Benjamini & Hochberg, 1995) was used where multiple tests were conducted. Confidence intervals (CI) (95%) were calculated on 1000 bootstrap samples. Please see Appendix E2 for details of how the data were tested against the parametric test assumptions and the results of any equivalent non-parametric tests that were conducted.

4. Results

Descriptive statistics for task performance in infancy (10-months, 16-months) and early childhood (3½ years) are reported in **Table 7** below.

Table 7. Chapter 7. Descriptive Statistics.

Task	N	Minimum	Maximum	Mean	SD
10-month Toy Prohibition Latency	148	.000	30.000	3.577	6.660
16-month Toy Prohibition Latency	80	.135	30.000	11.634	12.526
10-month Touchscreen Prohibition Latency	148	.000	30.000	3.079	5.826
16-month Touchscreen Prohibition Latency	81	.000	30.000	10.010	10.949
10-month ECITT (Accuracy Inhibitory Score)	130	.000	1.228	.588	.343
16-month ECITT (Accuracy Inhibitory Score)	65	.000	1.149	.543	.367
3½ year Treasure Delay Score	84	0	3	2.440	.797
3½ year Gift Delay Score	122	0	5	4.20	1.105
3½ year Dinky Toys Score	97	0	5	2.59	1.993
3½ year ECITT (Accuracy Inhibitory Score)	119	.327	1.049	.797	.156
3½ year Go / No-Go (Accuracy Inhibitory Score)	103	.000	1.234	.960	.205
3½ year Numbers	123	2	61	27.61	10.707
3½ year VCI	89	73	147	113.58	15.132

Note. VCI = Verbal Comprehension Index.

4.1. Change in Group-Level Performance

Although not pre-registered, it is important to consider how performance at the group-level changed across assessment points when the same tasks were used. Results of exploratory related samples Wilcoxon signed rank tests (**Table 8**) demonstrated significant performance improvements on the 'hot' inhibitory control tasks from 10- to 16-months, and on the ECITT from infancy to 3½ years. Results of equivalent parametric *t*-tests are reported in Appendix E2 and are aligned with the results presented below.

Table 8. Chapter 7. Group-Level Performance Change.

Tasks	Statistic
Toy Prohibition (10- and 16-months)	Z = 3.541, p <.001
Touchscreen Prohibition (10- and 16-months)	Z = 4.425, p <.001
ECITT (10-months to 3½ years)	Z = 4.442, p <.001
ECITT (16-months to 3½ years)	Z = 4.131, p <.001

4.2. Within-Age Associations – Inhibitory Control

The results of correlational analyses are reported in **Table 9**. As predicted (H1), significant associations were found between the Touchscreen and Toy Prohibition tasks in infancy. Note that because of this association, the scores have been combined to create a 'hot' inhibitory control variable at 10- and 16-months, as described in the pre-registration. Results also support H2, as no significant associations were found between the ECITT and 'hot' inhibitory control in infancy.

The results of exploratory analysis (H3) revealed a small significant association between performance on the ECITT and Go / No-Go task at 3½ years, although this result did not survive the procedure for controlling the FDR (N = 7 comparisons). The same result was found when using the 'Impulse Control' variable from the Go / No-Go task (exploratory, not pre-registered): r_s (97) = .231, p = .021, CI = .036, .400. This variable was automatically calculated from the Fish & Sharks task by the Early Years Toolbox (Howard & Melhuish, 2017) as: Go Accuracy multiplied by No-Go Accuracy.

At 3½ years, a moderate significant association was found between performance on the Gift Delay and Dinky Toys tasks (H4), as predicted. Additionally, there was a significant association between the Gift Delay and Treasure Delay tasks, although this association was in the opposite direction than expected and did not survive the procedure for controlling the FDR (N = 3 comparisons). There was no significant association between the Treasure Delay and Dinky Toys tasks.

The only significant association between performance on 'cool' inhibitory control tasks and 'hot' inhibitory control tasks at 3½ years (H5, exploratory) was between the ECITT and the Gift Delay task at 3½ years, however, this association did not survive the procedure for controlling the FDR (N = 7 comparisons). 'Cool' – 'Hot' exploratory correlational analyses (not pre-registered) were also conducted using the Go / No-Go 'Impulse Control Score' and no significant results were found (Appendix E2).

Table 9. Chapter 7. Results of Within-Age 'Hot' and 'Cool' Inhibitory Control Associations.

Type	Tasks	Assessment Point	Statistic
Infancy Within-Age Associations			
Hot	Touchscreen Prohibition and Toy Prohibition	10-months	**r_s (146) = .380, p<.001***, *CI* = .242, .523 [a]**
		16-months	**r (78) = .455, p< .001***, *CI* = .232, .634 [a]**
Cool and Hot	ECITT and Hot Inhibitory Control	10-months	r_s (128) = .074, p = .406, *CI* = -.105, .252
		16-months	r (62) = .015, p = .907, *CI* = -.217, .235
Early Childhood Within-Age Associations			
Cool	ECITT and Go / No-Go	3½ years	**r_s (97) = .233, p = .020*, *CI* = .024, .431**
Hot	Gift Delay and Treasure Delay	3½ years	**r_s (80) = -.200, p =.036*, *CI* = -.408, .010 [a]**
Hot	Gift Delay and Dinky Toys	3½ years	**r_s (95) = .397, p<.001***, *CI* = .207, .565 [a]**
Hot	Treasure Delay and Dinky Toys	3½ years	r_s (73) = .156, p = .090, *CI* = -.096, .381 [a]
Cool and Hot	ECITT and Treasure Delay	3½ years	r_b (81) = -.143, p = .103, *CI* = -.315, .042
	ECITT and Gift Delay	3½ years	**r_b (115) = .173, p = .017*, *CI* = .042, .306**
	ECITT and Dinky Toys	3½ years	r_b (92) = -.023, p = .766, *CI* = -.203, .146
	Go / No-Go and Treasure Delay	3½ years	r_b (67) = .040, p = .680, *CI* = -.154, .218
	Go / No-Go and Gift Delay	3½ years	r_b (101) = .038, p = .623, *CI* = -.137, .196
	Go / No-Go and Dinky Toys	3½ years	r_b (80) = .089, p = .286, *CI* = -.057, .232

Note: *** p < .001, * p < .05. Statistically significant results are highlighted in bold. [a] One-tailed test.

4.3. Longitudinal Associations – Inhibitory Control

Results of longitudinal correlational analyses (H6 – H9) are reported in **Table 10** below. The results support H6, as no significant association was found between performance on the ECITT at 10-months and 3½ years, but do not support H7 as there was no significant association between the ECITT at 16-months and 3½ years. In line with the hypothesis (H8), no significant longitudinal association was found between Touchscreen Prohibition at 10- and 16-months. There were also no significant associations between 'hot' inhibitory control in infancy and at 3½ years (H9).

Table 10. Chapter 7. Longitudinal 'Hot' and 'Cool' Inhibitory Control Associations.

Type	Tasks	Assessment Points	Statistic
Hot	Toy Prohibition	10-months and 16-months	r_s (74) = .019, p = .871, *CI* = -.211, .263[a]
	Touchscreen Prohibition	10-months and 16-months	r_s (75) = .180, p = .117, *CI* = -.043, .391[a]
Hot	'Hot' Inhibitory Control and Treasure Delay	10-months and 3½ years	r_b (80) = .004, p = .967, CI = -.178, .182[a]
		16-months and 3½ years	r_b (43) = -.094, p = .219, CI = -.325, .165
Hot	'Hot' Inhibitory Control and Gift Delay	10-months and 3½ years	r_b (94) = .095, p = .221, CI = -.051, .251[a]
		16-months and 3½ years	r_b (52) = -.170, p = .056, CI = -.416, .094
Hot	'Hot' Inhibitory Control and Dinky Toys	10-months and 3½ years	r_b (81) = .046, p = .574, CI = -.109, .212[a]
		16-months and 3½ years	r_b (47) = .062, p = .286, CI = -.145, .267
Cool	ECITT	10-months and 3½ years	r_s (78) = -.040, p = .726, *CI* = -.242, .180[a]
		16-months and 3½ years	r_s (43) = -.048, p = .378, *CI* = -.361, .270

Note: [a] Two-tailed correlational analysis.

4.4. Exploratory Longitudinal Associations (Inhibitory Control)

Results of exploratory longitudinal correlational analyses (H10 – H12) are reported in **Table 11** below. A significant association was found between 'hot' inhibitory control at 16-months and performance on the Go / No-Go task at 3½ years, however, this association did not survive the procedure for controlling the FDR (N = 4 comparisons). Also, this association was not significant when the correlation was conducted with the Go / No-Go 'Impulse Control' variable (exploratory, not pre-registered): r_s (44) = -.250, p = .094, *CI* = -.555, .066. However, there was a significant exploratory two-tailed association (not pre-registered) between the ECITT at 16-months and the Go / No-Go Impulse Control variable: r_s (37) = .459, p = .003, *CI* = .148, .694. This result remained significant following the procedure for controlling the FDR (N = 4 comparisons).

Table 11. Chapter 7. Exploratory Longitudinal 'Hot' and 'Cool' Inhibitory Control Associations.

Type	Tasks	Assessment Points	Statistic
Hot and Cool	'Hot' Inhibitory Control (infancy) and ECITT	10-months and 3½ years	r_s (93) = -.021, p = .843, *CI* = -.238, .196
		16-months and 3½ years	r_s (50) = -.096, p = .500, *CI* = -.341, .180
	'Hot' Inhibitory Control (infancy) and Go / No-Go	10-months and 3½ years	r_s (78) = .036, p = .750, *CI* = .201, .253
		16-months and 3½ years	**r_s (44) =.313, p = .034*, *CI* = -.034, .553**
Cool and Hot	ECITT (infancy) and Treasure Delay	10-months and 3½ years	r_b (70) = .155, p = .098, *CI* = -.049, .348
		16-months and 3½ years	r_b (37) = .048, p = .714, *CI* = -.226, .325
Cool and Hot	ECITT (infancy) and Gift Delay	10-months and 3½ years	r_b (78) = -.106, p = .225, *CI* = -.278, .052
		16-months and 3½ years	r_b (43) = .001, p = .991, *CI* = -.211, .222
Cool and Hot	ECITT (infancy) and Dinky Toys	10-months and 3½ years	r_b (67) = -.078, p = .391, *CI* = -.245, .114
		16-months and 3½ years	r_b (39) = .004, p = .972, *CI* = -.284, .273
Cool	ECITT (infancy) and Go / No-Go	10-months and 3½ years	r_s (64) = -.104, p = .408, *CI* = -.352, .142
		16-months and 3½ years	r_s (37) = .156, p = .343, *CI* = -.161, .470

Note: * p < .05. Statistically significant results are highlighted in bold**.** All analyses were exploratory (two-tailed).

4.5. Early Childhood Inhibitory Control and Pre-Academic Outcomes

4.5.1. Within-Age Associations (3½ years)

Results of within-age correlational analyses between inhibitory control measures and performance on tasks of early academic skills (H13 – H14) are reported in **Table 12** below. Contrary to the hypothesis (H13), performance on the Dinky Toys task was significantly associated with early numeracy and language ability, although no other hot inhibitory control tasks showed significant associations with pre-academic outcomes.

Contrary to predictions, (H14), there was no significant association between performance on the ECITT and the Numbers task, or the VCI. There was also no significant association between performance on the Go / No-Go task and early language ability or early numeracy performance (H14). Further exploratory correlational analyses (not pre-registered) were also conducted using the Go / No-Go 'Impulse Control Score' and no significant results were found (Appendix E2).

An additional exploratory (not pre-registered) correlational analysis was conducted to examine whether performance on the Numbers task and the VCI task was correlated; results suggested a large significant positive association: r (87) = .623, p < .001, *C*I = .482, .783.

Table 12. Chapter 7. Results of Within-Age Associations: Inhibitory Control and Pre-Academic Outcomes.

Type	Tasks	Pre-Academic Outcome	Statistic
Hot	Treasure Delay	Numbers	r_b (82) = .114, p = .192, *CI* = -.073, .289[a]
		VCI	r_b (79) = .098, p = .289, *CI* = -.081, .286[a]
	Gift Delay	Numbers	r_b (119) = .093, p = .190, *CI* = -.038, .217[a]
		VCI	r_b (87) = .109, p = .198, *CI* = -.057, .267[a]
	Dinky Toys	Numbers	**r_b (94) = .295, p < .001[***], *CI* = .139, .431**[a]
		VCI	**r_b (77) = .255, p = .003[**], *CI* = .092, .418**[a]
Cool	ECITT	Numbers	r_s (116) = .033, p = .118, *CI* = -.147, .210
		VCI	r_s (85) - .129, p = .118, *CI* = -.085, .336
	Go / No-Go	Numbers	r_s (100) = .093, p = .352, *CI* = -.098, .352[a]
		VCI	r_s (72) = .136, p = .247, *CI* = -.109, .379[a]

Note. [***] p < .001, [**] p < .01. Statistically significant results are highlighted in bold. [a] Two-tailed correlational analysis. VCI = Verbal Comprehension Index (from the WPPSI).

4.5.2. *Exploratory Longitudinal Associations: Infant Inhibitory Control and Pre-Academic Outcomes*

Results of exploratory longitudinal correlational analyses between infant inhibitory control measures and performance on tasks of early academic skills (H15 – H16) are reported in **Table 13** below. No significant associations were found between 'cool' inhibitory control tasks in infancy and early academic skills at 3½ years (H15) or between 'hot' inhibitory control in infancy and early academic skills at 3½ years (H16).

Table 13. Chapter 7. Exploratory Longitudinal Associations: Infant Inhibitory Control and Pre-Academic Outcomes.

