5-2019

Looking and Thinking: The Relationship Between Attention Functioning and Executive Functioning in 2.5- and 3.5-year-olds

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Recommended Citation

Kerr-German, Anastasia Nicole, "Looking and Thinking: The Relationship Between Attention Functioning and Executive Functioning in 2.5- and 3.5-year-olds. " PhD diss., University of Tennessee, 2019.
https://trace.tennessee.edu/utk_graddiss/5473

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I am submitting herewith a dissertation written by Anastasia Nicole Kerr-German entitled "Looking and Thinking: The Relationship Between Attention Functioning and Executive Functioning in 2.5- and 3.5-year-olds." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Psychology.

Aaron Buss, Major Professor

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(Original signatures are on file with official student records.)

Looking and Thinking: The Relationship Between Attention Functioning and Executive Functioning in 2.5- and 3.5-year-olds

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Anastasia Nicole Kerr-German
May 2019

DEDICATION

This dissertation is dedicated to my family. Thank you for your unwavering support, love, and encouragement. I would not have crossed the finish line without you.

ACKNOWLEDGEMENTS

I would like to thank my graduate advisor, Dr. Aaron Buss, for all of his guidance and wisdom throughout my graduate training. Aaron pushed me to think differently, work harder, and understand theory more deeply. I am forever grateful for those lessons. I also want to thank Caglar Tas for the countless hours she invested in my understanding of the experimental process and for spending so much time with me working on every step of this project. Her guidance in coding eye-tracking tasks and analyzing data was monumentally helpful for the success of this project. She has been a second advisor to me. I want to thank my husband for his unwavering support and encouragement. I want to thank my son for his sacrifice of my time and for inspiring me. My fellow lab mates, Kaleb Kinder, Jessica Defenderfer, Kara Lowery, Rachel Eddings, and Meagan Smith, were here at different times through all of these years in support of this degree and for that I am thankful. I would like to thank the members of my doctoral committee, Drs. Daniela Corbetta, Shannon Ross-Sheehy, and Xiaopeng Zhao, for all of their guidance throughout the doctoral process. These committee members, in addition to my advisor, invested countless hours in my progress, provided feedback and support, and have helped mold me into the researcher I am today. For that, I thank them. Finally, I would like to thank Maigread Lennon, Kelly Knag, and Megan Montana. These undergraduate research assistants aided in collecting all my dissertation data. Without them, this project would not have been possible.

ABSTRACT

Attention is the initial step in a cascade of perception and action. Cognitive processing, and subsequent encoding and retrieval are dependent on the success of attentional engagement and efficiency. Attention can be described as the ability to maintain an alert state, orient to internal and external events, and self-regulate responses to those events. In infancy, attention develops from being primarily exogenously drawn to endogenously controlled. Executive attention develops in late infancy and on in to early childhood and is considered a higher level of attentional functioning that involves not only attending to objects but attending to specific features of objects. Although executive attention is thought to build upon basic attentional processing such as orienting, alerting, and shifting, the relationship between these attention functions is unclear. Further, the relationship between these attentional functions and those involved in common measures of executive functioning (e.g., a collection of cognitive processes that aid in goal directed behavior) is unclear. The current project aims to characterize the relationship between different aspects of attention during the toddler to early childhood years via multiple methods to examine these relationships between brain and behavior during a battery of attention and executive functioning tasks. Specifically, fNIRS is employed to examine connectivity of these three attentional networks at rest (e.g., resting state functional connectivity) and compare how connectivity between and within regions relates to event-related hemodynamics, functional connectivity, and eye-movement data in a battery of tasks. Further, behavioral data and risk survey criteria are used to probe both eye-movement and neural data as well as group children by performance and risk level to further probe the developmental profiles associated with various brain-behavioral relationships.

PREFACE

"Don't become a mere recorder of facts but try to penetrate the mystery of their origin." Ivan Pavlov (1849-1936).

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CHAPTER I:

INTRODUCTION

Visual attention is the preferential allocation of cognitive resources to external visual stimuli. This cognitive process involves the filtering of incoming visual information and processing relevant visual information in the face of competition. In this way, the process of visually attending to objects and events in the environment can be characterized as the initial step in the cascade of perception and action (Amso & Scerif, 2015). Visual attention can be defined as a general cognitive ability but can also be distilled into functional characterizations. For example, visual attention can be characterized as the ability to *orient* towards an object or spatial location (Posner, 1980) *focus* on an object or spatial location (Duncan, 1981), or *regulate* between phasing attentional states and foci (Richards & Casey, 1991). The process of attention in the context of orienting and focusing emerges early in infancy and becomes relatively stable over the first two years (e.g., Orekhova, Stroganova, & Posikera, 1999; Rothbart, Sheese, & Posner, 2007). Regulating attention has a more protracted development and is less stable compared to these functions of attention in the toddler years (Conejero & Rueda, 2017; De Jong, Verhoeven, Lasham, Meijssen, & Van Baar, 2015; Gaertner, Spinrad, & Eisenberg, 2008). The dimension of time in the context of attentional engagement has also been used to parse out different types of attention functioning (e.g., sustained attention verses focused attention) in this literature. Other dimensions of attention include the quality of the attentional state (e.g., arousal) and the foci of attention (e.g., object-based, space-based).

From infancy (0-12 months) to toddlerhood (12-months to 3-years) to early childhood (3- to 5-years), one notable qualitative change occurs in attention development, the shift from space-based attention to the integration of space-based and object-based attention. Space-based attention is attention to *where* the object is in space with little emphasis given to the properties of the object, while object-based attention is attention to *what* the object is with little emphasis given to where it is located (e.g., Duncan, 1981, 1984; Posner, 1980; Posner, Rothbart, Sheese, & Voelker, 2014; Treisman, 1986). Functional characterizations of attention in infancy and toddlerhood are largely space-based, due to the early onset of this attentional priority. Attention in early childhood involves the integration of attention as a process contributing to higher-level cognitive outcomes. In this context, attention becomes focused on more subtle aspects of the visual environment, such as specific properties of objects. These higher-level cognitive outcomes are closely related to executive functioning, the collection of cognitive processes (e.g., working memory, inhibition, switching, planning) employed to achieve goal directed behavior. In this way, visual attention can be described as one *process* involved in executive functioning. In the context of executive functioning, visual attention can be *selective* to one object and/or location in a discriminatory way, *stable* to process task relevant aspects of an object and/or spatial location over a period of time, and *flexible* to move between task relevant aspects of an object and/or location as demands change. These attentional functions may have their roots in early development, however they show little stability in the toddler years (Miller & Marcovitch, 2015). Thus, these two ways of describing attention highlight the differences between processing capabilities in infants and young children. Attention transitions from being exogenously controlled to endogenously driven and integrated with other cognitive processes fluidly over the course of the first few years of life.

Cognitive neuroscience research extended this behavioral literature to demonstrate how spatial and visual information is represented in the brain of healthy adults in the dorsal and ventral pathways (Belger et al., 1998; Clark et al., 1996; Desimone & Duncan, 1995; Haxby et al., 1994; Haxby et al., 1991; Köhler, Kapur, Moscovitch, Winocur, & Houle, 1995). More recent data have demonstrated that a 'dual-stream' model of the dorsal and ventral pathways does not fully account for the perception of objects in the visual field (Marois, Leung, & Gore, 2000). Selective use of one pathway or the other for different functions is one part of the picture. The other part involves the integration of both spatial and object-based visual information (e.g., Dekker, Mareschal, Sereno, & Johnson, 2011; Durand et al., 2007; Konen & Kastner, 2008; Lehky & Sereno, 2007; Martinez-Trujillo & Treue, 2004; Milner, 2017; Perry & Fallah, 2014; Sereno & Maunsell, 1998; Tchernikov & Fallah, 2010; Wannig, Rodríguez, & Freiwald, 2007; Zachariou, Klatzky, & Behrmann, 2014). In infancy, object-processing pathways resemble early hierarchical organization across the dorsal and ventral visual pathways seen in the adult brain; spanning frontal, temporal, and parietal cortex (e.g., for review see Wilcox & Biondi, 2015). Activation in the ventral pathway, the 'what' pathway, has been demonstrated in 2-month-old infants in response to passively watching face stimuli (de Schonen, Mancini, & Liegeois, 1998). Aguiar and Baillargeon (2002) notably demonstrated that as early as 3.5 months, infants rely heavily on spatial information as well as spatiotemporal information about objects. Across theoretical perspectives on the development of attention, the importance of processing spatial information as well as spatial properties of objects (e.g. movement or action) for visual attention in infancy have been demonstrated (Colombo, 2001; Colombo, Shaddy, Richman, Miakranz, & Blaga, 2001; Perone, Madole, Ross-Sheehy, Carey, & Oakes, 2008; Reynolds & Romano, 2016; Spelke, Phillips, & Woodward, 1995; Wilcox & Schweinle, 2002; Xu & Carey, 1996).

The selective prioritized use of and integration between spatial and object-based attention is necessary for adaptive visual processing across the lifespan (e.g., reviews and studies from infancy, toddlerhood, and adulthood: Johnson, 2010; Soto & Blanco, 2004; van Hoogmoed, Van den Brink, & Janzen, 2013), despite some open debate on whether the two neural streams are best characterized as 'what' and 'how' or 'what' and 'where' (e.g., Cloutman, 2013; Goodale & Milner, 1992; Thompson-Schill, 2003).

Tensions in Concepts

It remains unclear how early attentional functioning (e.g., orienting, alerting, and regulating) relates to later attention in the service of executive functioning (e.g., selectivity, stability, and flexibility) or how the development of one might influence the development of another. Further, there is a substantial gap in the literature cataloging the developmental shift between infancy (0-12 months) and early childhood (3- to 5-years-olds) with regards to how attention development specifically unfolds in the toddler years (12-months to 3-years-old) and what long-term implications early attentional abilities might have on outcomes in early childhood.

One reason for this age-gap in the literature is that children from 18-months to 3-years-old are particularly challenging to study. Factors such as high variability in language acquisition and self-regulation during this developmental period as well as exceptionally high attrition from longitudinal studies for this group contribute to the limited literature on this age (Nicholson, Deboeck, & Howard, 2015; Thal, Bates, Goodman, & Jahn-Samilo, 1997). The limitations of this population can be considered one contributing factor in the disconnect in terminology pertaining to attention development. The specific combination of terms used are designed to fit the behaviors in each study. These terms may be well suited for that data and logical considering the range of uses in the literature pertaining to how attentional function is defined and characterized, however this practice has led to a disconnect in transferability across studies and task contexts as well as a fractured view of attention development.

The first challenge is the disconnect in terminology and characterizations of attentional functioning across early development. Gaertner, Spinrad, and Eisenberg (2008) conducted a study looking at focused attention in infants, toddlers, and young children but do not define focused attention, rather focused behaviors are described. Focused attention has been characterized as the ability to maintain attention specifically on an object or spatial location (e.g., Treisman & Gelade, 1980). This function of attention has been similarly noted in both the infancy and toddler literature (Casey & Richards, 1988; Gaertner et al., 2008) and as children develop further defined as the maintenance of attention over time to a specific stimulus. Gaertner et al. (2008) described focused attention based on what was being measured in a focused attention task. That is, they characterized focused attention by associated behaviors (e.g., continual orienting to object, active engagement with the object, prolonged intensity of interest with the object). Operationally, this culmination of behaviors lends to a definition of focused attention that is very similar to how selective attention is used in the early childhood literature with the addition of *time*. Here, focused attention is essentially *sustained* attention *focused* on an object or spatial location within the constraints and demands of a specific task. Based on this definition, it could be hypothesized that "sustained focused attention" in toddlerhood is the integration of focused attention and regulated attention as defined above. Successful integration of focused and regulated attention in toddlerhood could lead to successful selective attention in early childhood, as the definition of selective attention in this literature is processing of one object and/or location in a discriminatory way. However, there is no real principled way of linking these terms without making some compromise either in the definitions or described behaviors given in each study. Further, without more research focused on this age-group, it is hard to form consensus on how attention should be described or defined and whether the infant or early childhood literatures are better or ill-suited to inform these issues independently. Other work similarly addresses focused attention, sustained attention, selective attention, and regulated attention with descriptions of behaviors and definitions that are overlapping, combined, and/or interchangeably being used (e.g., Erickson, Thiessen, Godwin, Dickerson, & Fisher, 2015; Ito-Jäger, Howard, Purvis, & Cross, 2017; Lawson & Ruff, 2004; Putnam, Gartstein, & Rothbart, 2006; Rivière, Cordonnier, & Fouasse, 2017; Ruff & Lawson, 1990; Spaulding, Plante, & Vance, 2008).

The mosaic of terms and definitions used to describe basic attentional abilities across contexts creates a need for further clarification of the type of attention being studied in subsequent studies to distinguish the currently targeted behaviors from those previously targeted as evidence for a particular type of attention. For example, when looking at sustained attention separately from focused attention (Marchetta, Hurks, De Sonneville, Krabbendam, & Jolles, 2008), it is important to distinguish between sustained attention and focused attention from sustained focused attention (Ruff & Lawson, 1990) and further clarify what focused attention means in relation to selective attention (Commodari, 2017). In this example, focused attention has been defined as "the ability to respond discretely to specific stimuli" (Rueda et al., 2004) whereas selective attention is defined as "the ability to avoid distracting stimuli, processing only what is relevant" (Posner, Rueda, & Kanske, 2007). Further, Rueda, Rothbart, McCandliss, Saccomanno, and Posner (2005) discussed executive attention (regulated attention) as being dependent on sustained attention or the "ability to maintain focus on a specific stimulus"(Fuentes, 2004; Ruff & Rothbart, 2001). Graziano, Calkins, and Keane (2011) discussed how focused and sustained attention are the same and used interchangeably in the literature. Focused attention can be named as a necessary step in successful selective and regulated attention (Fisher, Thiessen, Godwin, Kloos, & Dickerson, 2013). However, sustained attention takes place over time, whereas focused attention is often described as phasic in aforementioned studies. Regardless of the term 'focused attention' being used interchangeably with 'sustained attention', the question of whether or not time plays a role in the presently used term is critical, yet inconsistent in any given paper. Ruff and Capozzoli (2003) assessed attention (i.e., casual, settled, focused) and distractibility from infancy to early childhood. Here, focused attention was defined as "concentrated attention that involved an intent facial expression, minimal extraneous bodily activity, a posture that enclosed the object of interest and brought it closer to the eyes, and either no talking or soft talking clearly directed to the self" and was specifically discussed as also being "focused in the presence of distractors" for older children while being "more distractible than the other children, even during focused attention" for younger children. From these descriptions and definitions, the transition from infancy to early childhood is one that is characterized as being more focused in the face of distractors which is similar to how selective attention is discussed in the early childhood literature. Here, selective attention is a more general state of being engaged selectively with task relevant stimuli, similar to how selectivity is described in early childhood, for example to specific properties of objects (for review of selective attention to object properties see also Hanania & Smith, 2010).

However, the emergence of selectivity is not explicitly used to describe the demonstrated increases in focused attention less pervious to distractibility with age in Ruff and Capozzoli (2003). The indiscriminate use of focused attention to account for qualitative changes in attention, based on very specific behaviors in this particular paradigm, is not easily transferable to other tasks or studies for two reasons. One, selectivity is not discussed. Focused attention, defined as this specific subset of behaviors, and selectivity as a marker of attentional developmental status generally for this ability is not possible because it is task specific within this paradigm. Without discussing fully, the similarity between definitions of focused attention and other attentional functions such as selectivity in early childhood, thus connecting to the broader literature, these specific behavioral patterns are nontransferable and the underlying explanations for attentional processing behind them is partially lost. This work is foundational in cataloging the developmental trends in behavioral change associated with attention to objects over the course of early development. However, the ability to transfer this explanation to other paradigms is limited because the process underlying these specific behaviors, which is the process underlying focused attention, is not fully explored.

In early childhood, orienting attention is often defined as the ability to disengage, from the current locus of attention, orient to a new locus of attention, and engage with a spatial location and/or object (Petersen & Posner, 2012; Posner & Petersen, 1990). Attention *shifting* is operationalized as the ability to flexibly reallocate attention within one's internal and external environments to support goal-directed behaviors, such as orienting to a spatial location or object. This ability has been linked with inhibitory control from 2- to 4-years-old (Fox, Henderson, White, Degnan, & McDermott, 2011). This definition of attention shifting is synonymous with definitions of *covert* attention (e.g., shifting focus to a new stimuli) and is the precursor to *overt* shifts in attention (e.g., behaviors such as making an eye movement to focus on a new stimuli) often described via orienting behaviors (e.g., for a review see Findlay & Gilchrist, 2003).

Further, attentional *flexibility* is operationalized as one's ability to disengage with stimuli that are no longer relevant and engage with stimuli that are relevant following new rules or task specifics and has been used in concordance with attention switching (e.g. for a review see Hanania & Smith, 2010).

To address these tensions, careful triangulation of descriptions, terms, and observations are required. That is, looking at the behaviors alone to find commonalities across what type of attention functioning is being described is not principled enough in creating consensus across ideas and observations concerning what is being measured from infancy to early childhood. There also needs to be consensus on how different types of attention are defined more generally. The aforementioned instances are just a few examples of how terminology and operationalizations can vary, highlighting the challenges that arise when trying to bridge developmental literatures from infancy through early childhood. In this way, finding common ground can be particularly challenging because definitions and tasks are tied to behaviors, but there is a breakdown in bridging definitions and behaviors where the definition is a description of the ability and the behaviors are an example of that description without being coequal. One strength of taking a processed based approach to bridging the literatures is that in place of designing a task based on an attentional function with corresponding behaviors within a specific paradigm, tasks can be designed based on the underlying process of attentional functioning and thus can be built upon an agreed definition of attention.

The second challenge is that attention is often defined by *how* it is assessed. The following narrative provides one example of how characteristics of infant and early childhood populations present issues for studying attention in toddlers. Infants and young children are largely tested using different methods. Toddlers and young children can be asked to verbally respond in a given attention ask (e.g., Anderson, 2002; Carlson & Zelazo, 2014; Schonberg, Atagi, & Sandhofer, 2018) while an infant is primarily tested via eye-tracking or other indirect method of measuring associated behaviors such as eye-movements or reaching (e.g. Gredebäck & von Hofsten, 2004; Holmboe, Pasco Fearon, Csibra, Tucker, & Johnson, 2008; Hunnius & Geuze, 2004; Johnson, Slemmer, & Amso, 2004; McMurray & Aslin, 2004; Wiener, Thurman, & Corbetta, 2017). Using psychophysiological data in isolation then to make inferences about the brain in young children when they can respond more explicitly, especially when considering additional variance from ocular-motor system development across developmental populations, is one limitation to directly transferring infant methodology to the study of young children (Karatekin, 2007). When testing young children, common practice is to design studies where children can indicate an explicit verbal or motor response (e.g. verbalize, point, make a choice via a touch to a computer monitor, push buttons on a keyboard or response box, etc.). When testing toddlers, both methods have been employed (e.g., Billeci et al., 2016; Setoh, Scott, & Baillargeon, 2016). These considerations warrant a new perspective that perhaps, when studying toddlers, both infant and early childhood methodology should be employed. Toddlers are limited in their ability to verbal express themselves, while also being more advanced that infants in their ability to explicitly respond when prompted. Further, there are considerable individual differences in cognitive and verbal abilities in toddlerhood and that these differences may have their roots in processing efficiency testable in infancy (e.g., Choudhury & Gorman, 2000; Fernald & Marchman, 2011). Thus, it is possible that a bridging of methods is most appropriate for probing the processes underlying attention function in this age group because of the transitional nature of this age. Using vocabulary assessments, eye-tracking, and neuroimaging to carefully control for these variations is necessary when studying toddlers.

Methods can in turn influence how attention is defined. For example *sustained* attention (i.e., maintaining attentional focus) and *alerting* attention (i.e., a state of preparedness to detect, attend, and maintain that attention); have both been used interchangeably, making it difficult to make distinctions between them (Graziano et al., 2011; Oken, Salinsky, & Elsas, 2006). Sustained and alerting attention, by the above definitions, are possibly two pieces of the same process. This process of being alert involves entering into and maintaining an attentive state. It might be the case that alerting attention (e.g., preparedness to attend to a spatial location and/or object) and orienting attention (e.g., ability to orient to a spatial location and/or object) together interact to achieve attentional regulation (e.g., inhibition of distractors or focused attention on relevant objects and/or locations to achieve a goal ; Posner et al., 2014). However, few distinctions between *tonic* alertness (i.e., intrinsic arousal that fluctuates on the order of minutes to hours) and *phasic* alertness (i.e., the rapid change in attention due to a brief event, the basis for operations such as orienting and selective attention) are considered in the use of general definitions of alerting attention for a specific task context outside of the adult literature (e.g., Degutis & Van Vleet, 2010; Zani & Proverbio, 2017). For example, physiological methods have been employed to link heartrate variability with phases of attentional alertness (Richards & Casey, 1991). However, due to the method employed, alertness can be easily confounded with sustained attention. For example, Griffiths et al. (2017) used heart rate variability to assess sustained attention and regulation (e.g., "Different measures of heart rate variability provide important insights into [the] sustained attention") in children with ADHD. However, the method does not equal the measure nor the construct. An infant's current level of alertness is measured as a function of a prolonged intense attentive state from which heart-rate variability is calculated. In this way, a capture of attentional alertness might be inseparable from a measure of sustained attention or focused attention over time when using this method as a proxy for a targeted attentional function. Both tonic (e.g., slow, gradient changes) and phasic (e.g., arousal level falling in and out of a state of preparedness to attend) features of attentional alertness play a role in the measure of alerting attention. They also play a role in sustained attention. In this way, the system's ability to attend may alter or interacts with orienting and attentional regulation down-stream. Some friction comes from this overlap in operationalizations and lack of specificity in terminology. Conflating terms with methods in this way can weaken explanations.

In early childhood, *attention regulation, attentional control, effortful control*, *executive function* (generally) or *executive attention* collectively expose a general operationalization of high-order attention with many terms. Depending on the disposition of the researcher, that is if they are coming from the perspective of the infancy literature with the goal of comparing infant attention to that of early childhood or if they are coming from the early childhood literature with the goal of comparing to infancy- terminology used will vary as a function (e.g., see Table 1, Conejero & Rueda, 2017). Conejero and Rueda (2017) describe tasks used to measure executive attention as falling into five categories (i.e., cognitive conflict, flexibility, error monitoring, inhibitory control, and self-regulation) where exemplar task measures of executive attention are given such as the Young-Child Attention Network Task (ANT), Dimensional Change Card Sorting Task (DCCS), Freeze-Frame, and Snack Delay. However, early childhood researchers

Table 1. This table shows the angular sizes for each type of stimuli in the four tasks where eye data was recorded. Calculations are done with a distance of 642 mm, which is roughly the average between the minimum and maximum distances they are seated from the screen. For the IOWA task, calculations for stimuli separation are done from the edge of the looming smiley to the edge of the target and from the edge of the looming smiley to the center of the cue.

Task	Stimuli	Stimuli Size (Vertical x Horizontal)	Stimuli Separation (Vertical)
IOWA	Looming Smiley	1.86° x 3.33°	in the center
	Cue	0.208° x .661°	2.5°
	Target	2.77° x 8.79°	1.218°
Flanker	Animals	1.165° x 3.70°	2.33°
DCCS & TC	Objects (Test and Target)	2.77° x 8.79°	Test to Target: .208° x 9.67° Target to Target: 2.77°

such as Zelazo et al. (2003) and others (e.g. Buss & Spencer, 2014) would call these measures of executive function (i.e. working memory, inhibition, and attention).

From the early childhood perspective, this general grouping of attention with executive functions stems in part from the *task purity problem* (Best, Miller, & Jones, 2009; Best & Miller, 2010; Booth, Boyle, & Kelly, 2010; Hughes & Graham, 2002; Huizinga, Dolan, & van der Molen, 2006; Lee, Bull, & Ho, 2013; Morris, 1996). That is, measures of attention in early childhood often inadvertently measure other cognitive processes as attention is deployed in the context of a particular domain and thus can contaminate a pure measure of that cognitive ability (Snyder, Miyake, & Hankin, 2015). For example, when asking a child to recall which item they saw on a previous trial both memory and attention are being tested because the ability to recall is reliant on attention to that stimuli in the first place, encoding of that stimuli in memory, and then accurate recall of it. Further, it is possible that individual differences in processing speed or different levels of experience can also influence performance in these tasks. Attempts have been made to account for these potential issues, such as using multiple measures of one 'component' of executive functions and then assessing common variance between task performance across these tasks (Friedman et al., 2008; Miyake et al., 2000). One particular issue task impurity creates for assessing attention in the early childhood is that measures of visual attention (e.g., flexibility, selectivity, stability) become bound in the context of executive functioning. Assessing attentional ability subsequently assesses the ability of other cognitive processes (i.e., working memory and inhibition) and thus it is hard to generalize findings to other attention domains. With this in mind, task choice and careful consideration to what processes might actually be involved are necessary ingredients for studying the toddler years. Thus, methods must be chosen with care from a perspective that emphasizes both the behavior and the process underlying them. Careful operationalizations of earlier (i.e., orienting, focusing, regulating) and later developing attention (i.e., selectivity, stability, and flexibility) across the literatures must be established before further light can be shed on the relationship between them over developmental time. Thus, shifting the perspective of how attention is defined in such a way that is accounts for what abilities come before and after a specific targeted behavior and thus designing studies that allow for easier generalization might resolve these tensions or at least force the field to grapple with them directly.

Some effort has been made to do just that. This line of work has attempted to link individual differences in scales of temperament traits longitudinally with both neural correlates of attentional functioning as well as behavior in a systematic way. Scales tapping into individual differences in temperament such as the Early Childhood Behavioral Questionnaire (EBQT) have been related to attentional outcomes, executive functioning outcomes, as well as activation in neural networks associated with different attentional functions (Posner & Rothbart, 2018; Posner et al., 2014; Rothbart, Posner, & Kieras, 2008). However, the process behind the neural and behavioral correlates of attention cannot be probed directly by these self-report measures. That is, temperament alone does not account for individual differences in performance across multiple domains.

One solution may be employing multiple methods of assessing attention (e.g., neuroimaging, eye-tracking, physiological measures, behavioral assessments, and self-report measures of individual differences). Coordinating multiple methods for measuring attention in infancy and in early childhood will be critical for motivating a collective consensus around fundamental questions addressing what attentional functions most predict and what they may affect later in the context of executive functioning.

One advantage of studying toddlers is that the discrepancies in consensus on what attention is, how it functions, and how it changes over the first 5 years of life, will have to be addressed. One way the current project aims to address these issues is to incorporate a more diverse methodology. Another possibility is finding tasks that can be scaled appropriately for both infants and children, finding a common framework in which to study toddlers that lends to translation between the infant and early childhood literatures. Targeting the tail ends of this age-gap in cross-sectional research, such as comparing 18-months to infants and 2.5-year-olds to 3.5-year-olds might further close the gap in the literature. In the remaining introductory sections I will outline visual attention in toddlerhood and early childhood. Next, I will briefly review the atypical literature for this age range in order to draw comparisons from the applied literatures on the necessity of understanding these basic relationships for children at risk for attention and executive dysfunction. Finally, I will propose a project to try and find the common threads or enduring processes/mechanisms that drive the development of attention in the first five years of life from infancy *through* early childhood.

To achieve this, the current project focuses on the transition from toddlerhood to early childhood. Thus, definitions of attention that are based on processes rather than task-specific behaviors will be adopted. Visual attention will be defined in the following ways: the ability to *orient* towards an object or spatial location (Posner, 1980), *focus* on an object or spatial location (Duncan, 1981), to *regulate* between phasing attentional states and foci (Richards & Casey, 1991), to *select* (i.e., the ability to process one stimuli in the face of distractors), to *flexibly shift* (i.e., the ability to switch focus between stimuli based on context/task demands), and to *stably attend* (i.e., the ability to maintain attention to relevant stimuli over time). These definitions are grounded in the attentional processing of visual information rather than task-specific behaviors within a specific paradigm. These definitions can then be used to anchor observable behaviors to a process of attending.

Visual Attention in Toddlerhood

One marker of development from infancy to early childhood is the shift from space-based attention to the successful integration of space- and object-based attention. As previously defined, space-based attention is attention to *where* the object is in space with little emphasis given to the structure of the object, while object-based attention is attention to *what* the object is with little emphasis given to where it is located (e.g. Duncan, 1981, 1984; Posner, 1980; Treisman & Souther, 1986). However, this is not to say that infants and children can identify the object to use object-based information as a problem-solving strategy (i.e., object individuation; Xu, Carey, & Quint, 2004). When given a visuospatial task where toddlers have to selectively attend to relevant information in the presence of salient irrelevant information they often fail or have difficulty doing so. Berthier, DeBlois, Poirier, Novak, and Clifton (2000) noted this transition in a visual search task where both space and object information are juxtaposed causing conflict. In this study children are asked to watch a ball go down a ramp and through one of four doors where a wall behind each door would stop the ball on every trial. Children were reminded of the ball's location by the location of the wall stopping the ball being taller and visible above the opaque board where the doors were located. However, only 3-year-olds reliably chose the correct door while some 2.5-year-olds did and most 2-year-olds did not. These data demonstrated a transition in focused attention (cited by the authors as selective attention), and the integration of spatial and object information between toddlerhood and early childhood. In this task, errors in searching were explored to see if younger children employed different strategies for looking for the ball instead of choosing randomly. Young children employed both a "favorite door" strategy and a "perseverative" strategy where they consistently choose a favorite door or the door the ball was last found behind on the preceding trial. Despite changing object-based information, that is the contingency between the wall indicating that the ball's motion was stopped at that location, toddler employed these two strategies more often when compared to 3.5-year-olds. The integration of object and space-based information is highlighted by this shift in performance. Such that, all children successfully searched for the ball at the correct location when the ball was hidden from the front of the apparatus. However, when the ball's location was dependent on the location of the wall and what the location of the wall indicated about the location of the ball, younger children performed more poorly. The use of space-based visual attention over object-based attention, that is perseverating based on previous choices or preferentially choosing one location as a problem-solving strategy regardless of conflicting or more relevant object-based information, has been noted as one potential marker of immature selective attention in toddlers in other tasks where as well (e.g., manual search tasks; Rivière & Brisson, 2014).

Focused attention and selective attention in toddlerhood, collectively, may be one attentional process by which children successfully process and extract meaning from objects in the visual world, when giving priority to space- and object-relevant information independently is more adaptive for success. However, pliably integrating these two strategies when needed may be more challenging for toddlers as demonstrated in tasks that require both object- and space-based information for successful performance. Further, within the domain of object-based attention, children show gains in selective attention for processing object-based information between 2- to 3-years-old (e.g., for a review see Lane & Pearson, 1982; Scerif, 2010). However, gains in what features of objects are given processing priority such as object dimensions (i.e., shape and color) has a more protracted development that continues to develop beyond the toddler years and is subject to influence from other cognitive processes (e.g., Enns & Cameron, 1987; Smith & Kelmer Nelson, 1984; Smith, 1989; Smith & Kelmer, 1977).

Mulder, Verhagen, Van der Ven, Slot, and Leseman (2017) administered a battery of EF-precursor tasks primarily consisting of memory (e.g., visuospatial working memory) and selective attention tasks (e.g., visual search). EF-precursor task performance at 2.5-years-old was predictive of emergent success in mathematics and literacy at 5-years-old. The generalizability of these findings is unclear. That is, the influence of selective attention on attention involved in other EF attention tasks was not explored in the context of this study beyond the visual search task. Mulder et al. (2017) suggested that, despite the dynamic and rapidly changing nature of cognition during this transitional period from toddlerhood to early childhood, future work should investigate whether EF measures in toddlerhood can accurately identify children at risk for significant learning impairment when they reach school age. One such avenue might be to identify children at risk for developmental disorders such as Attention Deficit Hyperactivity Disorder (ADHD) associated with learning difficulties in school.

Gaertner et al. (2008) found that focused attention at 18-months-old was predictive of focused attention at 2.5-years-old suggesting that this attentional ability stabilizes early in development. Here focused attention was not described as selectivity as previously discussed but described as sustained selective attention or the ability to stay actively engaged with task relevant stimuli over time. This study examined the relationship between parental interactions and strength of focused attention and found that parental interactions could mediate the predictive relationship of early focused attention for later focused attention abilities. Choudhury and Gorman (2000) found that infants and toddlers ages 17- to 24-months-old that had greater sustained attention focused on task relevant objects (e.g., duration of attention and frequency of off-task glances) were better problem-solvers and had higher scores on the intelligence scale of the Bayley Scales of Infant Development-II (BSID-II) in comparison to children with less sustained attention focused on task relevant objects. However, older children in this group had greater sustained visual attention focused on task relevant objects while having more frequent off-task glances suggesting that the relationship between regulated attention and focused attention during the toddler years may be relatively unstable despite competing findings. Further, de Jong, Verhoeven, and van Baar (2015) assessed attention (i.e., orienting, alerting, executive attention/attention regulation) in preterm and full-term toddlers and discuss how the ability to alert is necessary for orienting attention across these two populations. Further, they proposed that divergence in these attentional abilities can be seen early in toddlerhood and warranted the need for identifying children for interventions at this age based on these low-level attentional functions. Collectively, these studies together can motivate an explanation of the process of attending. The process of attending in any given context in toddlerhood first requires a state of alertness, then the ability to orient, finally the ability to selectively maintain attention. Despite the limitations mentioned in the previous section concerning consensus in the literature on attention development and the need for a more processed based approach, these data suggest early attentional abilities such as *alerting* and *orienting* possibly interact to achieve attentional *regulation* which gives rise to *focused attention* (i.e., selectivity in the moment or over time) during the toddler years.