Type	Tasks	Assessment Points	Statistic
Cool	ECITT (infancy) and Numbers	10-months and 3½ years	r (80) = -.064, p = .570, *CI* = -.275, .168
		16-months and 3½ years	r (44) = -.111, p = .461, *CI* = -.416, .213
Cool	ECITT (infancy) and VCI	10-months and 3½ years	r (76) = -.090, p = .433, *CI* = -.312, .137
		16-months and 3½ years	r (39) = .118, p = .461, *CI* = -.219, .442
Hot	'Hot' Inhibitory Control (infancy) and Numbers	10-months and 3½ years	r_s (96) = .189, p = .062, CI = -.021, .383
		16-months and 3½ years	r_s (53) = -.111, p = .418, *CI* = -.419, .186
Hot	'Hot' Inhibitory Control (infancy) and VCI	10-months and 3½ years	r_s (86) = .030, p = .783, *CI* = -.196, .243
		16-months and 3½ years	r_s (46) = -.072, p = .628, *CI* = -.365, .232

Note: VCI = Verbal Comprehension Index (from the WPPSI). All analyses were exploratory (two-tailed).

5. Discussion

This pre-registered study aimed to investigate concurrent and longitudinal associations between 'hot' and 'cool' inhibitory control in infancy (10-months and 16-months) and early childhood (3½ years) and to examine potential associations between early inhibitory control and pre-academic outcomes. This section will begin with a summary of the key findings, before discussing the implications of the results in the context of existing literature. The limitations and strengths of the study will be evaluated, and directions for future research will be proposed.

5.1. Summary of Key Findings

Results of this study revealed that performance on the 'hot' inhibitory control tasks significantly improved from 10- to 16-months of age, and that performance on the ECITT ('cool' inhibitory control) significantly improved from 10-months to 3½ years, and from 16-months to 3½ years (note that there was no significant performance improvement on the ECITT from 10- to 16-months). When examining within-age associations, it was found that performance on the two 'hot' inhibitory control tasks (Toy Prohibition, Touchscreen Prohibition) was significantly correlated at both 10- and 16-months, as predicted. In early childhood, there was a significant association between the 'cool' inhibitory control tasks

(ECITT and Go / No-Go), and a significant association between two 'hot' tasks (Gift Delay and Dinky Toys). The only significant association between performance on 'cool' and 'hot' inhibitory control tasks was a weak association between the ECITT and the Gift Delay task at 3½ years. A significant exploratory longitudinal association was found between 'hot' inhibitory control at 16-months and performance on the Go / No-Go task at 3½ years, and an exploratory (not pre-registered) association was found between the ECITT at 16-months and the Go / No-Go Impulse Control variable at 3½ years. No other longitudinal associations were found, hinting at a lack of stability in 'hot' and 'cool' inhibitory control in the first years of life. This study also examined within-age and longitudinal associations between inhibitory control and pre-academic outcomes. In early childhood, there were significant associations between performance on the Dinky Toys task and both the Numbers and VCI tasks. No significant longitudinal associations were found between inhibitory control in infancy and performance on the early academic tasks at 3½ years. This could potentially be because measures of inhibitory control in infancy were not yet stable. Overall, despite the lack of longitudinal inhibitory control correlations and no clear prediction of pre-academic outcomes from early inhibitory control skills, this unique longitudinal study contributes new knowledge that will act as an important springboard for future research.

5.2. Interpretation of Findings

5.2.1. 'Hot' Inhibitory Control in Infancy and Early Childhood

When examining within-age associations, a significant positive correlation was found between performance on the Touchscreen Prohibition task and performance on the Toy Prohibition task at both the 10- and 16-month assessment points. This result is in line with the study hypothesis and also replicates the findings of Hendry et al. (2021), where these tasks were used with a separate sample of 10- and 16-month-olds. As such, these results suggest that the two 'hot' inhibitory control tasks are reliably measuring the same construct (the ability to follow a prohibition) at both 10- and 16-months of age. There was no evidence for the stability of individual differences in performance on 'hot' inhibitory control tasks across the transition to toddlerhood, as also found by Hendry et al. (2021).

In early childhood, there was a strong significant positive association between performance on the Gift Delay and the Dinky Toys task. This association aligns with the hypothesis and suggests that individual differences in children's delay of gratification performance were similar on these two 'hot' inhibitory control tasks, which makes sense, as both tasks consist of a single trial and children are instructed not to touch. This result suggests that the Gift

Delay and Dinky Toys tasks are reliably measuring the same construct (which I intended to be the ability to delay gratification). Contrary to expectations, there was a significant negative association between performance on the Gift Delay and Treasure Delay tasks (where a positive association had been hypothesised). This result suggests that better performance on the Gift Delay task was associated with poorer performance on the Treasure Delay task, although it is worth considering that this association did not survive the procedure for controlling the FDR. This was unexpected as both tasks were designed to measure the ability to delay gratification.

One clear difference between the two tasks is that in the Treasure Delay task, children were given the opportunity to choose whether or not to delay gratification, reminded of their options before making a choice, and then clearly invited to make their choice. Whereas, in the Gift Delay task, children did have the choice not to delay gratification (i.e., by looking in the gift bag or touching the toy), but this was not presented as a clear option that children could choose from during the task setup, where the instruction was “Try not to touch it until I come back”. The role of choice in early EF has been highlighted by Carlson (2023), who hypothesised that young children will behave reflexively (exhibiting poorer EF) in situations where there is no perceived choice but will behave reflectively (employing executive functions to exhibit controlled behaviour) when autonomy is promoted, and a clear choice is available. Alternatively, it could be that the Treasure Delay task is not capturing delay of gratification but a different ability, such as children’s prosocial behaviour (e.g., choosing the smaller reward such that the pirate could have a larger reward) (Chernyak & Kushnir, 2018; Hepach et al., 2013). This is an interesting avenue of enquiry to pursue in future research that examines early childhood delay of gratification. However, since the Treasure Delay task is a novel task that has not previously been validated against other similar tasks, further validation efforts are needed before it is possible to unpack the potential reasons for this negative association.

5.2.2. ‘Cool’ Inhibitory Control in Infancy and Early Childhood

The ECITT was the only task used to assess ‘cool’ inhibitory control in infancy in the current study, and results from Chapter 5 had already revealed that there was no significant association between performance on the ECITT at 10- and 16-months. This result was expected and replicates the findings of Hendry et al. (2021). Results of the current study, however, also revealed that there was no significant association between performance on the ECITT in infancy and early childhood. Whilst it was not expected that there would be stability in ‘cool’ inhibitory control from 10-months to 3½ years, it was predicted that there

would be stability from 16-months. Previous research has found some evidence for stability in inhibitory control from 18-months of age (Holmboe et al., 2021), however, the majority of evidence indicates that stability of individual differences in EF occurs from around 24-months of age (Bernier et al., 2012; Broomell & Bell, 2022; Carlson et al., 2004; for review, see Miller et al., 2023). From the evidence presented in the current thesis, it appears that 16-months is too early for stability in individual differences for inhibitory control, however, few studies have examined the stability in executive function before 24-months and so more research is needed to examine *when* this stability emerges in the first years of life, as well as whether this differs for different facets of inhibitory control.

There is some preliminary evidence to suggest that performance on the ECITT at 16-months was moderately associated with the 'Impulse Control' variable on the Go / No-Go task at 3½ years. This could potentially suggest that 'cool' inhibitory control skills in toddlerhood are predictive of 'cool' inhibitory control skills in early childhood. Indeed, this is further supported by evidence at 3½ years, where there was a small significant association between performance on the ECITT and Go / No-Go tasks. Overall, this suggests that children performed consistently on the two 'cool' inhibitory control tasks at 3½ years, and that 'cool' inhibitory control at 16-months may be predictive of 'cool' inhibitory control at 3½ years. Whilst this is interesting, this result should be considered preliminary until it can be replicated in future studies. This is because the association was not found when using the Go / No-Go 'Accuracy Inhibitory Score' variable and because no significant association was found when examining performance on the ECITT at 16-months and 3½ years (where an association might be considered more likely, given that the task is the same across age points). Similarly, since the association between the 'cool' inhibitory control tasks at 3½ years did not survive the procedure for controlling the FDR, it also requires replication and should be considered preliminary.

Whilst this result was not predicted, theoretically, these findings would be expected since the tasks were both designed to measure response inhibition in young children and were structurally similar (the same number of trials, similar in duration, require the development of a prepotent motor response). The Go / No-Go task from the Early Years Toolbox has been well-validated with this age group and showed moderate convergent validity with the Flanker test (inhibitory control measure) from the NIH toolbox (Howard & Melhuish, 2017; Zelazo et al., 2013), and the ECITT has been well-validated in infants and toddlers (up to 24-months) and across the lifespan (Holmboe et al., 2021), but this study is the first to use the task with 3½-year-old children. As such, this association provides some support for the validation of the pre-school version of the ECITT as a reliable index of inhibitory control for 3½-year-olds.

5.2.3. Methodological Differences between Go / No-Go and ECITT

Whilst the 'cool' inhibitory control tasks used in this study (Go / No-Go, ECITT) were structurally similar and designed to measure response inhibition in young children, it is important to discuss key methodological differences between tasks that may have implications for the interpretation of results.

Firstly, choosing the appropriate index of response inhibition performance is an important point for consideration that can have an impact on results and their interpretation. In the current study, it was decided that the 'accuracy inhibitory score' would be used as an index of response inhibition performance for the ECITT, since this was the variable that had been used in the previous thesis chapters and in previous work with the ECITT (Fiske et al., 2022; Hendry et al., 2021; Holmboe et al., 2021; Lui et al., 2021). This variable was calculated as 1-(accuracy on prepotent trials – accuracy on inhibitory trials) / accuracy on prepotent trials. In rare cases where participants had greater accuracy on inhibitory trials than on prepotent trials, this variable was calculated as 1-(accuracy on prepotent trials – accuracy on inhibitory trials) × accuracy on prepotent trials. This way, the index of response inhibition measures the difference in accuracy between prepotent and inhibitory trials but also considers general performance on prepotent trials (which is particularly important in studies with infants and young children where general performance may be more variable for many reasons). The index of response inhibition automatically generated for the Go / No-Go task (Howard & Melhuish, 2017) was the 'Impulse Control' score, calculated as Go accuracy × No-Go accuracy, which does not consider general performance levels. Therefore, the accuracy inhibitory score was also calculated for the Go / No-Go task, using the accuracy data from Go and No-Go trials in place of data from prepotent and inhibitory trials respectively (note that there was a strong correlation between the Go / No-Go accuracy inhibitory score and the Impulse Control score). This allowed for performance on the two 'cool' inhibitory control tasks to be very easily compared.

However, this is problematic because the task demands on the Go and No-Go trials do not fully correspond with the task demands on prepotent and inhibitory trials of the ECITT. For example, whilst it is not possible to 'miss' a trial on the ECITT, it is possible to do so on the Go / No-Go task. A response is required on the ECITT before the next trial is presented, whereas the trials on the Go / No-Go task are fixed in duration and will move on automatically. As such, errors made on the ECITT can only be errors of 'commission' (i.e., an incorrect response) and can never be 'missed', whereas errors made on the Go / No-Go task could be either a commission error or an error of omission - where no response is made and so the trial is 'missed'. As a result, it is much easier for children to disengage or 'opt out' of the Go / No-Go task than it is the ECITT, and so it becomes difficult to distinguish whether

a non-response is due to correctly inhibiting a motor response or due to disengagement with the task.

Whilst indices such as the *d* ' sensitivity index have been commonly used to represent the standardised difference between 'hit' (e.g., correct Go trials) and 'false alarm' (e.g., incorrect No-Go trials) (e.g., Wiebe et al., 2012), this metric does not take into consideration how task engagement (or disengagement) could impact these variables. For example, a low 'hit' rate and a low 'false alarm' rate could be explained by factors such as motor or processing speed difficulties due to the timed trials but could also be explained by task disengagement (e.g., participant stopped responding). Further, instances of task disengagement where participants respond on every trial would inflate both the 'hit' rate (on Go trials) and the 'false alarm' rate (on No-Go trials), yet it is not possible to distinguish task disengagement from poor response inhibition ability. As such, the interpretation of scores on the Go / No-Go task with young children becomes very complex. Future research should aim to capture more dynamic performance changes across the Go / No-Go task to help disentangle consistently poor responding (e.g., due to poor motor skills) from disengagement over the session (e.g., due to fatigue or boredom), as it would be hypothesised that poor performance due to motor skills would be consistent across the session, whereas disengagement would be expected to increase across the session.

Additionally, although both tasks contain signal detection factors (i.e., detecting whether this is a 'Go' or a 'No-Go' stimulus or detecting if the smiley is 'here' or 'there'), there are several other factors that relate to performance on the Go / No-Go task that are not present in the ECITT. For example, in the Go / No-Go, some children were overly cautious at responding in fear of making a mistake or missing the moving stimulus, and some children were either afraid of or really interested in the shark (No-Go stimulus). Other children were purposefully defiant and were keen to see the experimenter's reaction when they pressed the shark (which also happened on the ECITT where children wanted to see what happened with the blank button, but since the trial does not move on in the ECITT this was not such an attractive option as pressing the correct response and seeing a cartoon). As such, behaviour towards the Go / No-Go task was somewhat driven by these affective factors, rather than adherence to the task rules and their inhibitory control abilities. Whilst the Go / No-Go task has been used consistently with older populations and with some success in young children (e.g., Howard & Melhuish, 2017; Wiebe et al., 2012), these practical considerations must be considered when evaluating results from studies using this task, and also in choosing age-appropriate response inhibition tasks in future studies.

Future research is warranted that further investigates the validity of data collected from young children during different versions of the Go / No-Go task across different samples of participants to determine how the issues described in this section can be mitigated or overcome. Age-appropriate response inhibition tasks are already very limited, and so it makes sense to thoroughly examine these methodological considerations in relation to task performance to ensure that the Go / No-Go task can be used as a valid and reliable measure of response inhibition in all young children.