Visual Attention in Toddlerhood Predicts Executive Functioning Outcomes

It is still unclear how early attentional functioning (e.g., orienting, focusing, and regulating) relates to attention in the context of executive functioning (e.g., selectivity, stability, and flexibility) across behavioral and neural domains. However, previous literature suggests that orienting (e.g., looking towards an object or spatial location) in toddlerhood is linked to later self-regulation and executive attention in early childhood (Rothbart, Sheese, Rueda, & Posner, 2011). For example, how infants regulate their emotional state (e.g., orienting away from emotionally uncomfortable or overwhelming stimuli) has been linked to their ability to later self-regulate their emotions and control their attention at age 3- and 4-years-old in the face of distractors or overwhelming irrelevant stimuli. These data suggest that early control of eye-movements might be a reliable early measure of attentional orienting and consequent self-mediation of emotional states in the toddler-years as they become more endogenously controlled. It might be the case that early experience, mediated by temperamental tendencies and self-regulation, in combination with the dynamics of ocular-motor control present in infancy could lead to better attentional regulation in early childhood. Thus, orienting attention may serve as one mechanism by which self-regulation and attention develops in the context of executive functioning from infancy to early childhood. Further, emotional regulation is one aspect of executive functioning, often noted as “hot EF” (e.g., Zelazo & Carlson, 2012).

Early attention abilities have been related to later executive functioning processes such as working memory, inhibition, and planning (i.e., cool EF). Cuevas and Bell (2014) linked attention at 5-months-old in infancy to executive functioning ability at 24-, 36-, and 48-months-old. These data were critical in demonstrating that early attention and consequent efficiency of processing marked by short-looker (more efficient processors) and long-looker (less efficient processors) distinctions in infancy could be a reliable predictive of later executive functioning scores such that those that were short-looks (e.g., more efficient processors) were also higher in executive functioning ability in early childhood compared to long-lookers. Thus, the early status of attention measured by looking behaviors was reliable in predicting later higher-order cognitive functioning across executive function domains (i.e., working memory, inhibitory control, cognitive flexibility). The relationship between distinct attentional abilities such as raw orienting, alerting, and executive attention measures within this predictive framework have yet to be explored. Further, questions surrounding atypical developmental accounts of visual attention and executive function, what variations in neural architecture might be involved in short and long-looker distinctions, or what long-term implications these have for the relationship between brain and behavior within this specific predictive relationship have yet to be answered. Reynolds, Guy, and Zhang (2011) measured ERPs via EEG recordings in infants to probe how short- and long-lookers differed neuraly in infancy. Short lookers in this study had higher amplitude late slow wave (LSW) at frontal and temporal locations during novel stimuli suggesting deeper processing of these stimuli whereas there was no difference in LSW for stimuli type for long lookers. Further, the short-looker group showed greater recognition and recall for familiar stimuli in comparison to long-lookers. These seminal works suggest that early visual processing speed and efficiency is important for later cognitive outcomes and could have their roots in neural differences early on. However, no recent work has explored how ERPs might change over time in the first 5 longitudinally with regards to this short- verses long-looker distinction.

Not only has early attention (i.e., orienting, alerting, regulated attention) been linked to later executive functioning outcomes, but longitudinal work exploring selective attention in 2.5-year-olds and executive function (i.e., specifically domains of working memory and inhibition) suggest that selective attention in the toddler years is predictive of executive function in early childhood (e.g., Veer, Luyten, Mulder, van Tuijl, & Sleegers, 2017). Path modeling was used on the measure of selective attention (i.e., visual search task) demonstrating that selective attention is relatively stable from 2.5- to 3-years-old in this task and that performance in this task at 2.5-years-old underlies executive functioning in a simple working memory and a response inhibition task at 3-years-old. These data suggest that early attention interacts with and predicts different aspects of later executive functioning abilities. However, little is known about how different attentional functions during the process of attention generalize in their predictability across executive functioning domains. Further, long-term predictability from infancy to early childhood across levels of measurements (e.g., behavioral and neural) has yet to be explored.

Assessment of Visual Attention in Toddlerhood

Previous research has demonstrated that eye movements are one way to measure visual attention and specific eye movement patterns have been associated with different types of attentional functioning in typical and atypical populations (e.g., Ben-Sasson et al., 2007; Klin, Jones, & Schultz, 2002; Parish-Morris et al., 2013; Pelphrey et al., 2002; Sasson, Elison, Turner-Brown, Dichter, & Bodfish, 2011; Sasson & Touchstone, 2014). For example, Alahyane et al. (2016) demonstrated that orienting latency in infants from 7-months-old to children 42-months-old (e.g., 3.5-years-old) decreased from infancy to toddlerhood. In this study, participants were asked to orient towards a cartoon character appearing in unpredictable locations on a screen for 140 trials. Overall, all children compared to adults, had longer saccadic RTs (e.g., longer to orient to the cartoon) and shorter saccade amplitude relative to target location (e.g., 10° eccentricity). Children, like adults, were able to adjust saccadic amplitude as a result of visual error on preceding trials over the course of the experiment despite making more errors than adults. These data suggest that despite immaturity in saccadic control in children, as cognitive abilities develop so do ocular-motor abilities, possibly dynamically interacting with one another over the course of development. In this way, eye-movements in isolation may not provide a pure assessment of attentional functioning as there is a clear interaction between cognitive functioning and motor-development in young children. Rather, multiple measures, such as eye-tracking in combination with neuroimaging, might be necessary to establish the developmental status of attentional functioning in children this young.

One notable task used to assess the developmental status of spatial attention early in development, specifically assessing orienting and alerting in a space-based attention paradigm, is the Infant Orienting With Attention (IOWA) task (Ross-Sheehy, Schneegans, & Spencer, 2015). This task has both control trials and spatial cueing trials spanning 5 conditions (e.g., tone, no tone, no cue, invalid, and valid trials). All 5 conditions contain trials that start with a central fixation attention "grabber" (e.g., looming smiley face), followed by either a cue at the right and/or left locations or a blank pure grey screen, a short 100ms delay, terminating in a target object appearing at the right or left of the center. On invalid trials, the cue appears opposite the side the target appears. For valid trials the cue and target appear on the same side. For tone and no tone trials, there is no visuospatial cue. Lastly, for double trials, the cue appears on both sides of the screen while the target appears on only one of these sides. Mean Reaction Time, Cue Facilitation, Cue Interference, and Cue Competition are calculated from these trial types.

Cue Facilitation, Cue Interference, and Cue Competition are composite attention scores. Cue Facilitation was calculated as the average latency to look during the tone condition subtracted from the average latency to look during valid trials normalized for each infant by dividing this difference score by the average latency to look during tone only trials. Cue Interference was calculated by subtracting the average latency to look on tone trials from the average latency to look on invalid trails, normalizing in the same way by the average latency to look during tone trials. Finally, Cue Competition is calculated by taking the difference between average latency to look during double and valid trial and normalizing in the same way as the other two composite scores by dividing by the average latency to look during tone trials. The IOWA task is traditionally used with infants and is considered a developmental assessment of orienting and alerting attention in this population. For example, the facilitation effects of the tone cue are thought to reflect the alerting ability of the infant whereas the difference in RT between invalid and valid trials is thought to be a measure of orienting ability. The IOWA task was designed to capture *visual orienting proficiency* (e.g., speed and accuracy) across degrees of visual competition based on principles of spatial cueing effects. Ross-Sheehy et al. (2015) posit that the IOWA task also taps in to covert attention, such that faster orienting to peripheral targets in the face of competition on invalid trials and facilitation on valid trials (e.g., measuring overt shifts in attention via orienting behaviors) are indicative of covert shifts in attention. Ross-

Sheehy, Perone, Macek, and Eschman (2017) demonstrated that differences in spatial attention in the first 12-months of life are evident in premature infants when compared to typically developing infants and that these differences might in part contribute to differences in long-term cognitive and learning outcomes for these children. Thus, this task might be a viable long-term predictor of later attentional outcomes in early childhood for atypical groups. How does this task relate to or predict to later attention to objects or the integration of space-based and object-based attention in early childhood? One potential avenue for exploring this would be scaling this task for toddlers and preschoolers in a battery of attention tasks and looking at how predictable behavior in this task is of long-term outcomes.

Recently, de Jong, Verhoeven, Hooge, and van Baar (2016) proposed the Utrecht Tasks for Attention in Toddlers Using Eye Tracking (UTATE) aimed at establishing reliable measures for assessing toddler's attention across three abilities (e.g., orienting, alerting, and executive attention) via a battery of eye-tracking tasks. In this study, four tasks (e.g., Disengagement Task, Face Task, Alerting Task, and Delayed-Response Task) were given to 18-month-old toddlers. This is the first and, to the authors knowledge, only study to assess these three attentional abilities simultaneously where both space-based and object-based attention and related information is relevant for success in children under 3-years-old. The Disengagement Task is a cued *orienting* task where a tone cue is used to prepare the toddler to make an eye-movement from a central object to one in the periphery. The Face Task is a measure of *alerting* and is essentially a change detection task where two identical children's face are presented side by side, then one of the facial expressions change where the side that is changing alternates and looking behavior is assessed across three domains (e.g., mean dwell time across both phases of the trial, total dwell time, and transition rate). The Alerting Task has a tone cue, or no tone cue, followed by an image of an animal that appears randomly at any of 8 different locations around the screen. Aptly named, The Alerting Task measures attentional *alerting*. Finally, the Delayed-Response Task is a modified A-not-B task where children are instructed to play hide and seek with a dog, whom hides in one of two dog houses on the screen, after which a worm distractor appears and dances in the middle of the screen for several seconds and then children are instructed to find the dog who reappears at the correct dog house location. The number of correct searches to the hiding location and delay to search to the correct location are scored. Here the Delayed-Response

Task is posited as a measure of *regulated attention*. Of these tasks, the Alerting Task was the least interesting for the children as demonstrated by the lower rate of looking (e.g., 60%) compared to the other three tasks, suggesting that perhaps this battery could be administered with just 3 of the 4 tasks while still yielding measures of *alerting*, *orienting*, and *regulated attention*. The feasibility of this task with older toddlers at 2-years-old has yet to be explored. The UTATE battery seems to tap in to both space-based and object-based attention for at least one of the tasks (e.g., Face Task). It is unclear how either the UTATE battery might fair with toddlers. The long-term predictability of performance in these tasks' measures of space-based and object-based attention for later attention abilities measured in early childhood remains an open question. These tasks might provide greater insight into these existing gaps in the literature surrounding toddler attention.

Neural Underpinnings of Visual Attention in Toddlerhood

Previous theories of neural development corresponding to attention development (e.g., orienting, alerting, and regulated attention; Posner & Peterson, 1990, 2012) have focused on three neural networks; attributing the development of attention to the maturation of these systems. The alerting system involves brainstem areas such as the locus coeruleus and corresponding norepinephrine projections from midbrain to frontal and parietal cortex. The orienting system, initially thought to primarily involve parietal cortex, has since been expanded with more recent work on orienting and executive functions. For example, Posner and Peterson (1990) suggested that the pulvinar and superior colliculus projections to parietal cortex were responsible for attentional functioning related to orienting. However, responding in these posterior areas is now thought to be dependent on long range connections with frontal cortex. Processing in parietal cortex has since been pushed to include functions outside of attentional orienting, with parietal cortex being implemented in both bottom-up and top-down processing within dorsal and ventral attention systems in the brain. For example, the orienting network also includes the dorsal (i.e., frontal eye fields (FEF) and intraparietal sulcus/superior parietal lobe) and ventral attention systems (i.e., temporoparietal junction and ventral frontal cortex); that is, top-down visuospatial attention and bottom-up reorienting of that attention. Thus, the orienting system is less separable from the executive attention system than previously thought (e.g., Bush, Luu, & Posner, 2000;

Fair et al., 2007; Fan, Flombaum, Mccandliss, Thomas, & Posner, 2003; Sridharan, Levitin, & Menon, 2008; Sridharan, Levitin, Chafe, Berger, & Menon, 2007; for a review see also Vossel, Geng, & Fink, 2014).

Finally, the executive attention system includes a frontoparietal regulatory system that guides moment-to-moment attentional regulation and execution. However, as previously mentioned, there is substantial overlap between this system and the recently expanded orienting system. The executive attention system also involves the cingulo-opercular system which is responsible for task set maintenance or sustained vigilance. This overlap is intuitive based on the behavioral data that suggest orienting and alerting attention interact with and influence regulated attention previously discussed in this paper. Recent work on resting state MRI provide support for these three neural networks being functionally distinct in adults while being behaviorally interrelated (for review see Posner & Peterson, 2012; see also Power et al., 2011).

Changes in activation within these three systems over the course of development demonstrate that with age, more efficient neural networks emerge that are locally tuned with broader, more diffused long-range connections (e.g., Johnson, Munro, & Bunge, 2013). Subcortical areas such as the anterior cingulate, implicated in executive attention, show stronger connections with bilateral frontal and lateral parietal areas by 2-years-old (e.g., Tau & Peterson, 2010). Further, bilateral parietal cortical areas show stronger connectivity with lateral and medial frontal areas over the course of the first 2 years of life (e.g., Posner & Peterson, 2012). Although orienting and alerting neural systems might develop more rapidly than the executive neural system, it is possible these connections are interacting with one another to further tune the emergent fronto-parietal and cingulo-opercular system involved in executive attention. However, little is known about the resting state functional connectivity of these attention systems in toddlers. Further, links between interregional and intraregional connectivity of regions involved in these networks in the context of executive function have yet to be connected. That is, although these theories together suggest overlapping neural regions across early attention abilities, connectivity of cortical regions involved in attention in toddlers has yet to be related to cortical connectivity involved in attention within the context of executive function in early childhood.

Visual Attention in Early Childhood

Visual attention in the preschool years is often characterized as being one *process* involved in executive functioning; showing robust developmental changes from infancy to early childhood (Colombo & Cheatham, 2006). Visual attention, in this context, can be expanded to include how visual information is used once object- or space-based attention is employed. Thus, visual attention in early childhood can be characterized as the ability to be *selective* (i.e., the ability to process one stimulus in the face of distractors in service of a goal), *flexible* (i.e., the ability to switch focus between stimuli based on context/task demands), and *stable* (i.e., the ability to maintain attention to relevant stimuli over time). These abilities too are a piece of the attentional process. Flexible attention is more specifically the ability to disengage with a stimulus or object and engage with other stimuli or objects that has become behaviorally relevant and necessarily requires alerting, orienting, and attentional regulation. Here, the focus is on flexibility in the context of attention and not flexible attention in the context of overall cognitive flexibility. Thus, the current examination will not elaborate on *cognitive flexibility* as a whole, as attentional flexibility is one process involved in this overarching ability (Dajani & Uddin, 2015). However, it is important to note that visual attention as discussed here is considered a general characteristic or property of cognition (i.e., subsystems such as attention contributing to the overall cognitive system in the service of higher-order cognition) and plays an important role in overall cognitive flexibility as it pertains to skills such as multitasking, novelty generation, and problem solving (for a comprehensive review see Ionescu, 2012). This is mentioned here because there is considerable overlap in the tasks discussed in this paper and this line of work. The focus of the current paper is attention development over the first five years of life specific to the core questions outlined in the introduction rather these expanding this question to all the possible interactions between attention and other cognitive processes that give rise to advancements in executive functioning.

One notable development in attention during childhood is seen in attentional flexibility and stability. Stable attention can be described as a state of attending maintained over time whereas flexibility can be described as shift in the focus of that attentional state that allows attention to shift to processing newly relevant information in the service of a goal (Buss & Kerr-

German, submitted). The ability to maintain focus on a particular stimulus over time and the ability to shift attention to other stimuli as they become relevant are two parts of the overall process of regulated attention. The push and pull between stability and flexibility has been an area of interest in recent years and have been thought to both help and hinder one another depending on the developmental status of other cognitive abilities also involved in executive functioning and the task demands or context in which the behaviors are observed (Benitez, Vales, Hanania, & Smith, 2017; Hanania & Smith, 2010). Further, these two types of attention have been linked to selective attention, described as the ability to bias the filtering of information that is behaviorally relevant in the face of distracting information. Selective attention to objects improves over early childhood such that children's attention becomes more refined, allowing them to not only attend to objects but features of particular objects in a goal directed way.

Children's attention becomes more selective over development. One task that demonstrates this progression is the triad or free classification task (Smith & Kelmer, 1977). In this task, children are asked to match one of two choice objects with a reference object on the premise of one choice object is most like the reference object. One of these choose objects is called the holistic match and matches the refence object somewhat along two dimensions (i.e., shape and color) whereas the second-choice object, the identity match, matches the reference object perfectly along one dimension and is maximally different along the other. In this task, selectivity to the relevant object feature increases, such that older children more frequently can select matching objects in a configuration based an exact match of specific relevant featural information within a dimension (e.g., color, shape, luminosity, size, etc.) without any explicit rules while younger children more frequently choose items that holistically match one another based on their overall dimensional similarity (Smith, 1989). Children also attend to shape and color differentially coinciding with their ability to produce labels for these dimensions, suggesting that learning and language knowledge might play a role in their performance in these tasks (Landau, Smith, & Jones, 1988; Perry & Fallah, 2014; Smith, 2000). Specifically, selective attention has been demonstrated to affect the processing of local and global features of objects; as selective attention improves so does a child's ability to focus attention to different features or global aspects of objects fluidly based on task demands (Porporino, Iarocci, Shore, & Burack, 2004).

Hanania & Smith (2010) discuss three trends of transition in selective visual attention to objects from early to middle childhood that can be summarized into the following: moving from more graded to more categorical perceptual discrimination, from imperfect to all-or-none selective attention, and from "sticky" attention to dimensions to flexible attention between dimensions. This comprehensive review of selective and flexible visual attention development to objects in early childhood also highlights how growth in selective attention influences other types of attention like flexibility as well as other cognitive processes involved in executive functioning. These transitions in attentional functioning also influence the development of other cognitive processes involved in executive functioning such as inhibitory control. Developmental increases in selective attention are exemplified in work demonstrating the shift from inhibitory control errors associated with task-irrelevant distractors to inhibitory control errors focused on task-relevant information (Clark et al., 2013). Inhibitory control is not only related to selective attention but is also linked to flexible attention performance (Rennie, Bull, & Diamond, 2004). Increased gains in inhibitory abilities have been demonstrated generally from toddlerhood to early childhood (Carlson, 2005; Diamond, 2013; Garon, Bryson, & Smith, 2008). Thus, it is possible these processes are interacting.

Assessing Visual Attention in Early Childhood

Visual attention in childhood can be probed via multiple behavioral (i.e., eye-tracking, touch screen motor responses, button presses, etc.) and neural (i.e., ERPs, fNIRS, fMRI) measures. However, little research has been done combining multiple methods to better understand and interpret attentional functioning in this age group. Despite this, countless tasks and manipulations have provided a rich understanding of targeted behaviors associated with attentional flexibility, selectivity, and stability. The following section will focus on these behavioral findings first.

One classic measure of selective attention to object features is a free classification task called the Triad Classification (TC) task (Smith & Kemler, 1977). The TC task taps into implicit, selective attention where children are required to make assumptions about the relevant featural information specific to different dimensions that are task relevant (i.e., luminosity, size, color, shape, etc.). In this task children are given a series of trials in which they are shown a reference object and asked to pick one of two choice objects that goes best with the reference object. One of these choice objects is called the identity object, which is the best choice if information is considered along one dimension where there is a perfect match. The other choice is the holistic object which is the better choice if information is integrated across dimensions. Previous studies have demonstrated that children's attention becomes more selective over development, such that older children more frequently select the identity match object over the holistic match object compared to younger children (Smith, 1989; Smith & Kemler, 1977).

The Dimensional Change Card Sorting (DCCS) task is one classic probe of attentional flexibility in early childhood (Zelazo, 2006). This task has also been shown to involve other cognitive processes such as inhibition and working memory as well as other types of attention such as stable and selective attention (Buss & Spencer, 2014; Gandolfi, Viterbori, Traverso, & Usai, 2014; Kirkham, Cruess, & Diamond, 2003; Morton & Munakata, 2002). In the DCCS, there are two cards placed in sorting trays that differ along both dimensions of shape and color called target cards. For example, there might be a purple house and a yellow fish in the two sorting trays. Children are then given a third card to sort into one of these two locations called the test card. The test card will match both target cards along the shape or color dimension. An example of a test card for the aforementioned target card pair would be a yellow house. In this way, conflict emerges as both dimensions on the test card are perfect matches to one of two dimensions in each target card. However, children are given sorting rules in this task of "shape" or "color". This allows children to selectively tune into the relevant dimension and inhibit the irrelevant one. Once children sort by one of these rules for a series of trials, then the rules switch to the opposite dimension. Younger children tend to perseverate or continue to sort by the pre-switch dimension whereas older children can flexibly switch rules to the new sorting dimension. Countless manipulations have been done with this task to reduce the demands on one or more of these cognitive processes to improve performance in this task. Regardless of this, one classic finding is that children become increasingly flexible with development such that most all 5-year-olds pass this task whereas a large amount of 3.5-year-olds fail it. In both this task and the TC, dimensionality is relevant. Further, selectivity seems to matter for both of these tasks. Recently, Buss and Kerr-German (submitted) proposed that stability, selectivity, and flexibly likely share a common mechanism across the TC, DCCS, and dimensional priming task (i.e., assesses attentional stability). This model suggests that in the context of dimensional attention, these attentional functions work together fluidly and that the process of attention involved in decision making within these tasks may share a similar neural mechanism. However, the expansion of this line of work to attention to objects outside of shape and color dimensionality is still somewhat unclear. Further, it has yet to be explored what this means for attention to objects in the service of executive functioning where dimensionality is not the focus.

Finally, stable attention in early childhood is often described as sustained attention and has been measured in a number of ways. DeGangi and Porges (1990) described three stages of sustained attention: attention getting, attention holding, and attention releasing. These stages also describe the process by which children can enter and maintain a stable state of attention. One way of measuring stable attention is having children watch a video or listen to a short story for several minutes. Scores from these types of tasks are often objective or use scales to quantify how long children-maintained attention in the given task. Other tasks have also been used to assess sustained attention such as Zoo Runner, the Continuous Performance Task for Preschoolers (CPTP), and the Preschool Vigilance Task (PVT)(Finneran, Francis, & Leonard, 2009; Harper & Ottinger, 1992; Kerns & Rondeau, 1998). Across these types of tasks, children show improvement between the ages of 2- and 5-years-old as well as continuous improvement throughout middle and late childhood. Other tasks markedly known for assessing the stability of attention to objects are priming tasks. In these types of tasks, stability is often talked about in tandem with selectivity such that the ability to maintain an attentional state allows for continual selectivity in processing. One such task used in early childhood is called the dimensional priming task (Benitez, Vales, Hanania, & Smith, 2017). In this task, children are given a series of priming trials where a configuration of three objects is presented. In this configuration, two objects match along one dimension and the third object does not match the other objects along either dimension. Unlike the TC and DCCS tasks, the dimensional priming task has priming trials where there is only one clear matching pair. Once children have been "primed", they are given a set of test trials where the third object now matches one of the other two objects along one dimension. Thus, during the test phase there are two viable correct matches in the configuration whereas there were only one during the priming phase. These data suggest that children's ability to stay in a stable state of selectivity (i.e., to the originally primed dimension) in the dimensional priming task is predictive of their ability to flexibly switch rules in the DCCS.

These data also suggest that gains in selectivity might also influence stability and flexibility and that there are dynamic interactions between these three types of attention in early childhood. In the context of the dimensional priming task, priming prepares the attentional system and imposes influence on subsequent decisions. During test trials, there is ambiguity surround which choice is the correct choice because there are two viable matching pairs. This ambiguity is minimized by the priming trials if children are able to stably 'hang-on' to the primed implicitly imposed "rule" provided by scaffolding in the priming trials. However, without that structure, children seemingly choose at random phasing out of stable responding. In this way, improvements in stability may related to improvements in the adaptive application of problem-solving strategies. That is, children's ability to apply previously successful rules (i.e., in the priming trials) to new situations or contexts where they might be appropriate (test trials). However, the relationship between stability in the context of executive functioning and stability as it is characterized in the sustained attention literature is somewhat unclear. Further, it is still unclear how the phenomenon of stability in this very specific set of tasks involving dimensional attention generalizes to attentional stability in other tasks or situations in early childhood.

To minimize potential issues that arise from assessing one type of attention in isolation during early childhood, batteries of attention tasks have been developed such as the Early Childhood Attention Battery (ECAB; Breckenridge, Braddick, & Atkinson, 2012). Further, to address the issue of how specific types of attention such as flexibility relate to other executive functioning skills, batteries such as the Minnesota Executive Functioning Skills battery (MEFS; Carlson & Zelazo, 2014) have been created. However, little work has been done with assessing attention to objects in the context of executive functioning that accounts for multiple attentional abilities (i.e., from early to later developing) as well as executive functioning. González, Fuentes, Carranza, and Estévez (2001) used temperament, a Stroop task, and a Flanker task to assess attention and self-regulation in older 7-year-old children. These data suggest that the dynamic interaction between attention and executive functioning development continues through middle childhood.

Visual attention in early childhood has been linked with outcomes later in life. One example of this is McClelland, Acock, Piccinin, Rhea, and Stallings (2013). This study suggested that sustained attention (i.e., *focused* and/or *stable* attention) in preschool was predictive of education outcomes 25-years-later such that those that exhibited greater attention spans in early childhood also had more educational achievements and greater success in college than those that had shorter attention spans. Further, attention span at age 4, controlling for school achievement at age 7, was predictive of reading and mathematics skills at age 21-years-old. This group also had a 48.7% greater likelihood of completing a 4-year college degree by age 25 compared to the low attention-span group even after controlling for maternal education level, adoption status, child vocabulary skills, and sex.

Neural Underpinnings of Visual Attention in Early Childhood

Similar regions as those mentioned in the above section on the neural underpinnings of visual attention in toddlers have been implemented in the early childhood and adult literature. Konrad et al. (2005) conducted an fMRI study to assess these neural networks in children as well as adults and found support for midline frontal areas as well as superior parietal lobe and lateral prefrontal cortex being involved in incongruent trial performance during the ANT task (see also Bush, Luu, & Posner, 2000). Alerting performance has been associated with right frontal and parietal cortex(Yin et al., 2012). However, our understanding of how neural activation in these regions is related to performance in this task with young children, prior to age 4, is limited.

Checa, Castellanos, Abundis-Gutiérrez, and Rueda (2014) modified the features of the stimuli used to indicate congruency (i.e., different shaped bots for flanking items on incongruent trials) within a child friendly flanker task, one highly similar to the child ANT, while also collecting electroencephalography (EEG) data utilizing event related potentials (ERPs) with 4-13-year-olds and adults. This study suggests that both the orienting and alerting networks modulate the efficiency and ability of the executive attention network.

Bunge, Dudukovic, Thomason, Vaidya, and Gabrieli (2002) conducted an MRI study with children ages 8-12 and adults with a modified flanker task. Similar to the traditional adult ANT task, this modified Flanker used arrays of arrows that were either congruent with the central arrow, incongruent, or presented as a singular central arrow. In addition to these trial types, a fourth go-nogo trial was introduced. Flanking 'X's around a central arrow indicated nogo trials. Collapsed across age groups, children generally recruited left prefrontal cortex (lPFC) but not right prefrontal cortex (rPFC) whereas adults activated both lPFC and rPFC. This difference in recruiting frontal cortex was hypothesized to be the cause of inhibition issues in this task for children on no-go trials in comparison to adults and suggest that this and failure to recruit other regions such as bilateral inferior parietal regions for cognitive control led to poorer performance compared to adults. Poorer performing children recruited both left ventrolateral prefrontal cortex and bilateral dorsolateral prefrontal cortex whereas better performing children recruited both lPFC and rPFC as well as bilateral inferior parietal regions. Thus, improvement in performance across development was associated with recruiting posterior areas in this task in addition to use of more relevant frontal regions. Inhibition is one core ability of EFs and is one of the cognitive process that has been linked with attention development from middle childhood to adulthood. However, the link between executive attention and EF, at both the behaviorally and neural levels in early development, is still unclear and somewhat controversial (for review see Diamond, 2013).

Recent work looking at attention in the context of executive functioning with 3.5- and 4.5-year-olds, namely selectivity and flexibility, demonstrated that children with high selective attention skills in a triad classification (TC) task engaged left frontal cortex, an area previously implicated in the development of flexible attention during the DCCS (Kerr-German & Buss, submitted). Children in this study who performed poorly in the TC task activated a wider range of frontal and posterior regions compared to those that performed poorly in the TC and succeeded in the DCCS. Children who performed well on the TC but failed the DCCS showed more diffused patterns of frontal-posterior activation. These data suggest that low performance in either the DCCS or TC is possibly due to the strength and specificity of long- and short-range connections within this fronto-temporal-parietal attention network.

There is a substantial gap in assessing these neural networks from infancy to early childhood that needs to be addressed. Atkinson and Braddick (2012) provide a comprehensive review of both atypical and typical development of attention over the first five years of life. In this review they point to future research investigating the ways various functional attention networks integrate over the course of early development. Further, they posit the need for understanding how structural development of the brain leads to different onsets of abilities, different rates of integration, and how this relates to distinctive developmental trajectories.

Atypical Visual Attention in Early Life

Thus far the focus of the current paper has been on visual attention as it typically develops from infancy to early childhood. Recently, Mahone and Schneider (2012) reviewed different factors that have been associated with risk for attentional difficulties and various developmental outcomes for attentional control and concluded these outcomes are largely influenced by genetics, experience, and temperament. The authors point to a field-wide gap in assessing and understanding the ontogeny of atypical development prior the age of 4- to 5-years-old. The aforementioned age-gap in the literature (i.e., toddlerhood) for typically developing children furthers the challenge surrounding the ontogeny of atypical attention development and downstream effects on executive functioning.

ADHD as a Clinical Comparison for Experimental Work

One developmental disorder that affects both executive functioning and attentional functioning is Attention Deficit Hyperactivity Disorder (ADHD). ADHD is a developmental delay characterized as a neurodevelopmental disorder with three subtypes that is diagnosed in childhood (DSM V; Steinau, 2013), Inattentive Type (ADHD-I), Hyperactive-Impulsive Type (ADHD-HI), and Combined Type (ADHD-C). Neurodevelopmental disorders appear early in development and include dysfunction of motor skills, adaptive behavior, memory, and learning. Little is known about the ontogeny of this disorder prior to the age of 5. The inability to reliably diagnose children prior to primary school age (roughly 7-years-old) further limits the study of this disorder early in childhood. One secondary feature of this disorder is the deficit in higher order cognitive processes used to organize information, problem solve, and navigating novel situations to adapt to one’s environment (Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009). Most notably, children with ADHD struggle with executive dysfunction; including working memory, verbal self-regulation, self-monitoring, inhibition of behavior, emotion regulation, and motor control (R A Barkley, 1997; Holmes et al., 2014; Kaiser, Schoemaker, Albaret, & Geuze, 2015; Roberts, Martel, & Nigg, 2017). Children with ADHD often struggle in social situations and relationships, have disorganized sleep, and are more prone to accidents (Barkley, 2002; Gardner & Gerdes, 2013; Stein et al., 2002).

ADHD is uniquely relevant to the goals of the current study because it involves dysfunction in executive function and attention and because this developmental delay is one of the most pervasive developmental disorders in industrialized nations, with notable increases in diagnosis in recent years in the United States in particular (Garfield et al., 2012). Epidemiologically, ADHD is found in about 6-9% of school aged children (e.g., Breton, Bergeron, Valla, Berthiaume, & Gaudet, 1999; Singh, Yeh, Verma, & Das, 2015). In clinical studies, the ADHD-C type is the most common. Overall boys are more likely to be diagnosed than girls 3:1. ADHD is found among all social classes although it may be more prevalent in lower socioeconomic status (SES) groups. Longitudinal evidence suggests that of those diagnosed in childhood, 60-70% of cases will persist into adulthood (e.g., Barkley, Fischer, Smallish, & Fletcher, 2002; Burke, Rowe, & Boylan, 2014; Keenan, Giovannelli, Delliquadri, Walsh, & Shaw, 1997).

Elsabbagh et al. (2013) examined infant orienting, disengagement, and general visual attention abilities at 7-, 14-, and 36-month-olds longitudinally using a spatial cueing task. They found that infants that develop autism and ADHD symptomology show atypical visual attention development during the first year. More specifically, disengagement at the 7-month assessment was not related with later atypical outcomes, but by 14-months disengagement was highly correlated. In addition to this, children that later developed autism and ADHD symptomology showed no increases in efficiency (e.g., speed) or flexibility of visual orienting between 7- and 14-months old. Autism and ADHD are often grouped together to study comorbidity or related symptomology (Yerys et al., 2017). Further, similar measures are often used when studying these populations. Thus, assessments of attention in studies looking at autism might help provide a framework in which to situate the study of attention in ADHD in young children (e.g., (Barbaro & Dissanayake, 2009; Clark, Vinen, Barbaro, & Dissanayake, 2018; Mammen et al., 2015; Sasson & Touchstone, 2014).

Johnson et al. (2008) utilized an attentional network approach to study children ages 12- to 13-years-old with ADHD by comparing performance on the ANT task (i.e., a measure of orienting, alerting, and executive attention) for 73 children with ADHD to 73 controls. There were clear differences in performance between the two groups. The group with ADHD showed greater errors in conflict resolution and slower RTs overall for executive attention scores in comparison to controls. Children with ADHD also made more omission errors (e.g., failure to respond), and lower scores on the alerting scale suggesting the maintenance of advantageous arousal levels for responding and attending might be unstable in these children. Interestingly, children with ADHD did not show deficits in orienting in this study.