5.2.4. The Early Development of 'Hot' and 'Cool' Inhibitory Control

The results of the current study found that there were no significant within-age associations between measures of 'hot' and 'cool' inhibitory control in infancy, replicating the findings of Hendry et al. (2021). In early childhood, a preliminary association was found between performance on the ECITT ('cool' inhibitory control) and on the Gift Delay task ('hot' inhibitory control) at 3½ years, although this finding requires replication. This result aligns in part with Mulder et al. (2014), who found significant positive associations in 2-year-olds between performance on 'hot' inhibitory control tasks (Gift Delay and Snack Delay) and performance on 'cool' EF tasks, but these tasks were designed to measure working memory, not inhibitory control. However, in slightly older children (25 – 41 months), Di Norcia et al. (2015) found no significant association between performance on a range of measures of 'hot' and 'cool' inhibitory control. Additionally, this current study found a significant exploratory longitudinal association between 'hot' inhibitory control at 16-months and the Go / No-Go task at 3½ years, however, this preliminary result requires replication before it can be meaningfully interpreted. No other significant longitudinal associations were found between the 'hot' and 'cool' indices of inhibitory control. This result, as well as the limited within-age 'hot' – 'cool' associations, could potentially suggest that the two facets of inhibitory control may be separable in early development.

Research into the structure of EFs in infancy and early childhood is mixed, with some research suggesting EF is best represented by a single latent factor in early development (Wiebe et al., 2008, 2011), and others finding evidence to suggest a clear distinction between 'hot EF' and 'cool EF' as two separate factors best describing EF in toddlerhood (Mulder et al., 2014). However, there is currently very little research that focuses specifically on the structure of inhibitory control in early development. Even less is known about the distinction between 'hot' and 'cool' inhibitory control, particularly as there is often a blurred line between the conceptualisation of tasks by one research group as measuring 'hot' inhibitory control and another research group that uses the same task to measure effortful

control or self-regulation (Blair & Ku, 2022). For example, research by Willoughby et al. (2011) presented evidence to suggest that 'hot' and 'cool' inhibitory control were separable but correlated factors in 4-year-old children. However, the 'cool' inhibitory control tasks used by Willoughby et al. (2011) were very different from the motor response inhibition tasks used in the current study since they used tasks that required children to slow a gross motor response (walking as slowly as possible) and to perform the opposite motor response than the experimenter. Therefore, the conceptualisation of tasks as measuring 'cool' or 'hot' inhibitory control can have important implications for the conclusions made about these skills in development, as well as raising questions about how to correctly categorise tasks, or whether categorisation should, in fact, be driven by the data.

The evidence from the current study did not find any clear evidence of significant 'hot-cool' associations in infancy or early childhood, or robust longitudinal associations across this period. However, it may be that as children age and their inhibitory control skills progress, performance on these two facets of inhibitory control become more closely associated. Factor analytic studies with large participant samples (focusing specifically across the first four years of life) are needed to help uncover whether there are latent structures and how these constructs relate to each other as they develop across early childhood. Additionally, research is needed that examines these skills in toddlerhood and fills the age gap in the current study (caused by the pandemic), to investigate whether the findings of Mulder et al., (2014) and Willoughby et al. (2011) can be replicated.

5.2.5. 'Hot' and 'Cool' Inhibitory Control and Early Academic Skills

Previous research that has examined links between 'hot' and 'cool' EFs in early childhood and early academic skills has commonly found significant associations between 'cool' EFs and early academic skills, but not 'hot' EFs and early academic skills, as performance on 'hot' tasks is more associated with behavioural problems in this early period (Kim et al., 2013; Mulder et al., 2014; Willoughby et al., 2011).

Whilst this current study found no evidence of significant associations between 'cool' inhibitory control and early academic skills at 3½ years, contrary to expectations, this study found a significant positive association between performance on the Dinky Toys task ('hot' inhibitory control) and both the Numbers and VCI tasks. This suggests that the ability to delay gratification is associated with better early numeracy and language performance at 3½ years. This appears to contradict previous findings, which have failed to demonstrate links between 'hot' inhibitory control and early academic performance (e.g., Brock et al., 2009; Mulder et al., 2014). The Dinky Toys task was presented by Kochanska et al. (2000) as a

measure of early effortful control and has frequently been to assess 'hot' inhibitory control (or effortful control) in early childhood (e.g., Conway & Stifter, 2012; Gagne & Saudino, 2010; Stifter et al., 2008; VanSchyndel et al., 2017). In the current study, this task consisted of a single trial whereby children were told to choose an attractive toy from an interesting box filled with different coloured toys by verbally saying what colour toy they wanted, without pointing to or touching the toys. To my knowledge, there has been no previous research that has found specific associations with Dinky Toys as the single 'hot' inhibitory control measure and two measures of early academic achievement. As such, it is extremely interesting that performance on this single trial task was significantly associated (with medium effect sizes) with both measures of early academic skills.

Whilst evidence from the literature is limited, I propose some potential explanations for these associations. First, expressive and receptive verbal skills are required in Dinky Toys and both the VCI and Numeracy tasks, so it may be that these associations are driven by underlying verbal ability. Post-hoc exploratory analyses revealed that when controlling for performance on the VCI task, the association between performance on the Dinky Toys task and the Numbers task was no longer significant (results reported in Appendix E3). This suggests that the association between performance on the Dinky Toys and Numbers tasks was driven by children's verbal ability. Since it was also the case that when controlling for performance on the Numbers task, the association between performance on the Dinky Toys task and the VCI tasks was no longer significant (results reported in Appendix E3), this led to the potential conclusion that the associations between performance on the Dinky Toys task and early academic skills are instead driven by the child's general ability level.

Data collected from this sample using the WPPSI included a scale for general intelligence (full-scale IQ; FSIQ), so this theory could be tested. Further post-hoc exploratory analyses (results reported in Appendix E3) revealed that there was a significant, moderate positive association between performance on the Dinky Toys task and FSIQ, which suggests that children who perform better on the Dinky Toys task (i.e., are better able to delay gratification) have higher levels of general ability. Similarly, strong significant positive associations were found between FSIQ and performance on the Numbers task and the VCI task, which suggests that performance on all three tasks is driven by children's underlying levels of general ability. Therefore, it is likely that the associations between performance on the Dinky Toys ('hot' inhibitory control) task and the Numbers and VCI tasks were at least partly driven by children's general ability levels.

It is also important to consider that the working memory demand in the Dinky Toys task may play a role in the association with the measures of early academic skills. In this task,

participants are given several specific instructions (e.g., “Put your hands on the table, try not to touch, tell me which colour toy you want”) which must be remembered even during the exciting event of being allowed to choose a toy. The combination of the working memory demands and the inhibitory demands required to be successful on this task may be associated with the child’s general ability level, which is also associated with successful Numbers and VCI task performance. Future research is warranted that replicates these current associations and that can further investigate potential factors that may be driving this association, above and beyond the child’s general ability level.

Finally, exploratory longitudinal analyses were conducted to examine the potential association between inhibitory control measured in infancy and pre-academic outcomes measured at 3½ years. No significant associations were found between inhibitory control in infancy and performance on the Numbers or VCI tasks at 3½ years. This is not unsurprising, since research has found that early inhibitory control skills show stability from approximately 2 years of age (Broomell & Bell, 2022; Holmboe et al., 2021). As such, it may not be until later in toddlerhood (i.e., after 16-months) that longitudinal associations between early inhibitory control and preschool academic outcomes might be expected.

5.3. Limitations and Future Directions

The current study aimed to investigate ‘hot’ and ‘cool’ inhibitory control in infancy and early childhood, and to examine associations with early academic skills. To do so, this study included longitudinal data collected from the same sample of participants at three assessment points (10-months, 16-months, and 3½ years). However, due to the onset of the COVID-19 pandemic, in-person test sessions were cancelled and so many participants were unable to return for their visit at 16-months. As such, the sample size at 16-months was substantially smaller than had been originally planned. Similarly, because of the large gap between assessment points (due to the pandemic), the return rate for participants at 3½ years was also less than it might have been without the pandemic disruptions. Again, this meant that the sample size at 3½ years was smaller than planned.

As a result of the smaller samples and reduced statistical power, the analyses that were appropriate for this longitudinal dataset were limited. Where advanced statistical techniques such as structural equation modelling or path analysis would have been informative about relationships between variables over multiple time points, these were not feasible to conduct with the limited sample size in this current study. Instead, most of the hypotheses in the current study were tested with one- or two-tailed correlational analyses. Due to the number of comparisons made, the Benjamini-Hochberg procedure for controlling the false discovery

rate was applied (Benjamini & Hochberg, 1995). As a result, many of the associations did not retain significance and so can only be considered as preliminary findings requiring replication. Whilst the results presented in this current study provide new information about an understudied topic, a larger sample size would have allowed for a more sophisticated analysis approach which could have provided more detailed insights about how inhibitory control and early academic variables are related within-age and longitudinally.

Additionally, lab closures and national lockdowns due to the pandemic meant that two assessment points were missed in an important developmental period (24-months and 30-months). It is the toddlerhood period where very little is known about EF development (named by Kerr-German et al., 2023 as the 'toddler data desert'), and yet research has shown that it is during this period where EF skills may begin to stabilise (Broomell & Bell, 2022; Holmboe et al., 2021). The lack of longitudinal associations found in the current study may be due to a lack of stability in inhibitory control in infancy, and because there is likely substantial change in inhibitory control ability from late infancy to early childhood. As such, studying inhibitory control during the toddler years would have provided important information that is missing in the current study regarding a key transitional period of inhibitory control development. Whilst the current study provides an examination of the developmental trajectory of early inhibitory control, it is clear that this is an incomplete picture. Future research that focuses on inhibitory control development in the toddler period is essential. In this way, the full landscape of early development can be covered to form a clear understanding of the developmental trajectory from infancy to early childhood.

Due to the limited number of validated tasks appropriate for measuring early executive functions in infants and children, there is not yet a clear 'gold standard' task for the assessment of 'hot' inhibitory control in early development. Treasure Delay is a novel task used in the current study to assess children's ability to choose to delay gratification for a larger reward, based on the Less Is More task (Carlson et al., 2005). Whilst the 'Less Is More' task has been well-validated and used with this age group previously (Carlson et al., 2005; Moriguchi & Shinohara, 2019), the Treasure Delay adaptation of this task has not yet been validated. In the current study, preliminary validation efforts were made in examining associations between performance on the Treasure Delay task and other measures of 'hot' inhibitory control at 3½ years. Here, a negative association was found such that poorer performance on the Gift Delay task (another commonly used measure of 'hot' inhibitory control; Kochanska et al., 2000) was related to better performance on the Treasure Delay task. This association was in the opposite direction than expected and needs further investigation in a separate sample before it can be interpreted. In light of this, and since no other associations were found, future research should focus on validating the Treasure

Delay task in a separate sample of 3½-year-old children, alongside measures frequently used to assess 'hot' inhibitory control in preschool-aged children. Further, modifications to the task could be made to make it more structurally similar to the other hot inhibitory control tasks used with this age group.

Another potential avenue for further research is to consider extending the level of challenge that the Gift Delay task provides for 3½-year-old participants. Indeed, average performance on this task was near ceiling (reducing the variance in performance) and so suggests that an increased level of challenge would be necessary to capture a wider variety of behaviour. For example, whilst it was deemed necessary for safety reasons for the child's caregiver to remain in the room during the 3-minute delay, and although caregivers were instructed to be "busy" during the task (e.g., on their phone or reading a magazine) and to engage as little as possible with the child, it is very likely that the presence of the caregiver influenced children's behaviour during this task. Indeed, it would be expected that children may show poorer delay of gratification if they were alone during the task and did not know that they were not being watched! Future research should investigate how modifying the experimental set-up of the Gift Delay task can alter children's delay of gratification behaviours.

Although not reported in the current study, questionnaire data were collected from parents at all assessment points that reported on EF, temperament, emotion regulation, and behavioural difficulties at 3½ years. Future research is planned that includes these parent-report measures in the assessment of links between early inhibitory control and academic and behavioural outcomes. This research would aim to investigate how the longitudinal development of these early executive and regulatory skills may predict academic and behavioural outcomes in early childhood. Since questionnaire data continued to be collected during the pandemic, data are available during the toddlerhood period, which as previously described, will help to provide a full picture of development across the first four years of life.

5.4. Strengths and Implications

A strength of the current study is the contribution it makes to the existing literature in the field of early inhibitory control development. This study has been able to further support the results of Hendry et al. (2021) by replicating results about the nature and (lack of) stability of inhibitory control in infancy. Further, this study has added new knowledge about the relations (or, again, lack of relations) between hot and cool inhibitory control across the first years of life and lays the groundwork for the formation of a potential developmental trajectory in these early years. This study also contributed new knowledge in finding links between 'hot' inhibitory control and pre-academic outcomes, whereas previous research had

demonstrated these links only with 'cool' indices of inhibitory control. Overall, this study has provided a novel opportunity to longitudinally examine the development of early inhibitory control and to identify links between these skills and pre-academic outcomes.

A unique element of this dataset is that longitudinal data were available from the same sample of participants at three time points in the early years of life, including two time points that capture the transition from infancy (10-months) to the second year of life (16-months), and one 'follow up' time point in early childhood (3½ years). This enabled the longitudinal examination of changes in early inhibitory control from infancy to early childhood, as well as the exploration of how measures of 'hot' and 'cool' inhibitory control may develop across this period. Similarly, the addition of early academic skills measured in this cohort of children at 3½ years adds further value to this dataset. Uniquely, it has been possible to examine longitudinal associations between inhibitory control measured in infancy, with these pre-academic skills in early childhood. This is particularly novel, as to my knowledge, no previous datasets exist that have examined infant inhibitory control as a predictor of pre-academic outcomes in early childhood. Whilst previous studies have investigated associations between early childhood EF and later pre-academic skills (Kim et al., 2013; Morgan et al., 2019; Mulder et al., 2014; Schoemaker et al., 2013; Willoughby et al., 2011), this study was the first to offer insights from executive function in infancy to outcomes in the pre-school years.