Recently, the early childhood attention battery (ECAB) was created to test focused, selective, and regulated attention in children ages 3- to 6-years-old (Breckenridge, Braddick, & Atkinson, 2012). This battery combines both early attentional abilities such as focused attention with later developing attention such as selective attention in the context of executive functioning. In combination with the Test of Everyday Attention for Children (TEA-Ch), a performance-based measure of attention, the ECAB creates an 'attentional profile' for each child that clinicians have begun using to aid in the characterization of neurodevelopmental disorders. The ECAB battery has been used to create attentional profiles of Williams Syndrome as well as Down Syndrome (Breckenridge, Braddick, Anker, Woodhouse, & Atkinson, 2013) and other developmental disorders known to be characterized by dysfunction in attentional abilities (Breckenridge, Braddick, Anker, Woodhouse, & Atkinson, 2013). Atkinson and Braddick (2012) point to ADHD as being one of the disorders that should be targeted by future research utilizing the ECAB or other batteries aimed at linking attentional profiles to dysfunction in both neural and behavioral domains. However, no such battery exists for children who are typically developing.

In clinical research, attention batteries such as the ECAB are being used in young children as early diagnostic tools or tools from which to identify children that may be at risk for developing disorders such as ADHD. However, the literature on typically developing children is still somewhat muddy both in how attentional abilities are operationalized and how they are measured. Further, the toddler age-gap in the literature creates an additional challenging in bridging the typical attention development in the first five years and in designing a similar profile of attention in children from infancy to toddlerhood.

The mechanisms driving change across multiple developmental timescales (e.g., short moment to moment and long-term predictability and trajectories) for visual attention in toddlerhood need to be identified. This will require a better understanding of the dynamic interaction between attention and executive functioning from toddlerhood through early childhood. It may be the case that early developing attentional abilities (orienting, alerting, regulated attention) serve as one mechanism by which later attention (selective, flexible, stable) in the context of executive functioning emerges. Perhaps the way in which later developing attention interacts with other cognitive processes under the umbrella of executive functioning (e.g., inhibition) is a downstream outcome of early attentional abilities present in infancy and toddlerhood. Finally, this might vary as a function of alternative developmental trajectories such as those in children with ADHD. These gaps in the typical and atypical literatures should be addressed in tandem to better refine theoretical approaches to our understanding of attention and provide a richer understanding of how function and dysfunction emerge in early life within one framework.

Neural Underpinnings of Atypical Visual Attention in ADHD

Structurally, children with ADHD tend to have a protracted development of the frontal lobe, and functionally reduced connections from frontal to striatal regions, reduced volume in the brain and smaller than average areas of the brain (e.g., right frontal areas; Bralten et al., 2016). Children with ADHD show a decrease in blood flow and decreased glucose utilization in frontal areas as well as differences in dopamine and norepinephrine production (Blum et al., 2008). Barkley (1997) proposed a unified model of ADHD that included behavioral inhibition, sustained attention, and executive functions as contributing to the four executive neuropsychological dysfunctions exhibited in this developmental disorder. There is considerable overlap in the cortical regions outlined above and associated deficits in inhibition, attention, and executive functions in this group (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Thus, further research is needed to disentangle the functions of these regions in the service of task specific demands, how attention relates to aspects of inhibition and executive function early in development, and differences between atypically and typically developing children prior to primary school years. Doing this in a systematic way, within the early childhood literature might be one avenue to dually refine theories of attention across typical and atypical development.

Assessing Risk for ADHD in Toddlerhood

The limitations in understanding the ontogeny of ADHD due to age of diagnosis have been discussed. Thus, one viable method of probing ADHD in younger children is by means of a risk assessment. ADHD has been linked to both genetics and environmental influences evidenced by both sibling and twin studies where heritability ranges from .50 to .85 (Nikolas & Burt, 2010). Works in behavioral genetics have suggested certain genes (i.e., DRD4, DAT1, DRD5, and 5HT1B) may be tied to ADHD (e.g., Faraone et al., 2005). Earlier work on the heritability of attention network functioning with adults administered the ANT, suggest there may be a greater link between genetics and attention above and beyond psychopathology (J Fan, Wu, Fossella, & Posner, 2001). Additional influences have been found to possibly contribute to the development of ADHD such as prenatal influences and birth complications (high correlation), maternal smoking and alcohol use, exposure to lead, maternal depression, and fathers with ADHD (Knopik, Jacob, Haber, Swenson, & Howell, 2009; Nomura, Marks, & Halperin, 2010; Starck, Grünwald, & Schlarb, 2016). Thus, using parental diagnoses or assessment for ADHD might serve as a proxy for risk level in children.

Further, there is some indication that ADHD may have links to unique trace behaviors observable in early in life. For example, some individual behaviors in infancy might be correlated with ADHD such as difficult temperament, high activity level, distractibility, less cooperative behaviors, and poor emotional regulation (e.g., Ilott, Saudino, Wood, & Asherson, 2010). How does the underlying brain functioning, connectivity, and neural ontology of this disorder in younger children compare to typically developing children in the same age range? Understanding how attention development unfolds in children with ADHD would be critical for implementing early interventions. These early interventions might also be transferable to typically developing children who struggle in similar domains but lack the ADHD diagnosis.

In general, dialog between the subfields of developmental psychology and developmental psychopathy is limited. Castellanos and Tannock (2002) call for greater collaborative efforts across clinicians and developmental researchers in the neurosciences to address these gaps in both literatures. The current study hopes to contribute, in part, to this dialog.

Conclusions

Visual attention is critical for extracting and processing meaningful information from the visual environment relevant for everyday life. Visual attention stabilizes early in life and continues to play a role in higher-order cognition such as executive function during the preschool years. How does the process of attending change from toddlerhood to early childhood? The current paper will focus on how early visual attention in toddlerhood relates to higher-order attentional functioning involved in EF during the preschool years. Further, the current paper aims to identify children that may be at risk for developing Attention Deficit Hyperactivity Disorder (ADHD) to preliminarily explore how the relationship between attention and EF might differ in different populations. Namely, how does visual attention to objects relate to later visual attention to objects in the context of executive functions change from toddlerhood to early childhood? A secondary question then is, how reliably can children be identified as at risk for developing attention dysfunction and what might that mean for future longitudinally work, given there are group differences on this premise. Previous work has examined how early attentional abilities and neural networks associated with these early ‘components’ of attention link to later executive function more broadly in both typically and atypically developing children in early childhood from 3- to 6-year-olds (Atkinson & Braddick, 2012). In the current study, a similar approach is adopted with typically developing children with both risk and no risk distinctions.

Current Study

The current study tested visual attention in 2.5- and 3.5-year-olds using a novel battery of tasks while recording both hemodynamic responses via functional near-infrared spectroscopy (fNIRS) and eye-movements via eye-tracking. Survey reports of temperament, demographics, and risk were also collected to further probe individual differences across participants in attentional performance across tasks. Attention performance across orienting, alerting, and regulated attention were then compared to measures of executive function in both age groups. Both age groups received one attention task and one executive functioning task that were the same for cross-sectional comparison. Based on the structure of the ANT task, a novel child Flanker was created to assess executive attention in isolation outside of a spatial cueing paradigm and is interpreted as both an executive attention and executive functioning task. The IOWA task, then, is used as a measure of orienting and alerting attention within a spatial cueing paradigm. These tasks were given to both toddlers and preschoolers in the current study. The DCCS and TC tasks are both measures of dimensional attention to objects where space-based information also plays a role in the attentional and decision-making process. These tasks serve as measure of selectivity and flexibility in the context of executive functioning and are given to preschoolers only. Finally, a measure of inhibition is used to gage how attention relates to other cognitive domains under the umbrella of executive function where attention is not directly measured. Both age groups received a measure of inhibition in this context. These tasks were carefully chosen to gage the developmental status of these visual attention skills as well as the basic relationship between them in toddlers and preschoolers.

General Hypotheses

Orienting, alerting, and regulated attention measures are hypothesized to predict resting-state connectivity in corresponding neural fronto-parietal attention networks during regulated attention tasks (Snack Delay and Day Night Task) for both 2.5 and 3.5-year-olds. Further, event-related activation in a selective and regulated attention task (i.e., Child Flanker) and a basic attention task (i.e., IOWA) will show developmental differences in neural activation as a function of age and performance criteria. Such that, children who perform higher in these measures will also have more refined short-range tuning as well as differential activation patterns across the three attention networks proposed by Posner & Peterson, 1990, 2012) while performing these tasks as evidenced by the event-related data. It is hypothesized that younger children will have lower performance in comparison to older children.

Performance during executive functioning tasks (i.e., 2.5-year-olds: Flanker and Snack Delay; 3.5-year-olds DCCS, TC, and Day Night), will be predicted by both behavioral performance and neural activation in the orienting, alerting, and regulated attention measures (IOWA and Day Night Task). Further, resting state functional connectivity will predict attention performance across these same tasks.

Behavioral and survey data will be used as additional covariates and predictor variables for these same outcomes. For example, temperamental differences and corresponding subscales will vary across age groups and composite score such as inhibitory control will predict inhibitory abilities in tasks such as the Day Night and Snack Delay. Further, as reviewed in the introduction, overlap in processes involved in regulated attention and executive function tasks will be highly correlated behaviorally in various ways across participants due to shared processing demands (i.e. overlap in cognitive processes being utilized for successful performance in the task).

CHAPTER II:

METHODS

Participants

Children 2.5-years-old (N=37, female=21) and 3.5-years-old (N=33, female=15) were recruited via a departmental database of children's birth records. All participant ages fell within ±6 weeks of the target age ranges. All children included in the analysis had normal hearing and no known cognitive or neural developmental delays or abnormalities. Consent was obtained via an Institutional Review Board (IRB) approved consent form (see also UTK IRB-17-04019-XP). Children received a toy valued at $5.00 and a certificate of completion as compensation for participation. In addition to consent for participation, parents were given the option to give further consent for their child to be featured in future presentations, recruitment materials, or lab social media; if given, a minor photo release form was obtained. However, consenting to this was completely voluntary and not required for participation in this study.

Apparatus and Materials

Functional near infrared spectroscopy (fNIRS) was collected at 25 Hz using a Techen CW7 system with wavelengths of 830nm and 690nm. Light was delivered via fiber optic cables that terminated in an array compiled of six sources and 12 detectors placed 3cm apart for a total of 16 channels. Placement of sources were relative to the 10-20 system over left and right frontal cortex (AF3-4; F5-F6) and left and right parietal cortex (CP1-4; P1-4; PO3-4). This probe was scaled for both a 52cm (N=23) and 54cm (N=47) hat to account for robust head size differences across these two age groups. Of those that used the 52cm probe, 12 were 2.5-year-olds and 11 were 3.5-year-olds. Participants were placed between 63.5-65cm from a computer monitor where an EyeLink © 1000 eye-tracker was mounted. A target sticker was placed on the fNIRS probe hat above the participant's left eye or in the middle of the forehead, depending on which was easiest to place without the child becoming aware of the sticker. EyeLink software was used to calibrate the eye-tracker and calculated fixation and saccade information online during each task. Calibration was done as many times as needed prior to the beginning of each task and data was collected via a sampling rate of 500Hz. The IOWA, Flanker, DCCS, and TC were the only tasks during which eye tracking data were collected. Both tasks with and without eye-tracking were administered via E-prime 3.0 by which behavioral responses were collected. All tasks were displayed on a 530mm x 330mm monitor with a resolution of 1280x960. Each session was video recorded, with a video camera positioned behind the child's head viewing both the response space (i.e., child and monitor) and the experimenter.

Parental-Report Measures

Questionnaires were completed by parents or legal guardians and were either administered with an Apple iPad Air 2 via quick response (QR) codes using Qualtrics © or by paper during each appointment. Data collection via the Apple iPad Air 2 and Qualtrics © was done via a secure network identity created for the laboratory by OIT at the University of Tennessee.

Demographics

A demographics questionnaire was given that was specifically designed to collect information concerning household income, parental education level, number of siblings and sibling order, eye-sight, race, sex, and childcare experience. Demographics were used for descriptive statistics and were not used in any of the other statistical analyses (see Appendix 1).

Adult ADHD Self-Report Scale (ASRS-v1.1)

Symptom Checklist Parental self-report screening scale for ADHD (Kessler, Adler, Ames, & Demler, 2005;Silverstein et al., 2017) was given to the accompanying parent/guardian. If both biological mother and father were present (N=3, of which risk N=1), data was collected from both for this assessment. Risk distinctions were only based on a biological parent or guardian filling out the form (no non-biological parent scored a 4/6 or higher on Part A of this form). Some parents recognized the self-report screening tool and mentioned they did or did not have a diagnosis of ADHD. However, this information was not formally recorded, and all children were grouped with risk or without risk distinction based on scoring of Part A on the ASRS-v1.1.

Children, whose biological parent scored a 4/6 on Part A, regardless of additional scoring of Part B, were given the risk distinction.

Early Childhood Behavioral Questionnaire (ECBQ)

Finally, parents were given a short temperament questionnaire specifically designed for children 1-3 years old (i.e., Early Childhood Behavior Questionnaire (ECBQ)– Short Form; Putnam et al., 2010) to complete. Temperament scores were derived from the survey via standard scoring and used in statistical analyses.

This paperwork, in addition to demographics and risk assessments, collectively took approximately 45 minutes to complete.

Procedure and Stimuli

The present study was cross-sectional. Children for both age groups were tested within one session, however the option for two sessions was available based on the researcher's discretion given unforeseeable circumstances (e.g. twins wanting to be tested together, micturate, hunger, etc.). These circumstances were minimized as much as possible by encouraging parents to schedule appointments with consideration given to meal, nap or snack times and having children use the restroom prior to testing. However, these precautions did not always mediate the aforementioned circumstances. If a second session was required, it was scheduled no later than nine days from the first session (N=3). Tasks for administered in a fixed order for each age group.

Parents/guardians and children came to the lab and sat on a comfortable couch while informed consent was obtained. Each session required two researchers, one to administer the tasks and one to run the eye-tracker and fNIRS machines. Time was allotted for the test researcher to talk with the child and acclimate the child to the lab while the second researcher received informed consent from parents/guardians and gave instructions pertaining to paperwork. A blackout curtain was then positioned to cover half of the opening between the parental seating area and the child testing area. A lamp was turned on adjacent to the parents so they could continue filling out paperwork while the main lights were turned off in the child testing area for both eyes-open and eyes-closed resting state tasks. The testing room received some light from the parental seating area, thus the monitor and indirect light from the lamp dimly lighted the room.

Eye-Tracking Protocols

At the beginning of each task children were reoriented to sit back in their chairs and the distance from the monitor to the child's eyes was adjusted as needed based on movement that might have occurred between the beginning and the end of the resting state tasks. Before beginning the remaining tasks, a five-point calibration and validation were used where children were instructed to "follow the black dot with your eyes". Once children completed this and validation was confirmed to be below 1° error, they were given the task instructions and the task would begin. If children could not sit still or look long enough to calibrate, had jittery eyes, or refused to look at the dots, they were still administered the task, but eye-data was not collected (see also Results). Only one of the tasks was gaze contingent (i.e., IOWA) while the rest of the tasks required the researcher to progress to the next trial. Angular sizes and separation of each stimuli presented across all eye-tracking tasks are given in Table 1. Both the eyes-open baseline and the Day/Night task display either static or dynamic stimuli that took up the entire computer screen. The snack delay is not administered via a computer screen. Thus, angular sizes of stimuli for these three tasks is not reported. A video of the session was recorded for all children to check for accurate task scoring, session quality, and identifying behaviors of interest post-hoc.

fNIRS Methods

Once informed consent was obtained, children were seated in a high-chair, without a tray, modified for older children. The circumference of the child's head was measured, and the vertex was measured (half way between the pre-aural areas and halfway between the nasion and inion) and marked with hypoallergenic infant face paint. The appropriate fNIRS hat ranging from 52-54cm was selected by adding 2cm to head circumference for proper probe placement and fitting. Once the hat was placed, Polhemus Patriot digitization system was used to create a 2D digitization of the probe placement. This digitization was then checked for accuracy utilizing MatLab and AtlasViewer software. Once probe placement was deemed accurate, the test researcher would use a pre-cut braided rope measuring 63.5cm to confirm the child was within a 63.5-65cm range from the display screen. Impedance in the fNIRS signal was assessed on each channel and adjustments were made accordingly prior to testing.