To longitudinally examine the development of inhibitory control across infancy and early childhood, it was important to keep tasks designed to measure the same constructs the same, or as similar as possible, across assessment points (Holmboe et al., 2021). This is because when different tasks are used at different assessment points, it becomes difficult to interpret results as being due to age-related changes in performance, or due to an inherent methodological factor related to the task design or demands. However, it is also important to ensure that tasks are administered that are appropriate for the age and developmental stage of the child. In the current study, tasks were selected for the 3½ year assessment point that were structurally similar to those used in infancy. For example, 'cool' inhibitory control was measured in infancy using the ECITT, and due to the scalability of this task for use, it was appropriate to use this same task (with a single modification; faster task speed) to assess response inhibition in 3½ year-olds. As such, when assessing associations between performance on this task in infancy and early childhood, the potential influence of task-related factors is significantly reduced. In infancy, 'hot' inhibitory control was measured with two prohibition tasks, where the ability to resist touching an attractive object when told 'no' was measured. Since these tasks would be too easy and likely result in ceiling effects in 3½ year-olds, alternative 'hot' inhibitory control tasks were employed at 3½ years to measure

the child's ability to resist touching an attractive object when told to wait (the Gift Delay and Dinky Toys tasks). These tasks were structurally similar to the infant tasks (although with higher cognitive demand), as they also required the participant to withhold their response to an attractive object until the prohibition was lifted.

An important strength of this study was that the research questions, variables, hypotheses, and analysis plans were preregistered. The aim of preregistering this work before analysis (although after data collection) was to improve the transparency of the study by clearly outlining hypotheses and exploratory analyses in advance of statistical analysis. In doing so, I have demonstrated a commitment to avoid p-hacking in this research and to ensure the reporting of non-significant findings, as these are still meaningful knowledge contributions (but are often omitted from published reports). Since many correlational analyses were conducted in this study, it was important for these to be defined in relation to clear hypotheses that would either replicate existing findings or advance knowledge in this area, rather than just running multiple tests to search for statistically significant results. Data and materials related to this study will also be available on the OSF (following thesis completion) to encourage replication and collaboration between research groups interested in topics in early executive function development.

Another advantage of this dataset is that only a subset of tasks were examined in the current study (those measuring inhibitory control), whereas the OEEF study also included measures of working memory, attention, and shifting. As such, future research can examine the contributions of these other executive skills on pre-academic outcomes. The longitudinal data presented in this current study are very informative about the way inhibitory control develops in the first years of life and provide evidence that contributes to the full picture of what this developmental trajectory looks like from infancy and into early childhood. The outcome of this research has important implications since it is well-known that there are clear links between EFs and early academic outcomes. For example, a longer-term implication of this research could be that if it is possible to predict which children may go on to have academic difficulties at school before they enter the primary classroom, then it may be possible for targeted interventions and support to be put in place as early as possible. This could have a significant impact most importantly on the child's education and later successes (e.g., Moffitt et al., 2011), but also in terms of providing targeted support and improving access to support in the first years of primary school, instead of several years into formal schooling.

6. Conclusion

First, this study investigated within-age associations between 'hot' and 'cool' measures of inhibitory control in infancy and early childhood. Performance on 'hot' inhibitory control tasks was significantly associated in both infancy and early childhood, and performance on 'cool' inhibitory control tasks was significantly associated in early childhood. Additionally, in early childhood, there was some evidence of an association between performance on the ECITT ('cool') and Gift Delay ('hot') tasks. When examining longitudinal associations, there was no evidence of stability in 'hot' or 'cool' inhibitory control from 10- to 16-months, or from infancy to early childhood. Results hinted that performance on the ECITT ('cool') and on the 'hot' inhibitory control tasks at 16-months were associated with Go / No-Go performance ('cool') at 3½ years, however, these results require replication. Secondly, this study explored potential associations between early inhibitory control and pre-academic skills. Results found significant concurrent associations between 'hot' inhibitory control (Dinky Toys) and early academic skills at 3½ years. No other significant associations were found, which could suggest that there are few links between inhibitory control and early academic skills, or it may be that 3½ years is too early to reliably assess these outcome measures.

Uniquely, with longitudinal data collected from the same sample of participants using structurally similar tasks across this early development period, this study hinted at changes in the organisation of 'hot' and 'cool' inhibitory control from infancy to early childhood and identified some links between 'hot' inhibitory control and fundamental academic skills in the pre-school years. Overall, this study contributed important new knowledge to a currently under-studied area which will serve as a solid foundation for future research to investigate the structure of inhibitory control from infancy to early childhood and potential predictive relationships with early academic skills. Although not an immediate implication of the current study, research that continues to build on this work will provide the opportunity for a better understanding of how early cognitive (and neural) development supports early academic achievement, and to identify what a typical developmental trajectory looks like for EF from infancy and into the early years.

Chapter 8

General Discussion

1. Introduction

The overarching aim of the current thesis was to longitudinally investigate the emergence and behavioural development of inhibitory control and the associated functional neural correlates across the first four years of life. To do this, four experimental studies were conducted that followed the same cohort of participants at 10-months, 16-months, and 3½ years of age to study their development across this early period. With this valuable longitudinal data, it was possible to capture real *change* in inhibitory control skills over the first years of life, rather than simply identifying differences in performance at each assessment point. This thesis contributes important new knowledge to the field by providing information about the emergence of response inhibition and the associated neural correlates in infancy using fNIRS and tracking its development in the same cohort of participants into early childhood.

In this final chapter, I will first summarise the current thesis and highlight the key results. I will then discuss the implications and highlight the novel contributions of this research to early EF development. Next, I will acknowledge the limitations of the research presented in this thesis and describe important future directions. Finally, I will close with a conclusive summary of the thesis.

2. Summary of Thesis

After overviewing the current knowledge in the field and identifying key gaps in the existing literature (Chapter 1), I laid out the methodological approaches that would be used in the current thesis to examine early inhibitory control in infancy and early childhood (Chapter 2), with a specific focus on fNIRS as an important tool for measuring brain activation in early developmental populations (Chapter 3). The study reported in Chapter 4 investigated the functional neural correlates of response inhibition in 10-month-old infants using fNIRS. Results confirmed the trial-type effect previously observed when using this task with infants and young children (Hendry et al., 2021; Holmboe et al., 2021) such that infants were significantly more accurate on prepotent trials than on trials where inhibition was required. This study revealed that 10-month-old infants recruited right-lateralised regions of the

dorsolateral prefrontal cortex (DLPFC), the orbital frontal cortex (OFC) and the parietal cortex significantly more when inhibition was required (compared to when there was no inhibitory demand).

The study presented in Chapter 5 of this thesis investigated response inhibition performance and the associated functional neural correlates in 16-month-old toddlers and examined longitudinal change across the transition to toddlerhood. The behavioural results again replicated the trial-type effects found in previous studies (Hendry et al., 2021; Holmboe et al., 2021) and at 10-months (Chapter 4). The fNIRS results revealed that 16-month-old infants recruited the left superior parietal cortex, the right inferior frontal gyrus (IFG), the bilateral DLPFC, and the bilateral OFC when inhibition was required. Two channels (covering the right DLPFC and right OFC) were active at both 10- and 16-months, and exploratory longitudinal analyses suggested no significant change in the recruitment of these channels between the two assessment points. Whilst there was no significant response inhibition improvement on the ECITT from 10- to 16-months, there were differences in the recruitment of brain regions across this period. Exploratory longitudinal analyses revealed a significant increase in activation in channels covering the right inferior parietal cortex, the left DLPFC and the right IFG (orbital) from 10- to 16-months, preliminarily suggesting an increasing involvement of these brain regions when inhibition is required at 16-months.

The study presented in Chapter 6 followed this same cohort of participants as they reached early childhood (3½ years of age). This study longitudinally investigated the behavioural development of response inhibition and the associated functional neural substrates across infancy and early childhood. Results indicated that 3½-year-olds were significantly more accurate and made significantly faster responses on the ECITT compared to 10- or 16-month-olds. Whilst accuracy performance improvements were significantly greater on inhibitory trials, reaction time improvements were significantly greater on prepotent trials. Channels covering the right inferior parietal cortex and the right IFG (orbital) were significantly more active when inhibition was required at 3½ years, including two of the same channels that were also recruited when inhibition was required at 16-months. This consistency of recruitment could be evidence for the formation of a maturing response inhibition network already in the first years of life. Additionally, regions of the bilateral DLPFC and left OFC were also recruited at 3½ years, although this activation appeared not to be associated with response inhibition.

Finally, Chapter 7 investigated associations between ‘hot’ and ‘cool’ inhibitory control in infancy and early childhood and examined how measures of inhibitory control related to early academic outcomes at 3½ years. There was evidence to suggest some consistency in ‘hot’

inhibitory control performance across tasks in both infancy and early childhood. Whilst in infancy there were no associations between performance on 'hot' and 'cool' tasks, by early childhood an association had emerged between performance on the ECITT ('cool') and the Gift Delay ('hot') tasks, as well as an association between the two 'cool' tasks (ECITT and Go / No-Go). Overall, there was little evidence for the stability of individual differences in inhibitory control between infancy to early childhood. In early childhood, evidence hinted that there may be an important link between 'hot' inhibitory control abilities on the Dinky Toys task and early academic skills, already at 3½ years.

3. Implications of Results

3.1. Measurement of Early Inhibitory Control

3.1.1. The ECITT as an Index of Infant and Early Childhood Response Inhibition

Previous research has demonstrated that the ECITT can be used as a reliable and valid measure of response inhibition in infants as young as 10-months of age (Hendry et al., 2021), in toddlers aged 16 – 30 months (Hendry et al., 2021; Holmboe et al., 2021), and across the lifespan (Holmboe et al., 2021). By replicating the trial-type effect observed in both the accuracy (10-months, 16-months, and 3½ years) and reaction time variables (16-months and 3½ years), the studies presented in this thesis provide further supportive evidence for the validity of the ECITT as an age-appropriate measure of response inhibition across infancy and early childhood.

Two versions of the ECITT were used in the current study - one in which prepotent and inhibitory trials were intermixed (behavioural ECITT), and one (optimised for fNIRS) in which the key comparison was between blocks of mixed prepotent and inhibitory trials (requiring inhibition) and blocks with only prepotent trials (no inhibitory demand). Across the three age points, there was evidence of moderate test re-test reliability of response inhibition performance between the two versions of the task. This replicates the findings of previous studies that used the ECITT with the same infant age groups (Hendry et al., 2021) and with older toddlers (Holmboe et al., 2021). In their recent article, Byers-Heinlein et al. (2022) called for infant researchers to consistently report measurement reliability, such as test-rest reliability, as a step towards more reliable infant research. Since this is something that is not commonly done in infant research, the investigation and reporting of test re-test reliability of the ECITT across all age groups in this thesis is a strength of this research. Specifically, this

reliability increases my confidence that the lack of longitudinal stability in individual differences observed from infancy to early childhood may be a true effect, rather than the result of an unreliable task.

Whilst there was no significant performance improvement from 10- to 16-months (replicating the results of Hendry et al. 2021), there was significant performance improvement in both accuracy and reaction time from 16-months to 3½ years, suggesting that children get better at inhibiting from toddlerhood. This result aligns with that of Wiebe et al. (2012) who examined the performance of 3 – 5-year-olds on the Fish & Sharks (Go / No-Go) task and found that the largest response inhibition improvements occurred between 3 and 3.75 years of age. Whilst it may be that the improvement in response inhibition performance would only be expected from 3 years of age (as in Wiebe et al., 2012), more research is needed in the second and third years of life to determine when improvements in response inhibition performance may begin. Finally, there were no significant associations in performance from 10- or 16-months to 3½ years of life, suggesting that there is a lack of stability in individual differences across this developmental period. This makes sense in the context of existing knowledge which suggests stability in EFs occurs from around 18-months (Holmboe et al., 2021) to 2 years of age (Broomell & Bell, 2022), and so it might be predicted in future research that ECITT performance in the latter half of the second year would be associated with performance at 3½ years.

As previously discussed, there is a shortage of age-appropriate tasks that can assess different components of EF in pre-verbal infants and a lack of tasks that can be used longitudinally at several points in early childhood. A unique component of the dataset is that the ECITT (Holmboe et al., 2021) was used consistently across all ages in the longitudinal study. To my knowledge, this is the first time that the same task has been used to assess the same skill in the same cohort of participants across infancy and early childhood. Minor adjustments were made to the ECITT to ensure its suitability for 3½ year-olds; however, these changes did not alter the task structure and instead had the benefit of ensuring that the same task was engaging and suitably challenging for pre-school children. As such, the research presented in this thesis was able to investigate changes in performance on the ECITT from infancy to toddlerhood, and in early childhood, with the same cohort of children. In this way, it can be said with more confidence that changes in task performance are because of age-related improvements in response inhibition performance rather than changes in task design. Many in the early EF research community will be interested in this research and will recognise the value of using the same task across this period of early development.

3.1.2. Longitudinal Approach

Despite challenges relating to attrition in longitudinal studies (Gustavson et al., 2012) and the heterotypic continuity of inhibitory control (changes in inhibitory control as a construct across development; Petersen et al., 2016), many important benefits can be gained from research that takes a longitudinal approach to investigate the development of inhibitory control (and other EFs). Informative longitudinal studies have previously been conducted that have provided new knowledge about developmental change in EF performance across the first years of life. For example, an impressive longitudinal study followed participants from infancy (5-months, 10-months), across toddlerhood (24-months, 36-months, 48-months) and into middle childhood (9 years) (Broomell & Bell, 2022). This study had a large sample of over 400 participants and was able to use sophisticated statistical techniques (autoregressive model) to investigate the development of EF in infancy and childhood. In doing so, this study found evidence to suggest that toddler EF is a stable predictor of later EF and used a data-driven approach to determine which tasks were reliable measures of EF at each age point (Broomell & Bell, 2022). Similarly, longitudinal research has provided evidence for links between attention in infancy and EF in toddlerhood (Cuevas & Bell, 2014; Johansson et al., 2016), of improvements and stability in EF from 2- to 4 years of age (Hughes & Ensor, 2007), and evidence for predictive associations between toddler inhibitory control and neural and behavioural indices of inhibitory control at 5-years of age (Conejero et al., 2023). The knowledge gained from these longitudinal studies has paved the way for future research (such as that presented in this thesis) that investigates inhibitory control development from infancy.

A significant strength of this thesis is that the same, relatively large, longitudinal dataset is used across the four experimental chapters, where data were collected from the same cohort of participants to track their EF development from infancy (10-months, 16-months) and into early childhood (3½ years). Whilst it is extremely challenging to collect longitudinal data from infants and young children (more so during a global pandemic), this data is valuable and offers the rare opportunity to ask and answer many important questions about early inhibitory control development over time. Although data is not available from the important toddler period, and the sample size is smaller than anticipated, this longitudinal dataset contributes novel findings that advance existing knowledge on the developmental progression of inhibitory control, and the structure and (lack of) stability of inhibitory control as it emerges in infancy and develops across the first years of life.

3.1.3. Inhibitory Control Task Battery

Chapters 4 – 6 of the current thesis relied on a single task (the ECITT; Holmboe et al., 2021) to index response inhibition performance in infancy and early childhood. Whilst there are benefits to using a single task across multiple age points in longitudinal research (as described above), there are also methodological challenges, such as how to disentangle the inhibitory demand from the broader task demands (e.g., the task impurity problem; Miyake et al. 2000). However, Chapter 7 of this thesis (and indeed the larger OEEF longitudinal study) adopted a task battery approach for the measurement of early EF skills, such that multiple tasks were included to capture each component of EF (inhibitory control, working memory, shifting). This approach is particularly useful in studies with infants and young children, where task performance is more easily influenced by different task demands (e.g., familiarity with stimuli, motor skills, working memory demands) and also by situational and affective factors (e.g., tiredness, hunger, fussiness). Therefore, instead of relying on a single task (that may be prone to bias) as an index of an EF skill, the task battery approach enables performance to be assessed across multiple task conditions and can provide a more reliable assessment of EF.

This approach has been successfully adopted by longitudinal researchers as a useful tool to investigate the structure and development of early EF (e.g., Mulder et al. 2014) and for review, see Miller et al. 2023). For example, researchers have used the task battery approach to investigate the hierarchical theory of EF development, where it is proposed that simple component skills such as attention early in infancy are the building blocks for more complex EF skills that develop with age (Devine et al., 2019; Johansson et al., 2016). Additionally, research using the task battery approach has uncovered latent variables that may underpin early EF skills. For example, Hughes et al. (2009) found that performance improvements in EF tasks from 4 – 6 years of age were related to improvement in an underlying latent construct (that may reflect EF), rather than because of age-related improvements in other non-executive skills related to the task demands. Similarly, Gandolfi et al. (2014) applied a confirmatory factor approach to examine the latent structure of inhibitory control in young children and highlighted that whilst a single latent inhibitory factor best fit the data from the toddlers (24 – 32 months), a two-factor model (reflecting response inhibition and interference suppression) best explained inhibitory control processes in early childhood (36 – 48 months).

By using a battery of inhibitory control tasks in infancy (10- and 16-months) and early childhood (3½ years) in this current thesis, it was possible to investigate the structure and development of early inhibitory control processes. Specifically, this thesis examined whether ‘hot’ and ‘cool’ inhibitory control are separable or related skills and identified how the

relationship between these skills changes across the first four years of life. The results reported in Chapter 7 of this thesis suggested that, whilst there was some consistency in performance on 'hot' tasks in infancy and toddlerhood, and on 'cool' tasks in early childhood, there was no evidence of associations between 'hot' and 'cool' performance in infancy, and very limited evidence in early childhood. This result aligns with findings from Di Norcia et al. (2015), who found no significant associations between 'hot' and 'cool' inhibitory control measures in children aged 25 – 41 months. Overall, it could be that 'hot' and 'cool' inhibitory control are separable in infancy and may become more integrated from 3½ years of age. However, more longitudinal research is needed that adopts a task battery approach (ideally using the same or similar tasks as in the current thesis, for comparability) to investigate the structure of 'hot' and 'cool' inhibitory control across the first four years of life.

There are some important directions for future research that would improve the replicability of longitudinal task battery studies of early EF, as well as improve the open science practices in this field. For example, it can sometimes be difficult to compare the results of two studies because they have used different tasks to measure the same construct. It is then hard to determine whether contrasting results are due to task-based differences, or a genuine lack of replicability. This again comes back to the need for reliable, age-appropriate tasks of early inhibitory control (Holmboe et al., 2021; Petersen et al., 2016). Once established, these tasks should be used consistently across studies (as well as other tasks in the task battery) and administration and scoring protocols should be openly shared to improve replicability and reproducibility efforts in the field.

3.1.4. Task Consistency in Longitudinal Studies

Although it was not always possible in the current thesis to use the same tasks at all ages of the longitudinal study (indeed it was stated in a meta-analysis by Petersen et al. (2016) that most inhibitory control tasks are only developmentally appropriate for 3 years), efforts were made to ensure that tasks designed to measure the same constructs were structurally similar in infancy and early childhood. In this way, the measurement of specific facets of inhibitory control (e.g., response inhibition, delay of gratification) remained as consistent as possible (yet still age-appropriate) from infancy to early childhood. This enabled the study of real change in these inhibitory control abilities over time. Future research should continue to utilise these structurally similar tasks, particularly across the toddlerhood period where data is lacking, to replicate and expand on the findings of the current study.

Whilst keeping tasks the same or structurally similar across ages reduces the risk that confounding task-related factors may be captured, it is still possible that the inhibitory control

tasks used in this thesis may not have measured the intended skills. As such, it is necessary to consider the margin of error that may be associated with the construct validity of tasks used in this battery when interpreting the results presented in this thesis. For example, the role of self-regulation was not investigated in the current thesis (beyond delay of gratification tasks, conceptualised in this thesis as measuring 'hot' inhibitory control) and so it could be that inhibitory control in early childhood is supported by self-regulation skills that, like EFs, are also developing rapidly in the pre-school years (Hendry et al., 2016; Willoughby et al., 2011). Specifically, it could be that self-regulation is the driving force between the association found between performance on the Dinky Toys task ('hot' inhibitory control) and the pre-academic tasks at 3½ years. Similarly, the role of temperament (which has been linked to both self-regulation and EF in toddlerhood; Gago Galvagno et al., 2019), was not considered in the current thesis but may have played a significant role in how children recruited executive processes for each unfamiliar task, in an unusual environment. Although not reported here, parent-reported measures of self-regulation and temperament were captured for participants in this cohort, so future research could examine the contributions of temperament and self-regulation to inhibitory control development (as assessed in the current study). After all, EF skills do not develop in isolation but in conjunction with these other processes (Doebel, 2020).

This also highlights important theoretical considerations, particularly concerning terminology differences. For example, what is described by one researcher as 'hot' inhibitory control may be perceived by another researcher as 'self-regulation' or 'effortful control' (Nigg, 2017). Within the literature it has become difficult to disentangle the often intertwined and interchangeable labels used by authors who are in the field of cognition or neuroscience ('EF'), those in the field of temperament and self-regulation ('effortful control') and those in the field of attention ('executive attention'). It therefore becomes hard to integrate knowledge from studies published using these differing labels, and it is not always clear whether the methodologies and definitions used to describe one construct (i.e., effortful control) are distinct from those used in other studies investigating EF when indeed there is substantial overlap between the two (see Blair & Razza, 2007; Zhou et al., 2012). Future research is needed that helps to establish the theoretical similarities and differences between these overlapping concepts to bring more clarity to the closely related fields of EF, self-regulation and attention.

3.2. The Development of Early Inhibitory Control ('Hot' and 'Cool')

Whilst there has been large research interest in investigating the structure of EF in early childhood (McKenna et al., 2017; Miller et al., 2012; Mulder et al., 2014; Wiebe et al., 2008, 2011), including the distinction of 'hot' and 'cool' EF (e.g., Zelazo & Carlson, 2012), very little research exists that has specifically investigated 'hot' and 'cool' inhibitory control from infancy and across the first years of life. It is important to understand how 'hot' and 'cool' skills emerge and develop early in life, and to uncover the brain mechanisms and maturational processes that may underpin the potentially differential development of 'hot' and 'cool' inhibitory control. Since these skills are related to tangible outcomes (behaviour and academic performance respectively (Di Norcia et al., 2015; Kim et al., 2013b; Willoughby et al., 2011), research needs to understand as much as possible about how these skills develop from infancy and into early childhood so that timely interventions can be implemented, and support can be provided *before* the child enters the classroom.

Considering 'hot' and 'cool' EF more broadly, Zelazo & Carlson (2012) proposed that distinct regions of the PFC may underpin 'hot' and 'cool' EF. Whereas 'hot' EF may be functionally correlated with the orbital PFC, a region of the brain associated with affective, motivational, and reward-based processing (Happaney et al., 2004; Rolls, 2004), 'cool' EF is thought to be underpinned by the lateral PFC, an area of the brain commonly linked to more cognitive executive processes (Ezekiel et al., 2013; Levy & Wagner, 2011; Owen et al., 1999). Research by Carlson et al. (2005) that used the 'Less Is More' task found that when rewards were neutral, 3-year-olds were significantly more likely to choose the smaller reward (so that they would win the larger reward, as per the rules of the task) than they were when the rewards were attractive (e.g., jellybeans), in which case they found it difficult to overcome the impulse to point to the larger reward. It was proposed by Zelazo & Carlson (2012) that this result could be explained by the fact that the 'cool' rewards were likely drawing on the lateral PFC, which develops more quickly than the orbital PFC, which may be recruited when the rewards were more affective ('hot'). Therefore, it could be the case that full convergence of these skills occurs later in childhood when the development of these sub-regions of the PFC is more advanced. An fNIRS study by Moriguchi & Shinohara (2019) found that the lateral PFC (a region usually associated with 'cool' EF) was activated more strongly when 3½ - 4½-year-old children chose a smaller reward on the Less is More task (e.g., successful delay of gratification). However, since the study did not measure brain activation over the orbital PFC and did not vary the reward in the Less Is More task (neural vs. attractive reward, as in Carlson et al. (2005)), future research of this kind is needed to further understand how different parts of the PFC may contribute to inhibitory control in infancy and early childhood.

Whilst the results presented in Chapter 7 hint at the separability of 'hot' and 'cool' inhibitory control in infancy and the possible start of convergence in early childhood, there remains a large gap during the toddlerhood period (where we were unable to collect data because of the pandemic) in which very little is known about the development of 'hot' and 'cool' inhibitory control skills. Focusing on EFs more broadly (and with 'cool' EF indexed by working memory tasks), Mulder et al. (2014) found significant associations between 'cool' and 'hot' EF factors in 2-year-olds. However, they also found that a two-factor model where 'cool' and 'hot' were separate factors better fit the data than the model with a single EF factor (Mulder et al., 2014). Similarly, research has found that a two-factor structure in which 'conflict EF' (e.g., working memory, shifting, inhibitory control) was separable from 'impulse control' (e.g., delay of gratification) in 2- and 3-year-olds (Bernier et al., 2010, 2012a). As it stands, the toddler period is currently a 'data desert' (Kerr-German et al., 2023), and so future research that focuses specifically on 'hot' and 'cool' inhibitory control skills between 18- and 30-months of age should be a priority for the field.

Previous research had already established a lack of stability in inhibitory control across the transition to the second year (Hendry et al., 2021), and although the exact age varies slightly between studies, research consistently finds stability in inhibitory control from the end of the second year (Broomell & Bell, 2022; Carlson et al., 2004; Holmboe et al., 2021; Miller & Marcovitch, 2015). The results of Chapter 7 demonstrated a lack of stability in both 'hot' and 'cool' measures of inhibitory control across infancy (from 10- to 16-months, using the same task) and also from infancy to early childhood (structurally similar tasks). Whilst it was anticipated that there would be a lack of stability from 10- to 16-months, it was predicted that there may be stability from 16-months to 3½ years (which was not the case). Likely, the substantial development of inhibitory control skills that occurs during toddlerhood could explain the lack of stability. Again, since it is the toddler years where previous research has demonstrated stability in inhibitory control, and this is the very age period where data is missing from the current study (due to the pandemic), it is not possible to pinpoint where stability in inhibitory control emerges between the ages of 16-months and 3½ years. However, from the previous literature, clear hypotheses could be made expecting stability from 24-months (Broomell & Bell, 2022), and possibly from 18-months (Holmboe et al., 2021). Once more, this highlights that research across the toddler years is the missing puzzle piece in our knowledge about the stability and structure of inhibitory control development in the first years of life.

3.2.1. Early Inhibitory Control and Pre-Academic Outcomes

The results presented in Chapter 7 of this thesis found limited evidence of associations between early inhibitory control and pre-academic outcomes, as only one 'hot' inhibitory control task (Dinky Toys) was associated with both numeracy and vocabulary outcomes. This result is particularly interesting, firstly because the associations were found with performance on a single trial task, and secondly, because this result contradicts the existing literature, which has previously only related 'hot' inhibitory control to behavioural, not academic outcomes (Di Norcia et al., 2015; Kim et al., 2013b; Mulder et al., 2014; Willoughby et al., 2011). However, it could be that an underlying cognitive factor (e.g., general intelligence, attention or working memory) or a behavioural factor (e.g., temperament or compliance), is driving this link. Whilst these findings from this thesis expand the existing literature, there is a clear need for further research that uses the same tasks, as well as other indices of inhibitory control, to replicate the current findings. This would enable us to understand whether the link between 'hot' inhibitory control and pre-academic skills at 3½ years was task-specific or related to inhibitory control skills more generally.

The current thesis also investigated predictive associations between emerging inhibitory control skills and later measures of pre-academic skills. Whilst several research studies have examined links between early childhood EF and pre-academic skills (Mulder et al., 2014, 2017; Schoemaker et al., 2013; Spit et al., 2023; Whedon et al., 2020), no previous research has longitudinally examined links between EFs measured in infancy and pre-academic skills measured in early childhood. Although a longitudinal study by Blankenship et al. (2019) examined links between attention in infancy and EF in infancy and early childhood with reading achievement at age 6 and found both concurrent links between EF and reading achievement at 6 years, and a relationship between infant attention and reading achievement that was mediated by EF at all time points.