Resting-state Protocols

All children first received a pair of resting state tasks: eyes-closed baseline followed by an eyes-open baseline. During the eye-closed baseline children were given the following instructions: "For this first game you will be closing your eyes and thinking of being still and calm. I am going to ask you to do this a couple of times before we get to watch some movies together. Can you be very still and calm with me (*test researcher demonstrating how to be still and calm as well with voice and demeanor; allow child to respond*)? Alright, when you hear the word "close", you are going to close your eyes and be calm and still. When you hear the voice say "open" you will open your eyes. Ready? (*test researcher pushes the space bar to advance the task; voice says "close"*). Close your eyes and be calm and still. (*10 seconds goes by, then voice says "open", test researcher reiterates to open eyes then presses space bar again).*" Children were asked to open and close their eyes a total of five times for an accumulated 50s baseline. During the eyes-open baseline three of five soothing videos were randomly chosen, each with instrumental music that was temporally synchronized with the movement within each video. Children were given the following instructions: "For this game you will be watching some movies. While you are watching, I want you to be still and calm. So, you will need to be very still and calm before I start the videos. Remember to keep your eyes on the screen while the movies are playing." Each video lasted between 45-90s. Volume of auditory components was stationary and set to be clearly audible over the noise produced by the fNIRS machine (68-70 dBC) from where the child sits for each task so they could be heard clearly and consistently throughout the attention battery. During the eyes-open baseline, a black screen first appeared with a white central fixation cross. There were three videos during the eyes-open baseline resulting in an accumulated baseline of 3.5-4.5 minutes for all participants (see Figure 1 for static

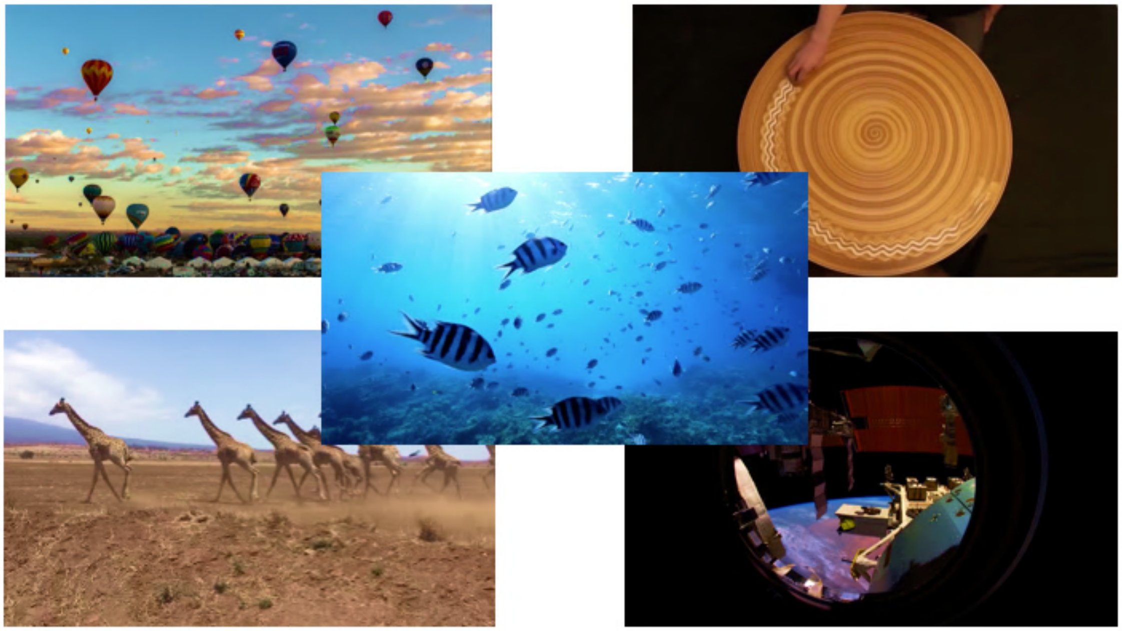


Figure 1. Static screenshots from the five possible videos children were shown during the eyes-open baseline. images of videos used). Once baseline was complete, the lights were turned back on and children began the remaining battery of tasks. Children in the 2.5-year-old group received the IOWA, Flanker, and Snack Delay while the 3.5-year-old group received the IOWA, TC, Flanker, Day/Night, and DCCS.

IOWA Task

For the IOWA task, children first saw a looming smiley face in the center of the screen. Once they looked at the smiley face, the test researcher initiated the trial. The trial consisted of a 200ms cue followed by a 100ms delay (i.e., blank grey screen), followed by the presentation of a target. The cue was randomly chosen to be on either the left, right, both left and right, or neither side for each trial. A fifth cue type had an auditory cue in place of the visual cue (i.e., 500 Hz pure tone). Target stimuli were presented at either the left or right location after the delay period. Based on the combination of cue type and target location, there were five trial types (i.e. nocue/tone, notone/nocue, valid, invalid, and double; see also Figure 2). In this task instructions were modified to keep toddlers and preschoolers both engaged with the task and aware of what was expected of them. To achieve this, the following instructions were given: "You are going to see a smiley face appear on the screen. Then you will see silly objects pop up on the sides of the screen. These are smiley's toys. You need to use your eyes to help find smiley's toys by looking at them. Are you ready? (*pause for child's response*)". Children were redirected to the screen and given these instructions as many times as needed.

Flanker Task

The Flanker task was administered to both age groups. Stimuli consisted of six different animal stimuli (i.e. frog, cricket, dog, duck, and two types of fish; see Figure 3) instead of arrows as in the traditional flanker and ANT tasks. Three trial types typical of the flanker task were administered in random order: congruent, incongruent, and neutral. Each stimulus was used in each type of trial twice; one for right and one for left orientations. For example, the duck stimuli would appear six times, one time in the left orientation and one time in the right orientation for each of the congruent, incongruent, and neutral trial types. There were two phases of the task (i.e. practice and test) where six practice and 45 test trials were administered. Only the cricket

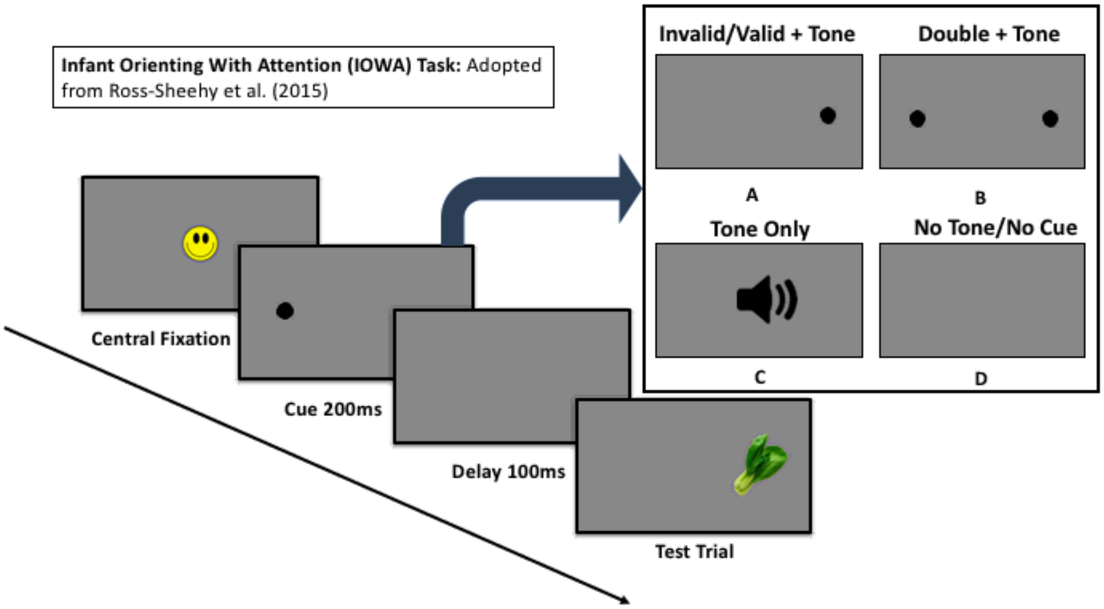


Figure 2. Example of the sequence of events in an invalid trial during the IOWA task used in the current study.

stimuli were used during the practice trials and all animal stimuli were used during the test trials. Within each trial type, only one type of stimuli was shown (e.g., if incongruent then only cricket stimuli in left and right orientations were used). Incongruent trials consisted of five stimuli, where two flanking stimuli on both the right and left would be facing the same direction but opposite of the middle animal. Congruent trials consisted of five stimuli all facing in the same direction, either to the right or left. Finally, neutral trials consisted of one stimulus in the middle of the screen, facing to the right or left.

Children were given the following instructions prior to practicing the task: "(*Before beginning the trial*) You are going to see animals on the screen. Sometimes they will be alone and sometimes they will have friends with them. I want you to pay attention to the animal in the middle of the screen. The animal in the middle is hungry, so your job is to feed it by pressing the blue button that matches the way the animal is facing. When you feed the animal, it will say yummy. (*Start trial*) OK, pay attention to the animal in the middle. Is he facing this way (*point to the right*) or this way (*point to the left*)? If he's facing this way (*point to the right*) press this button (*point to the right button*). If he's facing this way (*point to the left*) press this button *(point to the left button*)." The practice consisted of 6 trials during which the test researcher oriented the child to the task and pointed to the correct response if the child was struggling to understand the rules. There were no RT cut-offs during the task. All RT exclusion criteria were assessed post-hoc via group means as this study was the first to assess toddlers in within this paradigm. Further, the rules were explained as many times as needed during the practice trials. After the practice trials, the test researcher did not provide the correct answer regardless of the child's performance, however they did give the following instructions as many times as needed: "Remember, to feed the animal in the middle (*pointing to the middle*) you push this button (*pointing to the right button*) if they are going this way (*pointing right*) and this button (*pointing to left button*) if they are going this way (*pointing to the left*)". Children were encouraged to go as quickly as they could while also trying to be accurate. Only positive feedback was given in the form of a female voice exclaiming "Yummy" for all correct responses in both the practice and test phases. No negative feedback was given.

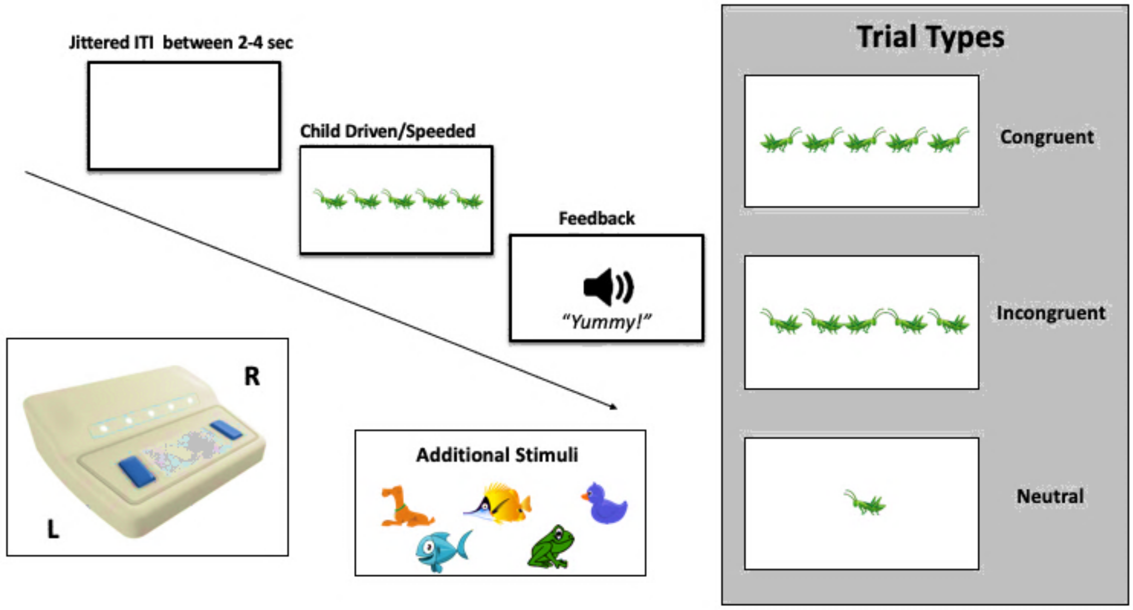


Figure 3. This figure depicts the sequence of events during a congruent trial in the Flanker task. At the bottom, all possible animal stimuli are shown. On the bottom left, the serial response box used is shown.

Snack Delay

The Snack Delay task was only administered to the 2.5-year-old groups. First, children selected whether they preferred goldfish crackers or fruit gummy snacks. Children were told they would get to eat some snacks during this game. The Snack Delay consisted of one practice trial and four test trials with varying delay durations (10, 15, 20, and 30s). During all trials, a small clear cup was staged on the tray of the highchair that snapped easily onto the base tray. The following instructions were given during the practice trial: "I am going to place a gummy/goldfish snack under this cup here (*pointing to the clear cup*). When I ring the bell, you can eat the gummy/goldfish snack. (*ring the bell as a practice and let the child get the gummy/goldfish and eat it*)". During the test trials, these instructions were repeated only once during the first trial and then not again for the remaining three trials. Children received the delay durations in a fixed order from shortest to longest. Halfway through these durations (see Figure 4B), the experimenter reached for the bell and held it until the full duration had passed at which point, they rang the bell indicating it was time to eat the snack (see Figure 4C). Children's behaviors were coded before the trial started, when the test researcher picked up the bell, and when the bell was rung. The test researcher picked up and rang the bell in this way for each trial regardless of whether the child ate the snack early. Children's snack delay performance was scored based on Spinrad, Eisenberg, and Gaertner (2007) (see Table 2 for comparison of scoring).

For the Snack Delay, a score of 0-5 was given based on video coding of children's behaviors. A score of 0 was given if the child ate the gummy/goldfish before the bell was lifted, a score of one if the child are the gummy/goldfish after the bell was lifted, a score of two if the child touched the bell or cup before the bell was lifted, a score of three if the child touched the bell or cup after the bell was lifted, and a score of four if the child waited for the bell to ring before touching the cup or bell and retrieving the gummy/goldfish to eat (Kochanska, Murray, Jacques, Koenig, & Vandegeest, 1996). Each delay duration received a score. Then, a total score was calculated by taking an average of all four scores.

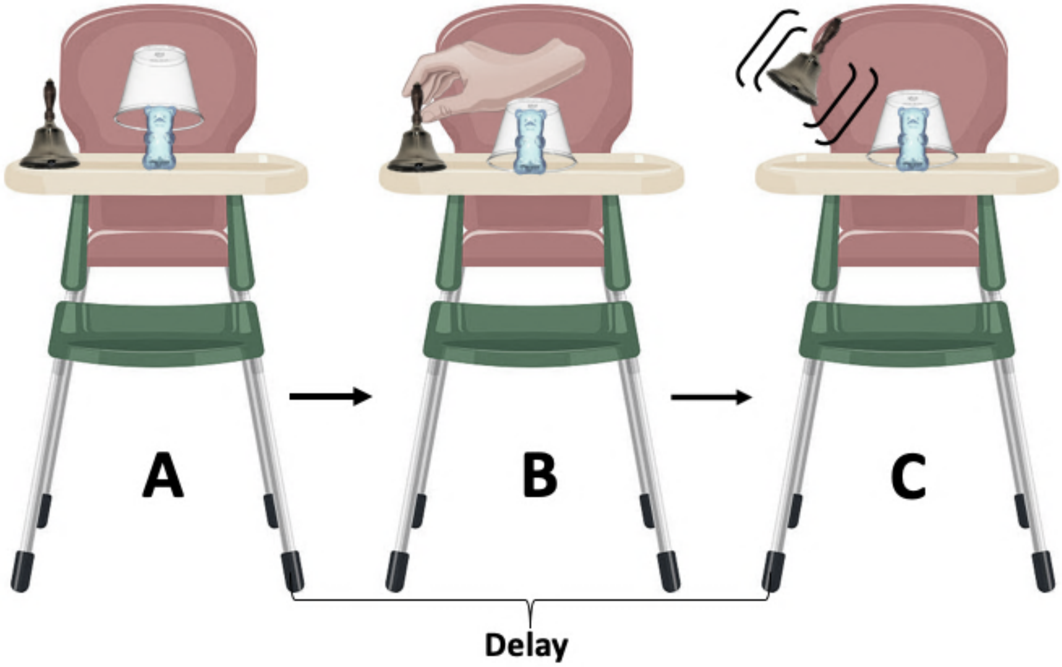


Figure 4. This figure depicts the sequence of events in the Snack Delay.