This novel component of the study enabled me to test whether inhibitory control processes already within the first year of life may be a precursor or building block for later pre-academic skills. However, the results presented in Chapter 7 found no evidence of longitudinal associations between inhibitory control in infancy and pre-academic skills measured at 3½ years. Despite the null result, this finding still has important implications as it may be that individual differences in inhibitory control are not yet consolidated or stable enough in infancy to drive pre-academic skills at 3½ years. This is highly likely, based on other evidence presented in Chapter 7 of this thesis which found a lack of stability in individual differences in inhibitory control performance from infancy to early childhood, as well as findings that 'hot' and 'cool' inhibitory control appear to be largely separable in infancy and

early childhood (although there was some evidence for convergence starting at 3½ years). As such, future research may be more likely to find significant predictive associations when examining links between inhibitory control in the second year of life (when evidence appears to suggest stability, e.g., Broomell & Bell, 2022; Holmboe et al., 2021) with early academic skills in the pre-school years.

3.3. The Neural Correlates of Response Inhibition across the First Years of Life

The research presented in Chapters 4 – 6 of this thesis starts to piece together a developmental trajectory of response inhibition and the associated neural correlates from infancy to early childhood. Whilst in infancy (10-months), activation was localised to right-lateralised regions of the DLPFC, OFC, and parietal cortex during inhibitory demanding blocks, the transition to toddlerhood (16-months) saw more widespread, bilateral PFC activation and left parietal activation, despite no change in response inhibition performance. By early childhood (3½ years), response inhibition performance is significantly improved, and activation is localised to the right IFG and the right parietal cortex, including two channels overlying these regions that were consistently recruited at both 16-months and 3½ years. This could mark the start of the maturation process for the neural regions that support response inhibition as it begins to improve in early childhood. Indeed, there is evidence to suggest that the involvement of the IFG may occur later in development and so may be a sign of more mature inhibitory control (Durston et al., 2006; Rubia et al., 2007; Schroeter et al., 2004). There was also evidence for the involvement of the bilateral DLPFC and the left OFC at 3½ years, although, contrary to expectations, this activation was not related to the inhibitory demands of the task. Whilst further research is needed to replicate these results, it could be that the involvement of these brain regions during the ECITT is related to activation of the default mode network (Bulgarelli et al., 2020; Raichle, 2015), or in monitoring processes and proactive control (Aron, 2011; Botvinick et al., 2001; Braver, 2012; Chevalier et al., 2015) – all of which appear to play an important role at 3½ years (but not in infancy). Until now, no previous fNIRS research has contributed knowledge about the developmental trajectory of the neural correlates of response inhibition from infancy to early childhood using a longitudinal sample of participants. As such, this thesis provides foundational knowledge about the development of response inhibition and the associated neural correlates very early in development, from which future research can continue to map out the neural correlates of response inhibition as it matures across later development.

A significant portion of the current thesis was dedicated to the use of fNIRS for the study of the neural substrates of response inhibition development across the first four years of life. As

a technique that is relatively new to the field of developmental cognitive neuroscience, fNIRS has opened many unexplored avenues for understanding the functional neural underpinnings of several facets of early development – in this case, response inhibition. Whilst neuroimaging research exists that identified the neural correlates of response inhibition in older children and adults (e.g., Aron et al., 2014; Aron et al., 2004; Durston et al., 2006; Tamm et al., 2002), it was not previously known whether infants and toddlers activated the same areas of the PFC (specifically the right IFG and DLPFC) and parietal cortex as adults when inhibition was required. Additionally, using a task that is structurally similar to response inhibition tasks used by older children and adults allows for the comparison of the results presented in Chapters 4 – 6 with knowledge about brain regions previously found to support response inhibition in older children and adults (e.g., Aron et al., 2014, 2004; Chikazoe et al., 2007; Swick et al., 2008). With the knowledge gained from Chapters 4 and 5 about the transition from infancy to toddlerhood, and from Chapter 6 about the transition to early childhood, this research enables, for the first time, a clear developmental trajectory to be delineated, one that tracks how the maturation and reorganisation of the PFC may support response inhibition development across the first four years of life.

An important direction for future research relates to the functional connectivity between prefrontal and parietal cortices that may support the development of response inhibition. Research by Mehnert et al. (2013) revealed that mature response inhibition in adults was supported by long-range functional connections between the bilateral PFC and parietal cortices, whereas response inhibition in young children (4 – 6 years) was associated with stronger short-range connections between right-lateralised prefrontal and parietal regions. Whilst the scope of the studies reported in the current thesis did not extend to functional connectivity analyses, this would be an important next step in further understanding how maturation of prefrontal and parietal cortices support response inhibition development. In this way, knowledge would be gained about how these regions of the brain work together to support inhibition performance as it progresses across development.

3.3.1. Brain Development and Inhibitory Control in the First Years of Life

It is useful to reflect on how the findings about the neural correlates of response inhibition in infancy and early childhood reported in Chapters 4 – 6 of this thesis relate to existing theories and studies of brain development. According to Kievit & Simpson-Kent (2019), there are three key theories for determining the relationship between brain development and cognitive improvement. These theories are ‘structural scaffolding’ (the current brain structure and function determines the change in cognitive performance), ‘cognitive plasticity’ (the

current cognitive ability drives the reorganisation of cortical structures), and 'correlated change' (advances in cognitive skill and changes in brain structure are correlated). The structural scaffolding theory (Kievit & Simpson-Kent, 2019) appears to align with Johnson's (2001) maturational perspective of functional brain development, which suggests that improvements in cognitive performance are attributable to the maturation of the associated brain regions. As such, an important question for the current discussion is whether brain activation precedes cognitive advancements in inhibitory control skills in infancy and early childhood, or whether cognitive advances drive the reorganisation of cortical regions.

The results of the current thesis suggested that whilst there was no significant change in response inhibition performance from 10- to 16-months of age, there were important differences in the recruitment of the prefrontal and parietal cortex when inhibition was required. Specifically, activation was right-lateralised to regions of the DLPFC, OFC and parietal cortex at 10-months, whereas more widespread bilateral regions of the DLPFC, OFC, and left parietal cortex were recruited at 16-months. This could be evidence to suggest that reorganisation of the prefrontal and parietal cortices occurs *in advance of* improvements in cognitive performance, therefore supporting the structural scaffolding (Kievit & Simpson-Kent, 2019) and maturational (Johnson, 2001) theories of brain development. Additionally, response inhibition performance improvements were found from 16-months to 3½ years, and there were also changes in the recruitment of prefrontal and parietal regions when inhibition was required. Whilst it was not possible to examine in the current thesis (due to longitudinal sample size limitations), it would have been informative to test the potential predictive role of earlier neural correlates for later behavioural performance on the ECITT. For example, to test the structural scaffolding theory (Kievit & Simpson-Kent, 2019) by examining whether brain activation at 16-months predicted later performance on the ECITT at 3½ years. On reflection, due to the lack of behavioural stability between these time points, further neural development over the toddler years likely needs to occur before significant predictive associations can be found. Future longitudinal research should continue to collect data using the ECITT and fNIRS across the toddler period to determine *when* response inhibition performance improves across this period, and whether there is evidence for changes in the neural correlates of response inhibition *before* performance improvements are observed.

Another important question for discussion is whether it would be expected that activation in the PFC and parietal regions (in response to an inhibitory demand) would increase across infancy and early childhood, or whether activation would decrease with age as brain regions may become more specialised (e.g., Durston et al., 2006). Recent EEG research by Whedon et al. (2020) demonstrated that an increase in frontal alpha power from 10-months to 4 years was directly associated with better inhibitory control performance (and indirectly associated

with better academic outcomes), at age 6. This suggests that increasing recruitment of the PFC with age directly supports improvements in inhibitory control performance. However, there is also evidence to suggest that there is decreased recruitment of neural regions with development, specifically that there is a shift from broad, global activation of the PFC to more refined, localised activation of the PFC during EF tasks (for reviews, see Casey et al., 2005, and Fiske & Holmboe, 2019). For example, fMRI research by Durston and colleagues (Durston et al., 2002, 2003, 2006) has demonstrated that compared to adults, children (aged 6 – 10 years) showed more widespread activation of the PFC during a Go / No-Go task. Similarly, fNIRS research by Chevalier et al. (2019) found that 5 – 6-year-old children with better cognitive control performance more strongly recruited the PFC, but by 8 – 9 years, better cognitive control performance was associated with less PFC activation.

The results of the current thesis appeared to suggest that there was a significant increase from 10- to 16-months in the recruitment of channels overlying the right inferior parietal cortex, the left DLPFC and the right IFG when inhibition was required, and a significant decrease in the recruitment of one channel over the right DLPFC from 10- to 16-months. However, this was not associated with performance. Additionally, activation in the same channel in the left DLPFC that increased significantly from 10- to 16-months, was also found to significantly decrease from 16-months to 3½ years. This may be evidence to suggest that widespread regions of the PFC and parietal regions are recruited in toddlerhood to support response inhibition, but that the involvement of these regions decreases and becomes more refined by early childhood. However, since there is such a large gap between 16-months and 3½ years, this thesis provides an incomplete picture of the changes in the recruitment of prefrontal and parietal regions across early development, and so future longitudinal research that also covers the toddler period would provide a more informative account. Further, cross-sectional research that examines differences in the recruitment of prefrontal and parietal regions during the ECITT in adults could help to test this theory, as the strength of activation in the mature brain could be compared with activation across several points in development.

It is also important to consider the relative contributions of the parietal cortex, as well as the PFC, to response inhibition performance across infancy and early childhood. Existing research has highlighted the role of functional connectivity between prefrontal and parietal regions in inhibitory control (Buss & Spencer, 2014, 2018; Kerr-German et al., 2022; Mehnert et al., 2013a; van Belle et al., 2014), and the interactive specialisation theory (Johnson, 2001, 2011) proposes that the formation of functional brain networks that become more specialised with development may underpin cognitive advances. Whilst functional connectivity analyses would be informative, they are beyond the scope of the current thesis and will be revisited in future research.

Despite this, it is possible to examine the contribution of the parietal and PFC during the ECITT in relation to Morton and Munakata's (2002) neural network models of perseveration. In line with this theory, it could be argued that the parietal cortex activation found across all three age points in the current thesis might be associated with perseveration and activation in the PFC may be related to successfully overcoming this perseveration. In this way, it would be expected that parietal activation would decrease as response inhibition performance improves, as there would be less perseveration. However, this does not appear to be the case in the current study (although note the constraints around signal quality in parietal channels, particularly at 3½ years). Existing studies have confirmed the recruitment of the parietal cortex in response inhibition tasks (Bunge & Wright, 2007; Durston et al., 2002; Garavan et al., 2006), and there is some evidence to support its involvement in the stopping process (Kolodny et al., 2017; Osada et al., 2019). Although it could be that the role of the parietal cortex in the ECITT task may be related to perseveration (as proposed by Morton & Munakata, 2002), it is more likely that it reflects some element of inhibitory processing. Future research that replicates the results of the fNIRS studies reported in this thesis will help consolidate the role of the parietal cortex in early response inhibition, however, extra attention should be paid to ensuring that optode-scalp coupling in parietal regions is optimised to improve the data quality from these channels.

Finally, it is important to consider the unexpected activation found in the bilateral DLPFC and the left OFC at 3½ years that was not related to the inhibitory demands of the ECITT. According to Duncan (2010), specific regions of the frontal and parietal cortices are recruited for a range of executive processes, and their adaptive neural coding framework (Duncan & Miller, 2002; Duncan & Owen, 2000) proposes that the PFC is flexible and can be recruited in response to a range of different contexts and demands. It may be that the unexpected findings at 3½ years are evidence of the flexible and adaptive role of the PFC in the cognitive processes involved in the ECITT task (e.g., working memory, goal maintenance, proactive control). However, it could also be related to the lack of challenge in the control blocks compared to experimental blocks (e.g., reflective of activation in the default mode network, or of 'off-task' thought; see Chapter 6 for more discussion). This evidence shows that even with the same task, and the same cohort of children, there is still clear development across not just inhibitory control processes, but also other cognitive domains related to task performance (that may also be facilitated by the PFC, e.g., context monitoring (Chatham et al., 2012)). The results of this thesis appear to suggest that these higher-order skills come 'online' at 3½ years but are not required during the ECITT in infancy and toddlerhood. Future methodological research with preschoolers (along the lines of work by Simpson and colleagues (Simpson et al., 2012; Simpson & Carroll, 2019; Simpson & Riggs,

2005a, 2006, 2005b) is needed that manipulates the level of inhibitory challenge and further probes the way preschoolers approach inhibitory control tasks like the ECITT. In this way, it may be possible to move towards a clearer picture of the neural correlates of response inhibition in early childhood.

4. Limitations

4.1. Sample and Statistical Analysis Limitations

Due to disruptions to the OEEF study caused by the COVID-19 pandemic, the sample size at all assessment points was significantly smaller than planned (planned *N* = 200). In an attempt to mitigate the impact of the attrition, data collected from pilot participants was included in this thesis. The pilot participants formed a mini-longitudinal cohort, as many of the pilot participants had also contributed data at 10-months and went on to contribute pilot data at 3½ years. Whilst the reduction in sample size due to the pandemic could not have been anticipated, it is important to note that this is a major limitation of the current study. This is because it reduced the statistical power for analyses and, as such, significantly limited the strengths of conclusions that can be drawn from this research. As such, the results of the current thesis warrant replication in future research to further support the preliminary (yet still valuable and informative) conclusions made here.

4.1.1. Sample Attrition

The usual attrition that would be expected in longitudinal studies over a prolonged period (Gustavson et al., 2012) was amplified somewhat because of the interruption to the study due to the COVID-19 pandemic. As such, there was significant attrition from infancy to 3½ years (54% response rate for session attendance at 3½ years, compared to 83% response rate for session attendance at 10-months). It is also highly likely that the resultant sample at 3½ years was biased towards a less diverse (i.e., predominantly White), higher socioeconomic status (SES) cohort of families who felt they were still able to participate after the pandemic disruptions. This is a major limiting factor of the study sample, which was already somewhat biased towards these population characteristics when the study started before the pandemic (although these characteristics represent the majority of families living in Oxford and the surrounding areas). This also limits the impact of the results presented in the current thesis as they may potentially only apply to predominantly white, high SES populations. As such, the generalisability of the results to broader populations is constrained

until further research with more diverse populations can be conducted and results are replicated.

Future research should make a specific and conscious effort when recruiting to ensure that families from a wide range of backgrounds are recruited to ensure diversity in the participant sample. For example, more time should be dedicated to engaging parents from all backgrounds in every stage of the research project, such that the needs of families are listened to (e.g., times they are more likely to be able to attend laboratory visits, what remuneration would be appropriate, preferred email frequency etc.) to improve the retention rate across the study. Further, efforts should be made to engage with families in their communities, including play days and other outreach events that increase the awareness and visibility of the Babylab within local areas, and to help to mitigate the potential misconceptions about infant research that may exist. This may involve expanding the reach of the recruitment drive to involve local areas that are more deprived but are slightly further away from the Babylab. Finally, although costly and potentially more challenging from a logistical perspective, to engage with families that may be harder to reach (thus under-represented in psychological research), it could be beneficial to bring the laboratory into the home. For example, with new advances in wireless fNIRS technology (Frijia et al., 2021; Zhao et al., 2019), it is very much possible to conduct more naturalistic testing sessions in the family home or local community (Dopierala & Emberson, 2023; Lloyd-Fox et al., 2019), thus removing some potential barriers to research and increasing the diversity of the participant pool.

4.1.2. Statistical Analysis Limitations

An associated challenge of the limited sample size at each assessment point and the cancellation of testing due to the pandemic is that the planned analysis techniques were no longer feasible to use with the reduced dataset. It was originally intended that structural equation modelling would be used to examine the relationships between variables across time points in the longitudinal study. As such, it was planned that a model would be developed that attempted to explain the development of EFs from infancy and across toddlerhood and this would be tested against the data collected in the OEEF study. However, due to the complexity of this technique, a sample of at least 200 participants is required (as previously explained, it was intended that data would be collected from 200 participants at each time point), and so it was no longer possible to perform this advanced statistical technique with the dataset collected.

As such, many of the statistical tests conducted on the data presented in the current thesis were correlational and examined the strength of the association between two variables. This analysis technique is informative as it enables the investigation of how individual performance differences in one variable are related to individual differences in another. However, it is limited in that if an association is found, it cannot be certain what is causing the association. Although causality can also not be assumed from structural equation modelling techniques, this analysis approach would have provided the 'big picture' of how variables relate to each other at the same time. Similarly, it may be that there is a third, unmeasured variable that is the cause of the shared variance between performance on two tasks. A correlational analysis will move knowledge forward by revealing the association, but there is room for error where researchers are left to make assumptions (based on theory or other evidence) about what is driving the association.

Further, as multiple tests were conducted on the same data, the problem of multiple hypothesis testing occurred in which it was necessary to control the false discovery rate (FDR) using the Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995). Whilst this procedure is less rigorous at controlling Type I errors (false positive results) than the Bonferroni correction, it does have greater statistical power and reduces the number of false positives (Haynes, 2013). It must be considered that many of the effects presented as significant in this thesis did not retain their significance once the FDR had been controlled. This is problematic in that these results can only be considered preliminary and should be followed up with other studies or replicated in other datasets. Consequently, this means that the conclusions that can be drawn from the data in this thesis are limited and should be considered with caution.

Whilst it is necessary to be transparent about the preliminary nature of these results, it is important to also point out that much of this work is novel and contributes new knowledge about the early development of inhibitory control in the first years of life. This work certainly warrants further investigation in future studies, and if results are replicated, will strengthen the conclusions of this current thesis. I am keen to continue this line of research with larger and more diverse samples and by using advanced analysis techniques to determine whether the results can be replicated.

4.1.3. Methodological Limitations

There are a number of methodological points that are worth discussing, specifically related to the approaches selected for analysing the ECITT at both the neural and behavioural level in Chapters 4 – 6 of this thesis. The first point relates to the variable number of trials

completed by participants in the ECITT within each assessment point. Since the task had no set stopping point and was only stopped once the participant was showing signs of disengagement, this meant that different participants completed different number of trials. It follows then that some participants who completed more trials would have had more opportunity to develop a strong prepotency, and also would have had more exposure to inhibitory trials (and so more opportunity to practice inhibiting) than other participants. It could be that these participants are at an advantage compared to participants who completed less trials, and so it becomes difficult to compare individual differences in performance when these differences may be due to factors other than inhibitory control abilities (e.g., fussiness). Although, individual differences in related executive skills (e.g., sustained attention) may also be related to the number of trials completed by participants. At present, these factors could introduce a potential confound in the data. A potential way to overcome this bias may be to calculate a weighted accuracy score, which takes into account the number of trials completed by each participant in their overall accuracy score for each trial type. This would be necessary across all assessment points and is important as it would allow for a more reliable insight into individual differences in children's inhibitory control abilities.

Relatedly, it is important to consider how the exposure to more trials over time (which in theory leads to the development of a stronger prepotency) may be masked or distorted by dividing the haemodynamic response into 5 s time bins (as in the fNIRS analysis presented in Chapters 4 - 6. This is because it may be reasonably expected that the haemodynamic response would build over the block time course and so segmenting the continuous data into time bins may warp our understanding of the neural response across the block time course. The purpose of this analysis was to understand more about the timing of the neural response across the time course, which was informative because I was able to examine patterns in neural responses over time and across assessment points. However, it may be that there is a conflict between this segmenting approach and the intention of the task to encourage the development of a prepotency over time, which is important to consider when interpreting results. Future research should examine ways to utilise the full continuous block time course and take into account the varying durations and number of trials, without making pre-determined assumptions about the shape of the HRF (as is typical in general linear model approaches). This is a statistical and methodological challenge that I hope will be possible to resolve in the near-future and apply to this dataset in order to provide a more complete picture about the neural response to the ECITT.

A further limitation of the time-bin analysis approach was that, due to the variable duration and number of trials, it is likely that when comparisons were made between block types,

trials of the same type may have been pitted against each other. For example, because the experimental block contained both trial types, comparisons could have been made between prepotent trials in the control block and prepotent trials in the experimental block. Whereas the more powerful comparison (e.g., where we would expect there to be differences in neural activation due to different demands), would be to compare prepotent trials in control blocks with inhibitory trials in experimental blocks. Whilst the latter is still happening within the analyses that were conducted, it is likely that the prepotent vs. prepotent comparison could have diluted some of the differences in neural activation between conditions. This analysis approach was necessary due to the blocked design of the task in order to examine differences in neural activation between block types, and to probe how this varied over the length of the block time course. As such, it remains an appropriate method to enable me to examine neural differences between control blocks with no inhibitory demands, and experimental blocks where inhibitory processes are recruited.

However, it cannot be ignored that results might have been stronger and / or more likely to survive correction for multiple tests if the comparison was made between prepotent trials (control blocks) and inhibitory trials only (experimental blocks). Whilst I have included a discussion about the benefits and limitations of blocked design vs. event-related design for the ECITT with fNIRS in Chapter 3 of this thesis, it is worth highlighting that this is an important area for future research. Specifically, to consider how best to utilise the ECITT task design and to identify the best statistical analysis approach for this design to uncover the neural correlates of early inhibitory control. This would also open doors to employing different methodologies (such as EEG) alongside the ECITT to further contribute additional knowledge about the timing and strength of neural responses in different trial types. This knowledge would complement the findings of this thesis about the recruitment of specific regions of the frontal and parietal cortices when inhibition is required in infancy and early childhood (see Section 5.3. of this chapter for related discussion about the benefits of employing the ECITT in other experimental contexts).

4.2. Laboratory Environment

As is the case for almost all developmental research, it is important to consider the laboratory environment within which data were collected from participants, particularly for 3½-year-olds. Although participants visited the lab twice at each age point, the environment likely remained unfamiliar to participants, and they may have engaged with different researchers at each visit. Whilst this may not have had much impact on performance in infancy, it is still likely that individual differences between participants concerning

temperament may have impacted infants' engagement with an unfamiliar experimenter. Additionally, participants were exposed to a range of unfamiliar technology, including the fNIRS cap, which some children would have coped with easier than others. This would have been the case more so at 3½ years - because data was collected shortly after the pandemic, there were large differences between children with regards to how quickly they warmed up, their confidence in a new environment, their social engagement with the experimenter (who was wearing a face mask and other personal protective equipment), and their compliance with task instructions.

Although laboratory-based research may lack ecological validity and the tasks that children are required to complete may employ EF skills in a different way than in naturally occurring scenarios in everyday life, the data collected in this study still provide an important snapshot of the inhibitory control abilities of infants and young children. Future research that focuses on capturing inhibitory control (and other EFs) ability as they occur spontaneously in everyday life, in situations such as during play (Veraksa et al., 2022) or during a structured activity (such as children may experience at preschool, e.g., Moreno et al., 2016; Obradović et al., 2017) would be a fundamental next step to understanding how inhibitory control develops across the early years of life (see also Moreno-Llanos et al., 2023). As well as this, it may be possible to investigate how inhibitory control develops alongside other skills such as language and theory of mind (e.g., d'Apice et al., 2019; Draperi et al., 2022; Hughes & Ensor, 2005, 2007; Trouton et al., 2002; Verhagen et al., 2017). This would link nicely with the recent calls to reframe our thinking about measuring EF development by considering EF not in isolation but in parallel to other skills and with cultural and environmental influences (Doebel, 2020).

4.3. fNIRS Methodological Limitations

The current thesis presented a series of three experimental chapters in which fNIRS was used to investigate the functional neural correlates of response inhibition across the first four years of life. As a technique that is still relatively new, more so to the field of developmental cognitive neuroscience, there are some important methodological challenges associated with fNIRS that must be addressed (although it is worth noting that all neuroimaging methods come with their strengths and limitations).

The first point for consideration is the amount of attrition that should be expected when using fNIRS with early developmental populations. Although significant attrition is expected in infant fNIRS studies (Baek et al., 2023), attrition at both 10- and 16-months was higher than the average attrition rate found in the meta-analysis. The reasons for infant-driven attrition of

fNIRS data at 10-months were: refused to wear the fNIRS cap at all (*N* = 3) or for long enough (*N* = 3), did not complete a sufficient number of blocks whilst wearing the fNIRS cap (*N* = 16), and that there was no longer a sufficient number of blocks once invalid blocks had been excluded (*N* = 13). Signal-driven attrition at 10-months was minimal: 7 participants were excluded because more than 2/3 of channels had either very high or very low optical density. A large proportion of attrition at 10-months was unfortunately due to the placement of the fNIRS cap being invalid (*N* = 19). At 16-months, infant-driven attrition was still substantial: refused to wear the fNIRS cap at all (*N* = 8), or for long enough (*N* = 5), did not complete the required number of blocks (*N* = 3), and did not have the sufficient number of blocks once invalid blocks were removed (*N* = 4). Signal-driven attrition at 16-months was minimal (*N* = 2). However, again, a large proportion of attrition at 16-months was due to the invalid placement of the fNIRS cap (*N* = 16). Note that the 16-month sample size was already limited due to the pandemic, and so the additional attrition of fNIRS data meant that the sample was relatively small (*N* = 43), although still comparable (Porto et al., 2020), if not larger, than that of other infant fNIRS studies (Bulgarelli et al., 2020; Mateus et al., 2021). At 3½ years, very few participants (*N* = 5) were excluded due to poor cap placement (although note that generally 3½-year-olds were much more compliant when the fNIRS cap was fitted to their head). The child-driven attrition came from the following: the child refused to wear the fNIRS cap at all (*N* = 10), or for long enough (*N* = 2), or because they did not have a sufficient number of blocks once invalid blocks were removed (*N* = 8). Signal-driven attrition at 3½ years was higher than in infancy (*N* = 13), but this was likely due to issues with optode-scalp coupling due to children having more hair at 3½ than in infancy.

It is fundamental that the fNIRS cap is placed in the standardised position on each participant's head to increase the certainty that the channels are positioned over the cortical regions they were designed to cover. There is undoubtedly always going to be some margin of error in doing so, both due to the variability of head size and shape between participants, but also in the agreeability of the young participant on the day. Since it became apparent during infant data processing that it would be easy to improve the attrition particularly related to poor cap placement, this was something that I worked hard on when running fNIRS testing sessions at the 3½ year assessment point. I will be certain that when conducting any future fNIRS research appropriate training will be provided about the optimal position of the fNIRS cap and to consider more carefully the delicate balance between getting the cap position correct and starting the task whilst the participant is still attentive and engaged.

The second point for consideration is the lack of standardised experimental and analysis approaches in the field of fNIRS research. To my knowledge, the research presented in the current thesis was the first time that fNIRS had been used with infants under 2 years of age

to study the neural correlates of response inhibition. As such, there was no template to follow and no study to replicate. Similarly, since the field of fNIRS is still relatively new, there is no standardised approach that is commonly used in the field. At present, most researchers use their own design and analysis approaches that have been passed down within their lab. This meant that conducting fNIRS research for the first time as part of my thesis was an incredibly challenging process. In an attempt to combat this, there has been a recent 'best practices' guide written by experts in the field to take a step towards improving the standardisation and reproducibility of fNIRS research (Yücel et al., 2021). To increase the transparency of this infant and early childhood fNIRS research, extensive pre-registration documents were submitted to the Open Science Framework (OSF) outlining the research questions, hypotheses, analysis plans, task design, and data set used. In addition, data sets relating to each chapter are freely available on the OSF to encourage reproducibility efforts and further use of the data.

5. Future Directions

5.1. fNIRS Functional Connectivity Analyses

The fNIRS data presented in the current thesis aimed to identify the functional neural correlates of response inhibition in infancy and early childhood. The approach to doing this was to investigate the haemodynamic response in channels overlying specific regions of the frontal and parietal cortices and to compare differences in haemoglobin concentration in blocks where inhibition was required to blocks with no inhibitory demand. The result of this was that I was able to isolate specific areas of the prefrontal and parietal cortex that underpin response inhibition in the first four years of life. However, it is unlikely that the brain regions identified in this study are working in isolation. Previous research has suggested that functional connections between frontal and parietal cortices strengthen with development to support the improvement of executive processes in toddlers and young children (Buss & Spencer, 2014, 2018; Kerr-German et al., 2022; Mehnert et al., 2013a). As such, it would make sense that an important next step to this current series of fNIRS studies is to apply connectivity analyses to the existing data. In this way, it would be possible to elucidate whether the regions of the brain found to be active in the current set of studies are functionally connected, and also how functional connections between brain regions in the frontal and parietal cortices may change with age to support response inhibition development. It would also be possible to examine whether functional connectivity between the regions of interest is associated with inhibitory performance as measured by the ECITT.