Table 2. Scoring Comparison for the Snack Delay

Spinrad, Eisenberg, & Gaertner (2007)		Current Study	
Score (1-9)	*Behavior*	*Score (1-5)*	*Behavior*
1	ate the snack right away	1	ate the snack right away or touches bell, cup or snack immediately after the trial starts
2	ate the snack after the experimenter lifted the bell	2	ate the snack after experimenter lifted the bell
3	touched (but did not eat the snack) in the first half of the trial	3	touched the snack, cup, or bell in the first half of the trial
4	touched the snack during the second half of the trial	4	touched the snack, cup, or bell in the second half of the trial
5	only touched the cup during the first half	5	waited the entire time before eating the snack or touching anything on the tray
6	touched the cup during the second half of the trial		
7	waited the entire trial to eat the snack		
+ up to 2 additional points	Kept hands on mat in front of them		

Triad Classification (TC) Task

The TC task was only administered to 3.5-year-olds. The TC task consisted of two practice trials and 50 test trials. During both the practice and test trials children saw three objects appear on the screen. First, a reference object would appear at the top center of the screen. Then, after a 1500ms delay, two target objects appeared. Children were then given the following instructions: "Which of these (*pointing to target objects*) is most like this one (*pointing to reference object*)? You can point to the one you think is most like this one." During the practice trials, children received one trial with a color identity match and a second with a shape identity match in a fixed order where color always came before shape (see Figure 5). Stimuli in the TC had visual features that could be metrically controlled in order to equate manipulations to the two dimensions perceptually. Shapes were defined using Fourier space (see Figure 5b), as defined by Drucker and Aguirre (2009), and colors were defined in CIELab space (Kuehni, 1976). A set of 60 objects were used in which colors and shapes were each stepped in 6º increments for 60 steps. On each trial, an object was randomly selected from this subset of objects to be used as the reference object. The ID object was then chosen to be exactly the same as the target object along either the color or shape dimension (i.e. matching in degree the shape or color of that dimension from the aforementioned set of objects), depending on which dimension was relevant for each trial (i.e. color match or shape match trials). The other dimension of the ID object was selected to be 180º different. For example, if the trial is a color match trial and the reference object is 90 degrees on the color wheel then the identity object would also be 90 on the color wheel but 270 degrees on the 'shape wheel'. The features of the holistic object were chosen to be between 90 and 114 degrees different along both dimensions (i.e., 15 steps of 6° and 19 steps of 6° respectively). For example, when for the above example of a color match trial, the shape of the holistic item could be between 15 (i.e., 90°) and 19 (i.e., 114°) steps different from the features of the reference object. However, for a shape match trial, the holistic object could be 17 (i.e., 102°) or 19 (i.e., 114°) steps different and color would be between 15 (i.e., 90°) or 17(i.e., 102°) degrees different.

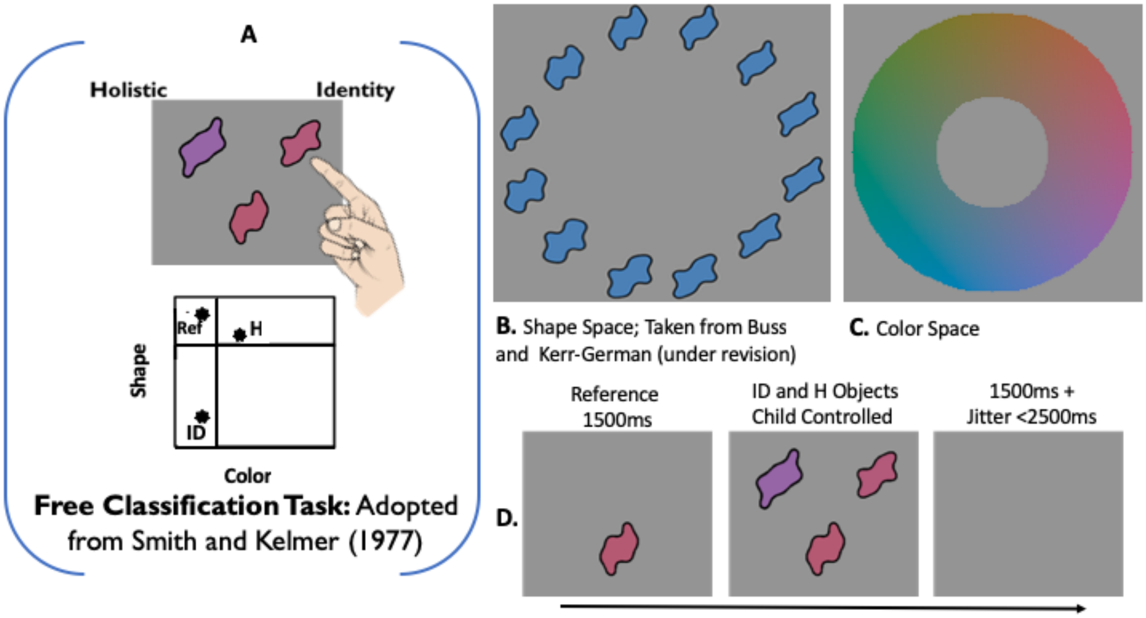


Figure 5. This figure depicts the TC task. On the left (A) an example of the stimuli configuration is given where the finger is pointing to the correct identity (ID) match item. Below this, is the perceptual similarity of the holistic match (H) and ID match items in relation to the reference object. On the top right (B and C) the shape and color space used in this task are demonstrated. Finally, on the bottom (D) the sequence of events in this task is given for an example color match trial.

Day/Night Task

The Day/Night task was only administered to 3.5-year-olds. Children’s responses were recorded online via the test researchers and validated by comparing recorded responses to the video recording from the session. All accuracy scores were checked between the video recording and E-Prime 3.0 © output. In the Day/Night task, there were six practice trials and 16 test trials. During the first two practice trials, children were engaged in a conversation about the sun and moon, where both would be presented one time in a fixed order where sun was presented before moon and stars. The conversation was scripted and deviated minimally from the following “(*The sun will appear on screen. Engage the child in a conservation about the sun. Say something along these lines.*) What is this? (*Once they identify it as the sun ask the following.*) When is the sun in the sky? (*score, then moon will appear on screen. Engage the child in a conversation about the moon. Say something along these lines*.) What is this? (*Once they identify it as the moon ask the following.*) When is the moon in the sky?”. If a child could not correctly identify either the sun or moon and make the appropriate association between the stimuli and time of day (i.e. day/night) they were not administered the rest of the task (Gerstadt, Hong, & Diamond, 1994; Carlson, 2005). The next two practice trials consisted of the sun then moon again in a fixed order while the following instructions were given: “Now we are going to play the opposite game. In the opposite game, when you see the sun, I want you to say “night”. Can you say “night”? (*next the moon*) In the opposite game when you see the moon and stars, I want you to say “day”. Can you say “day”?”. These two trials and their corresponding opposite game rules were repeated once more prior to the test trials. During the test trials, the sun and moon stimuli were randomly displayed. The test researcher did not pause between the practice and test trials (see Figure 6).

The Day/Night task was scored based on two criteria; comprehension and accuracy. For comprehension, children were marked as passing if they understood the stimuli and their associations with the time of day (i.e. day/night) and marked as failing if they did not. Children who failed comprehension did not proceed to the next stage of the task. Next, an accuracy score was calculated as a percent correct during test trials. Chance was calculated as above (>50%) or below (<50%). Children were grouped by this factor for behavioral and neural analyses.

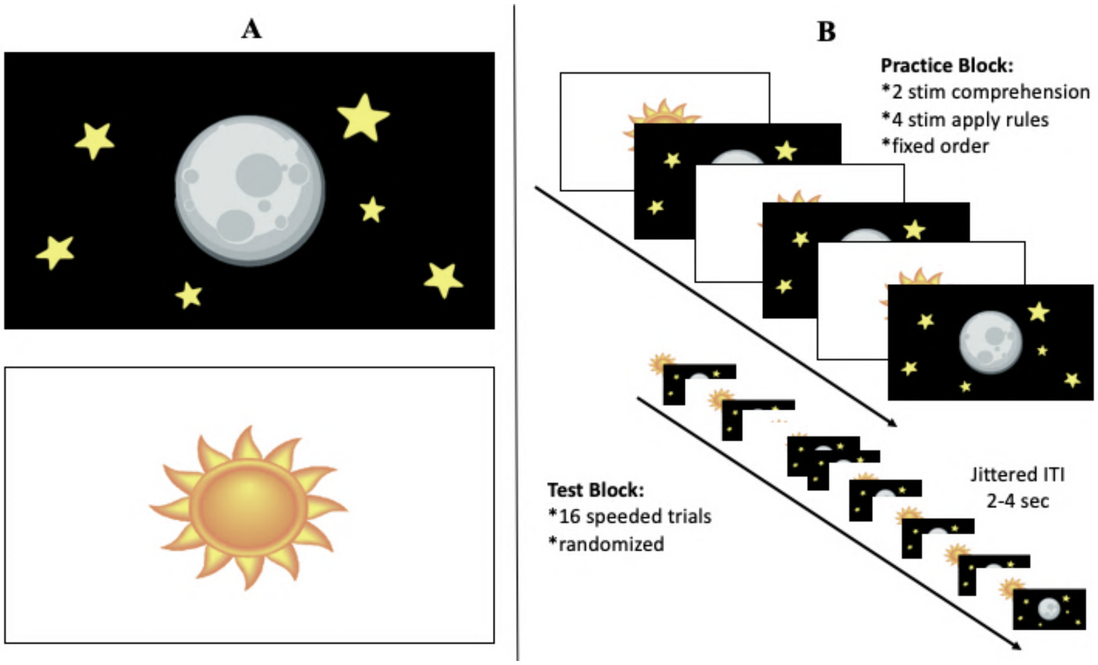


Figure 6. This figure depicts the Day Night task. Stimuli (A) are on the left and the sequence of events (B) is on the right with practice trials on top and experimental trials on bottom.

Dimensional Change Card Sort (DCCS) Task

The DCCS task was only administered to 3.5-year-olds. In the DCCS task there were three phases; the pre-switch, post-switch, and mixed block. All children received color as the pre-switch and shape as the post-switch dimension (see Figure 7a). During the pre-switch, children were instructed to play a color game. The pre-switch phase consisted of five trials where the test card to be sorted was randomly selected. The test card matches both the target cards positioned in sorting trays along one dimension. After the pre-switch phase, the post-switch phase was administered. Children were given the following instructions during the color game in the pre-switch phase once the target cards positioned in sorting trays appeared on the screen: "OK, we are going to play the color game. In the color game, yellow ones go here (*point to corresponding target card*) and purple ones go here (*point to corresponding target card*)." Then the test researchers initiated the trial and the test card would appear at which point they would as children to respond via pointing to the following question "Where does this one go? (*pointing to the test card*)". Next, the post-switch phase was administered. In this phase, the dimensional rules were changed from color to shape (see Figure 7b). Instructions were structured the same in the post-switch phased except were instructed to play the shape game and the features used to describe the sorting rules (e.g. yellow or house) were changed (e.g., fish and house) to reflect the current dimensional rules. There were five post-switch trials. The target cards in the pre- and post-switch phase stayed the same. Finally, a mixed block was administered where the target cards were changed along both the dimension of color and shape (e.g., red bunny, green chair) and the test cards reflected these changes (e.g., red and green bunny, red and green chair; see Figure 7c). The mixed block phase consisted of 28 trials where the dimensional rule was randomly chosen on each trial from a list of 10 color trials and 18 shape trials.

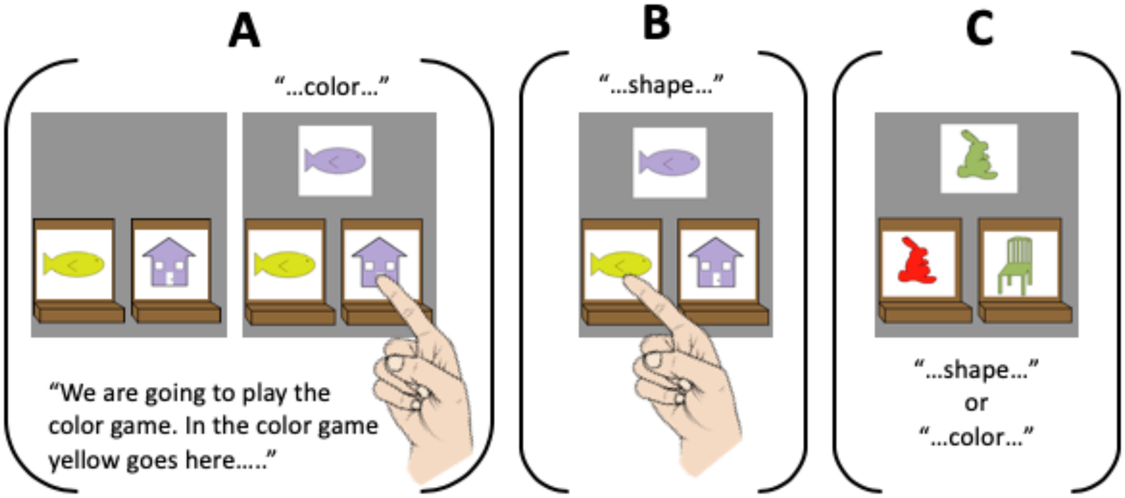


Figure 7. This figure depicts the sequence of the DCCS, with pre-switch trials (A), post-switch trials (B), and mixed block trials (C).

Data Analyses

Self-Report Measures

A designation of ADHD-Risk was assigned to each participant based on whether a parent/guardian scored a 4/6 or higher on Part 1 of the ADHD assessment. Temperament was scored (Putnam et al., 2006, 2010) for 15 temperamental subscales (i.e., Positive Anticipation, Smiling/Laughter, High Intensity Pleasure, Activity Level, Impulsivity, Shyness, Discomfort, Fear, Anger/Frustration, Sadness, Soothability, Inhibitory Control, Attentional Focusing, Low Intensity Pleasure, and Perceptual Sensitivity) and three broad dimensions of temperament (i.e., Extraversion/Surgency, Negative Affectivity, and Effortful Control). Demographics were used to report information about the current sample pertaining to environmental factors such as household income, home environment, childcare, and education levels. Self-report measures were then compared with behavioral outcomes via Pearson correlations to test the relationship between temperament and task performance. A select group of temperament subscales thought to be related to ADHD on other temperament scales (i.e., Activity Level, Impulsivity, Inhibitory Control, and Attentional Focusing) as well as Anger/Frustration were assessed via independent samples t-test with a grouping variable of risk to test the relationship between temperament and risk in this sample (McIntosh & Cole-Love, 1996). To the authors knowledge, this temperament scale has not been used to profile ADHD risk in young children prior to the current study. The subscale of Anger/Frustration was added to these analyses because it is possible children who struggle in the four domains previously associated with ADHD, might also rank higher in frustration/anger.

Behavioral

Performance was first inspected independently for 2.5- and 3.5-year-olds across all tasks. In addition to this, performance was also collapsed across age for the Flanker and IOWA tasks to examine cognitive abilities (i.e. attention and inhibition) as continuous metrics. Analyses for the IOWA task was previously discussed as those performance scores were derived solely from eye-tracking data. The resting state tasks were not scored but children who did not complete all five eyes-closed trials and/or all three eyes-open trials were excluded from further analyses. In addition, any inattentive behaviors such as talking or looking around was coded via video recordings offline and considered in decisions concerning dropping or keeping participants in the final dataset. Assessment scores and risk scores were also used to group the behavioral data.

For the Flanker task, a conflict score was calculated by subtracting average reaction time (RT) for congruent trials from average RT during incongruent trials. Average RTs for congruent trials were compared to baseline RTs (i.e. RT during neutral trials). Only trials that fell within the 14 second RT range were included in these averages. Accuracy was also calculated for congruent, incongruent, and neutral trial types as a percent correct score. Again, trials were pruned for RT in this task. Accuracy and RT were compared between 2.5 and 3.5-year-olds.

Total percent correct (i.e. accuracy) and fail/pass scores (i.e. for the DCCS: perseverators/switchers; for the TC: > or <70% correct) were generated for both the TC and DCCS tasks (Kerr-German & Buss, submitted). Further, TC total scores were broken down into shape and color scores (i.e. percent correct identity match by dimension).

Eye-Tracking

For the IOWA task, RT and directional responses were given by saccade and fixation data recorded via the eye-tracker. For each trial, children first had to be fixed on the central fixation (i.e., looming smiley). Then, latency to look to the target was calculated based on the first look from the central fixation to the right or left target location. Trials were scored as accurate if the first look after the cue and delay period was to the correct location of the target and inaccurate if it was to any other location. Looks that occurred faster than 90ms after this period were considered reactive and excluded. Incorrect trials were not included in the final RT averages or composite attention scores. Scores for percent correct (PC), average RT, and composite attention scores (facilitation, interference, and competition) were calculated based on these measures of latency and accuracy. PC for each trial type were the average number of trials that children correctly looked to the target location. Average RTs were calculated as the average latency to look to the target on correct trials for each trial type. All composite attention scores were normalized by dividing difference in average latencies by Tone RT. Facilitation scores were by subtracting the average Valid RT from the average Tone RT and then dividing it by the average Tone RT. Interference scores were calculated by subtracting the average Tone RT from the average Invalid RT and dividing by average Tone RT. Competition scores were calculated by subtracting the average Valid RT from Double RT and dividing by average Tone RT. Finally, error in the task was calculated based on the average error (percent incorrect) during invalid and double trials (Task Error) and the average of error in no tone, cue, and valid (Baseline Error).