Plans are in process that, following thesis submission, I will undertake training on this advanced analysis technique to apply functional connectivity analyses to these existing datasets, with the planned outcome of a publication.

5.2. Replication in Larger Sample

Although not my own research, my supervisor Dr Karla Holmboe has recently started another longitudinal study that largely replicates the OEEF study. As part of this study, the ECITT will be administered alongside fNIRS with infants aged 10- and 16-months. As previously mentioned, many of the results from the fNIRS studies presented in this thesis did not survive the procedure for controlling the false discovery rate, and so require replication. Therefore, the results from the new longitudinal fNIRS research will act as a replication of the results reported in the current thesis, and if the results are aligned, will strengthen the conclusions made about the functional neural underpinnings of response inhibition in infancy. Additionally, the new study will have sufficient statistical power to examine brain-behaviour and brain-brain associations longitudinally, which the current study was not sufficiently powered to do. Further, there is potential for the two samples to be combined and for analyses to be conducted on a very large sample of infant participants, which would be extremely novel in the infant fNIRS community. These efforts will be beneficial from an open science perspective in that results are reliable and replicable, and also in terms of the contribution of reliable new knowledge about early inhibitory control development. However, if the results do not align (which is not expected), this will make for an interesting examination of potential methodological limitations and sample differences that could have caused results to diverge. I will be able to work alongside Dr Holmboe to address these differences and will contribute to a publication where the discrepancies or similarities in results are examined. This is good practice for the fNIRS community and will set an example of transparency in science, whereby discrepancies in results are not hidden or conceived to take away from the contributions of studies, but instead to examine potential explanations for differences in results.

Similarly, since the new longitudinal study will use many of the same ‘hot’ and ‘cool’ inhibitory control tasks in infancy (10-months, 16-months), it will be possible to examine whether the results presented in Chapter 7 of the current thesis will be replicated in a larger sample of participants. Since data can be collected from the full sample of ~200 participants at 10- and 16-months, we can determine whether statistically significant results that did not survive correction for the FDR in this current study were true results (e.g., replicated in a larger sample) or indeed false positives. This opportunity of replication in a large sample with

the same tasks and same age groups will allow for a more in-depth examination of early inhibitory control development and will complement and extend the results presented in this thesis.

Additionally, I will apply for post-doctoral fellowships where I intend to continue this line of research in my independent work. This will focus on investigating the development and functional neural correlates of early EFs in toddlerhood (e.g., 18 – 36 months). This age group is of particular interest to me because this is the age group that was not studied in the OEEF longitudinal study (due to the pandemic-related lab closures), and also because of the clear lack of research that exists in this period. In this way, I will be able to contribute to the literature by adding new knowledge about this early developmental period that may 'fill in the gaps' of this current thesis.

5.3. Using the ECITT in Other Contexts to Examine Early Inhibitory Control

In the context of the current thesis, I have presented evidence for the validity and reliability of the ECITT as a measure of response inhibition in infancy and early childhood. This thesis has also demonstrated how the blocked ECITT can be used alongside fNIRS to uncover the functional neural correlates associated with response inhibition across early development. However, it is important to consider the ways in which future research could further utilise the ECITT in other contexts – both in terms of alongside different neuroimaging modalities, and to examine early inhibitory control development through a different lens.

There were several advantages to using fNIRS to examine the functional neural correlates associated with inhibitory performance on the ECITT – not only the child-friendly nature of the neuroimaging technology, but also the spatial resolution that offered unique insights into the functional activation of specific regions of the parietal and prefrontal cortices. However, this is not without limitations (as described previously). A potential point of consideration is that, when examining neural activation in different block types (control, experimental), it is possible that comparisons are sometimes made between trials of the same type, due to the necessary design of the experimental block which also contains prepotent trials. This may mean that some of the neural activation specifically associated with the inhibitory process is masked by the activation associated with prepotent trials in the experimental block. With the current task design and analysis procedures, it was not possible to disentangle this activation and so it likely that there is more information to be gained about the neural substrates of inhibitory control that cannot be uncovered within the current methodological parameters.

As such, it is important to consider that there may also be benefits for future research that uses other child-friendly research methods and neuroimaging modalities, such as EEG, to provide additional knowledge about the neural processes that may underpin performance on the ECITT. The enhanced temporal resolution of EEG (compared to fNIRS) alongside the behavioural version of the ECITT would provide an opportunity for new information relating to the timing of neural activation in both trial types to be discovered using event-related potential paradigms. Further, this would enable comparison with other EEG studies that have investigated early inhibitory control using tasks such as the traditional A-not-B task (Bell & Wolfe, 2007; Whedon et al., 2020), which would help further validate the results of the ECITT at both the behavioural and neural levels. An additional direction for future research would be to utilise eye-tracking methodologies alongside the ECITT to provide a further layer of information about inhibitory processing in infants and young children. For example, by understanding whether there is a consistency (or indeed inconsistency) between participant's motor responses and eye movements would help inform us about the relationship between visual and motoric responding and would uncover how this relationship changes across early development. This eye-tracking information could also improve the validity of the behavioural coding on the ECITT as it may indicate the intended direction of the participant's intended motor response, even when motor responses may not be clear and direct (particularly the case with younger infants). Overall, this work would enhance the existing findings gained from the current thesis and contribute new knowledge that would support the development of a full picture of the neural correlates and behavioural development of early inhibitory control.

Finally, it is also important for future research to explore the social development implications of early inhibitory control development. As previously stated, EFs do not develop in isolation and it is necessary to consider EF in the context of the developing child in a social world (Doebel, 2020). Infants and toddlers are embedded in their social environments and are continuously exposed to new opportunities to practice engaging their newly developing EF skills and are also absorbing knowledge about how those in their social environment employ EF skills to solve problems. In this way, it could be said that the child's social environment and interactions within that environment are crucial for the development of their EF skills (Bernier et al., 2012b; Marciszko et al., 2020). Indeed, research has established links between parent and child EF (Kao et al., 2018), highlighting the key role that parents play in the development of early EF skills. The role of the social environment is particularly important at the transition to toddlerhood, where many children experience new social environments as they attend early childcare settings, which itself introduces important implications for early EF development (Berry et al., 2014). For example, research has

demonstrated how reconceptualising EF activities through play offers early childcare practitioners the opportunity to integrate opportunities for EF practice into their daily teaching practice, in turn supporting children's developing EF skills (Fleer et al., 2017). As such, a fruitful area for future research lies in examining early EF through a social lens in order to better understand the factors that may influence its development at both the behavioural and neural level. This also enables a more wholistic perspective of child development and could provide opportunities for future research that uses naturalistic settings and tasks to assess early EF skills within the context that they are used on a daily basis.

5.4. Hot Inhibitory Control in Early Childhood: Strategy Use and Task Validation

Future research is planned that investigates the use of strategies during delay tasks at 3½ years of age. During piloting for the 3½ year assessment point, it became apparent that throughout the waiting period in the delay of gratification tasks (e.g., Gift Delay, Treasure Delay) children displayed an incredibly rich variety of behaviour that could not be captured by a simple 5-point numeric coding scheme. It was obvious that children showed a range of different behaviours to help them cope with the period of waiting, and that some children appeared to find the waiting period easier than other children. This is something that became very interesting to me, as this behaviour may be very informative about the success or failure of children to delay gratification. Research into self-control in young children by Mulder et al. (2019) suggested that different distraction strategies may be used by children during a waiting period, some of which are more beneficial to the successful delay of gratification. For example, this study found that children who spent longer looking away from the attractive object and holding their hands back were more successfully able to delay gratification. To open a similar line of investigation, it was decided that an adapted version of the behavioural coding scheme used in Mulder et al. (2019) would also be used during the Gift Delay and Treasure Delay tasks (Chapter 7 of this thesis) to capture the strategies used by 3½-year-old children during the waiting periods of these tasks (see Appendix F1).

In preliminary work based on task administration and video coding, I have potentially identified four behavioural profiles shown by the 3½ year-olds in this sample on the delay of gratification tasks:

1) 'Good' inhibitory control - use limited or no strategies and pass the task (didn't need many strategies to pass the task, found waiting easy)
2) 'Developing' inhibitory control – lots of strategies were used but passed the task successfully (appropriate strategies chosen to support the ability to delay gratification)

3) ‘Poor’ inhibitory control – lots of strategies were used but failed the task (trying out lots of strategies but not yet able to choose the appropriate strategies to support the successful delay of gratification)
4) Failure to delay gratification – little-to-no strategies were used, failed the task (child doesn’t use strategies because these may not yet be available to them, and so aren’t able to apply any strategies to try and delay gratification).

According to Mulder et al. (2019), 2 – 3-year-old children who engaged in strategy use (particularly distraction strategies that avoided the object) early on in the waiting period were more likely to be successful at delaying gratification. This result leads to a testable hypothesis that I am planning on testing with the strategy data collected from 3½-year-old participants on these two tasks. I am interested in investigating whether pass/failure of the task is linked to the number of different strategies used, or the type of strategy used (e.g., distracting or focused behaviours). I am also keen to discover whether strategy use during these delay of gratification tasks has any associations with children’s ‘cool’ inhibitory control abilities at 3½ years of age, as well as with their pre-academic outcomes. I am hoping to conduct this analysis and prepare a publication on this topic following the submission of this thesis, in collaboration with my previous placement student Alicia Mortimer.

Similarly, as the Treasure Delay task used in this thesis was a novel task, adapted from the Less Is More task (Carlson et al., 2005) by Alicia Mortimer and myself, I am planning to conduct follow-up work that aims to validate the task and demonstrate its reliability as a measure of delay of gratification in early childhood. This will likely involve data collection from another sample of 3½-year-old participants, as well as examining the relationship between performance on the Treasure Delay task and other measures of inhibitory control (as in Chapter 7 of this thesis). It is planned that the task validation efforts will form part of the distraction strategy paper (as described above), which I will work on post-thesis submission.

5.5. Inhibitory Control in the Context of Early Executive Function Development

Finally, an important direction for future research would be to consider the development of inhibitory control in the broader context of early EF development. The larger OEEF longitudinal study included several tasks that were designed to measure attention and EF in infants and young children, and so data are available on this same cohort of participants at 10-months, 16-months, and 3½ years of age. As well as this, parent-reported questionnaire data are available (also across the understudied toddler years) on EFs, as well as many facets of development including temperament, language, motor skills, sleep, socio-emotional

development, behavioural and emotional problems. This information will provide invaluable insight into development more broadly, as well as the interplay between EF development and the development of other important skills in the early years (Doebel, 2020).

This thesis focused specifically on inhibitory control development and explored themes relating to the structure and stability of early inhibitory control, as well as the functional neural correlates of early inhibitory control across the first years of life. However, the findings of this thesis would be enhanced by placing this knowledge in the context of broader EF development (e.g., executive skills such as working memory and shifting). This would also have important theoretical implications relating to examining the structure of early EF already in infancy. For example, by contributing to the discussion in the literature about whether early EF may be best described by a single latent factor or multiple factors (Miller et al., 2012; Mulder et al., 2014; Wiebe et al., 2011), but with the addition of examining how structure may change across development. Additionally, it would be possible to consider whether inhibitory control performance could be predicted by or may be influenced by performance on other executive tasks or wider facets of development.

Finally, it would be possible to examine relations (both concurrent and longitudinal) between the pre-academic numeracy and literacy measures collected at 3½ and other skills measured across infancy and early childhood. This would provide new knowledge, beyond what is presented in the current thesis, about how facets of EF development, as well as a broad range of other early skills, may support early academic skills (e.g., Becker et al., 2014; Brock et al., 2009). This line of research is something that I am very passionate about continuing as I start my post-doctoral career, and I believe that this valuable longitudinal dataset would enable me to gain a contextualised perspective of inhibitory control, and EF more broadly, as it develops across the first four years of life.

6. Conclusion

This thesis explored the early development of inhibitory control in the first years of life, identified the neural correlates associated with this development, and mapped behavioural developmental trajectories into early childhood. Chapter 4 of this thesis utilised a novel methodological paradigm to demonstrate the reliable measurement of response inhibition already in the first year of life and to identify with fNIRS, for the first time, the involvement of regions of the right prefrontal and parietal cortices in the infant brain when inhibition is required. Extending this research by examining the development of response inhibition and the associated neural correlates across the transition to the second year of life, Chapter 5 of this thesis demonstrated that, despite there being no change in response inhibition

performance from 10- to 16-months, the functional neural substrates that support response inhibition are changing across this period. This potentially suggests that the functional mechanisms mature *in advance* of behavioural performance improvements. Chapter 6 demonstrated that response inhibition performance improves significantly in early childhood and that the associated neural correlates in the right inferior parietal cortex and the right IFG were somewhat consistent from 16-months to 3½ years, possibly marking the start of the formation of a mature response inhibition brain network. Finally, Chapter 7 contributed new knowledge about the structure of 'hot' and 'cool' inhibitory control both in infancy and early childhood and highlighted preliminary links between 'hot' inhibitory control performance and early academic outcomes at 3½ years. Whilst no clear links were found between infant inhibitory control and pre-academic skills at 3½ years, this research was the first to investigate this association from infancy to early childhood.

Overall, this thesis sheds new light on the development of inhibitory control from its emergence in infancy and as it develops across the first years of life. Using novel methodological techniques this thesis has also uncovered the functional neural mechanisms that underpin response inhibition development from infancy and across early childhood. The rich longitudinal dataset has enabled the contribution of significant new knowledge to the field of early EF development, which will act as a much-needed springboard for future research to continue investigating the emergence and development of early inhibitory control, with a particular focus on the toddlerhood period (where this dataset was limited). The knowledge gained from this thesis advances the field and takes us one step closer to mapping the full developmental trajectory of inhibitory control from its emergence in infancy and across the lifespan.

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