For the Flanker task, fixation durations were calculated for each trial for each ROI and then averaged across different trial types and accuracy types separately. Proportion of time spent looking to the middle item vs. the flanker items were calculated based on total time spent on the screen and total time spent looking at the objects where proportions were reported for looking at middle and flanking items out of total time spent looking at items on the screen and out of total time looking at the screen. Looks off screen were not included in the results but were explored to see if children looked considerably longer at the buttons when making a response than they did looking at the stimuli when processing them. Again, trials with RTs that were too long were excluded from these calculations.

For the DCCS and TC tasks, fixation data was averaged across correct and incorrect trials. For the DCCS fixation data was organized based on phase of the task (i.e., pre-switch, post-switch, and mixed) as well as accuracy. Fixation data for the TC was organized into accuracy and dimensional groups (i.e., shape correct, shape incorrect, color correct, color incorrect) as well as collapsed across dimension (accurate, inaccurate). In both of these tasks, trials were excluded based on RT criterion except one analysis exploring the first switch trial in each phase of the DCCS where a large portion of the sample took longer than the mean RT for all trials to apply the new rule and response. Thus, those trials were included regardless of RT exclusion criterion.

fNIRS

For the tasks where an event-related analysis was used (i.e., IOWA, Flanker, DCCS, Day Night, and TC) trials were excluded from the final fNIRS analyses if RT exceeded 14 seconds in length. However, during behavioral analyses trials were excluded if the RT exceeded two standard deviations above the mean of RT for that task or task condition. EasyNIRS was used for all pre-processing of data. Data were first converted to an optical density measure. A wavelet-based motion artifact removal tool within EasyNIRS was used to correct motion artifacts in the data (iqr=.5). Next, data were band-pass filtered (high-pass filter=.019, low-pass filter=.5) before converting to absolute concentration values using the modified Beer-Lambert equation (DPF values of 6.0 and 6.0 were used). The average amplitude of oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (HbR) were calculated for each trial type on each channel within the time range of 0-8 seconds post trial-onset to capture the peak of the hemodynamic response in this age group (de Roever et al., 2018; Lu et al., 2010; Whiteman, Santosa, Chen, Perlman, & Huppert, 2017). Both HbO_2 and HbR are reported here, where activation is seen as a significant difference between HbO_2 and HbR where HbO_2 is positive going to reduce the risk of false positives and false negatives in the hemodynamic results (e.g., Tachtsidis & Scholkmann, 2016). Mixed-factor ANOVAs were used to analyze changes in hemoglobin (HbO_2 and HbR) during these tasks in relation to performance (high, low), and accuracy (inaccurate, accurate).

For the tasks that utilized functional connectivity (FC) or resting-state functional connectivity (rFC) analyses (i.e., eyes-closed and eyes-open resting state, snack delay), similar pre-processing steps are used in EasyNIRS. Data were first converted to an optical density measure utilizing the Beer-Lambert law. Then artifact was removed across all channels if levels of HbO_2 or HbR exceeded .35 in one timestep. Next, remaining data in the time series was condensed and correlation matrices were generated for each participant calculated by comparing data on every channel at every time step to every other channel at that same time step for the entire time window. For eyes-closed resting state children had to have 45 out of 50 seconds of eyes-closed data remaining after artifact removal to be included in this final step. For eyes-open resting state the inclusion criteria were 2.5-minutes of data out of 3.5-4.5 potential minutes. Finally, averages for each group (i.e., 2.5-year-olds, 3.5-year-olds, risk, and performance based) were calculated across all of these individual matrices to obtain group rFC results (e.g., Wang, Dong, & Niu, 2017). Group level FC maps were generated for HbO_2, HbR, and HbT but only HbO_2 was used to target channel relationships that were significant at the .001 level. Then, individual correlation coefficients for each participant were extracted for those significant regional relationships and used in statistics for those groups. Correlation coefficients on significant channel pairs were used as a score for the strength of FC between those two cortical regions or channels (i.e., channel pairs). Thus, regressions were used on all of these coefficients to test if any regions functional connectivity was predictive of both HbO_2 levels in those channels during event-related tasks and the associated behavior in that task. Specifically, channels that showed significant FC were matched with channels that showed event-related activation to test if the strength of functional connectivity between specific regions at rest was indicative of task-related activation in those same regions during executive function and attention tasks within the current battery. Finally, temperament and FC at rest were assessed via similar regressions with temperament composite and sub-scores of interested as predictors and FC strengths as dependent variables. For a review of variables across task and methods see Table 3 and Figure 8.

Table 3. Variables for Cross-Sectional Comparison

Age Group	Task	Eye-Tracking	fNIRS	Behavioral
All Children	Resting State (EO, EC)		o Functional connectivity o Strength and channel pairs	
	Flanker *(Executive Attention & Executive Function)*	o Proportion of time looking (on screen, on stimuli, to specific stimuli) o Fixations Durations (average, total)	o Event-related activation	o RT o Accuracy o Flanker Effect
	IOWA *(Orienting, Alerting)*	o RT (Latency to look to target after the cue) o Composite Attention scores, based on normalized differences in RT o Accuracy (correct look to target or not) o Percent correct based on accuracy o Error based on accuracy	o Chromophore levels (averages for HbO2, HbR) o Event-related activation based on chromophore average	
2.5	Snack Delay (*Inhibition*)		o Functional connectivity o Strength and channel pairs	o Scores on the 4 delay durations o Average performance across delay durations
3.5	Day Night *(Inhibition)*		o Chromophore levels (averages for HbO2, HbR) o Event-related activation based on chromophore average	o Total percent correct o Pass/Fail (above chance, below chance)
	DCCS (*Executive Function*)	o Proportion of time looking (on screen, on stimuli, to specific stimuli)	o Chromophore levels (averages for HbO2, HbR)	o Total percent correct

Table 3 Continued.

Age Group	Task	Eye-Tracking	fNIRS	Behavioral
		○ Fixations Durations (average, total) for trial types (switch trials, phases of task, accurate/inaccurate)	○ Event-related activation based on chromophore average	○ Post-switch performance (switch, perseverate)
	TC *(Executive Function)*	○ Proportion of time looking (on screen, on stimuli, to specific stimuli) ○ Fixations Durations (average, total) for trial types (accurate/inaccurate)	○ Chromophore levels (averages for HbO2, HbR) ○ Event-related activation based on chromophore average	○ Total percent correct

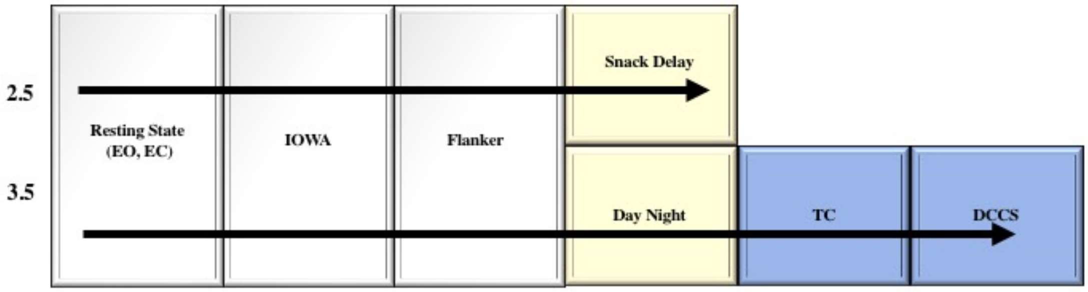


Figure 8. Cross Sectional Task Order.

CHAPTER III:

RESULTS

Introduction to Results

Below, I examine a series of hypotheses that were described above. I hypothesized that orienting, alerting, and regulated attention measures would predict resting-state functional connectivity in corresponding neural fronto-parietal attention networks during regulated attention tasks (Snack Delay and Day Night Task) as well behavioral performance in those same tasks for 2.5- and 3.5-year-olds respectfully. Further, event-related activation in a selective and regulated attention task (i.e., Flanker task) and a basic attention task (i.e., IOWA task) were hypothesized to show developmental differences in neural activation as a function of age and performance criteria, such that, children who perform higher in these measures would also have more refined short-range tuning as well as differential activation patterns across the three attention networks proposed by Posner and Peterson (1990, 2012) while performing these tasks as evidenced by the event-related data. Further, it is hypothesized that younger children will have lower performance in comparison to older children. Resting state functional connectivity was also hypothesized to predict performance in both the Flanker and IOWA tasks. Performance during executive functioning tasks (i.e., 2.5-year-olds: Flanker and Snack Delay; 3.5-year-olds: DCCS, TC, and Day Night), will be predicted by both behavioral performance and neural activation in the orienting and alerting attention measure (i.e., IOWA).

Self-report measures were hypothesized to be related to these same behavioral and neural outcomes. For example, temperamental differences and corresponding subscales will vary across age groups and composite score such as inhibitory control will predict inhibitory abilities in tasks such as the Day Night and Snack Delay. Further, as reviewed in the introduction, overlap in processes involved in regulated attention and executive function tasks will be highly correlated behaviorally in various ways across participants due to shared processing demands (i.e. overlap in cognitive processes being utilized for successful performance in these task). These hypothesizes are tested and further explored in the following sections.

The results chapter is divided into sections. The first section defines the current sample and presents descriptive statistics on self-report and general correlations between behavioral measures. In this section attrition in the current study is also addressed. The second section reports resting state functional connectivity(rFC) during eyes-open baseline, group differences in rFC and the relationship between rFC and behavior in the current battery of tasks. The final section goes through each task, behavioral results first followed by eye-tracking if this method was employed for the current task, followed by fNIRS event-related or functional connectivity analyses, and then a summary section.

The Current Sample

Descriptive Statistics and Survey Results

A total of 71 children enrolled in the current study after pilot data collection. Due to the length of the battery, use of multiple methods, and age groups being studied, there was some attrition. The current study used an extensive demographics survey to quantify environmental factors such as household income, parents in the home, number of siblings, parental education, and child care practices (see Figure 9). Of the 71 children enrolled in the current study, four were reported as being left handed, 11 as ambidextrous, and 56 as right handed. The majority of children fell within an upper middle-class white demographic. The current sample was not representative of race and ethnicity frequencies in the United States or the education level in the general population where 87.3% of adults have a high school diploma or equivalent and 30.9% of adults have a 4-year-degree or higher (USA Census Bureau, 2017). Further, temperament scores for each age group and the risk group are depicted in Figure 10.

To better understand the rate of reporting ADHD symptomology among parents via the ADHD self-report measure, all children who were enrolled into the experimental sessions including pilots (N=83) were calculated to compare base-rates for the current population in comparison to the national and regional averages for ADHD (see Figure 11). Interestingly, the current sample did not show over-reporting of ADHD symptomology among parents compared to the region ($t(82)=-1.423$, $p=.159$) or nation ($t(82)=-1.0$, $p=.320$), suggesting this method of identifying children who might be at risk for developing ADHD prior to school aged may be a viable one.

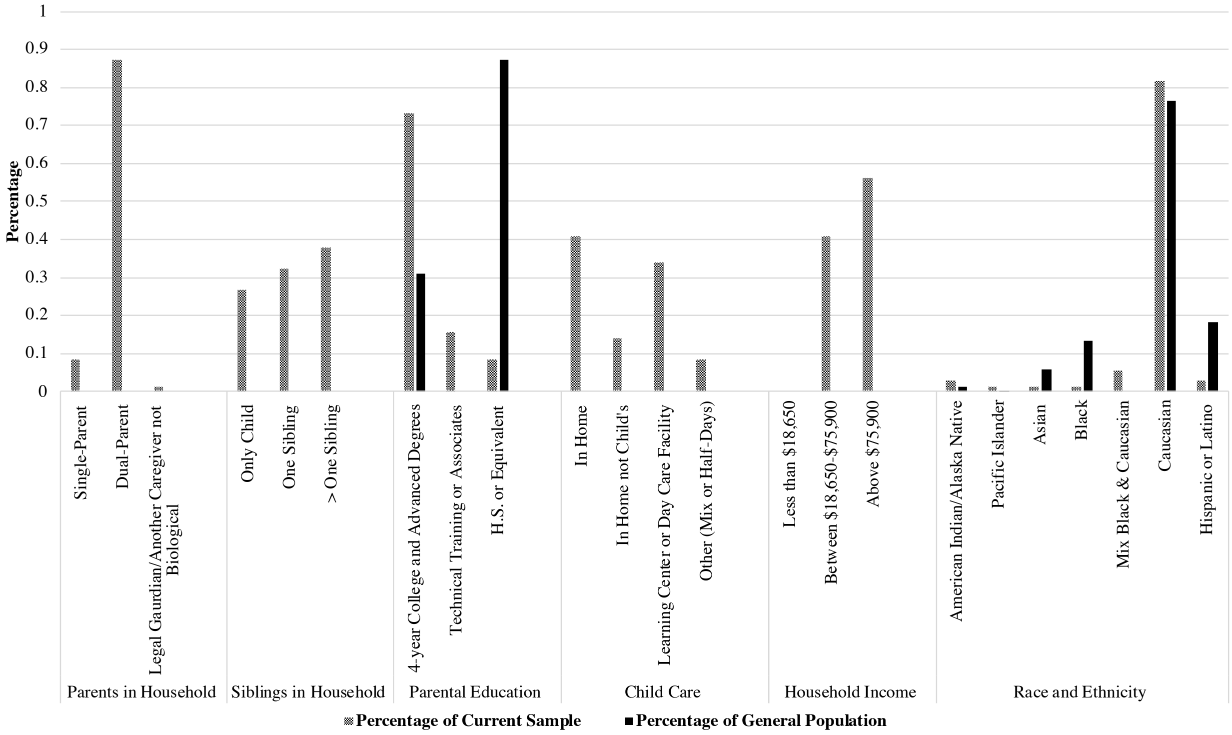


Figure 9. Frequencies of reported demographics in the current population compared to reported frequencies in the general population based on USA Census Bureau Data from 2017.

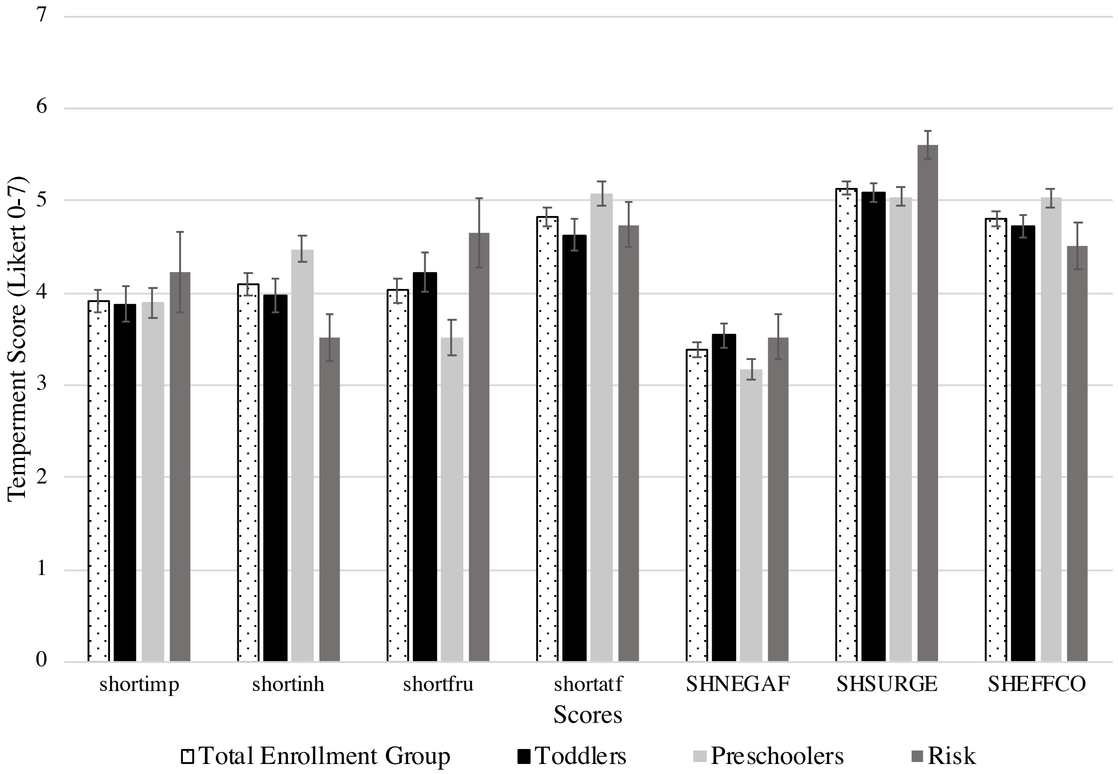


Figure 10. Mean scores for the four subscores of interest from the ECBQ (i.e., shortimp=impulsivity, shortinh=inhibitory control, shortfru=frustration, shortatf=attentional focus) and the three composite scores (i.e., SHNEGAF=negative affect, SHSURGE=extroversion and surgency, SHEFFCO=effortful control) for the current sample. Mean scores are broken in to age and risk groups as well as collapsed across all groups reported as a total mean for the sample.

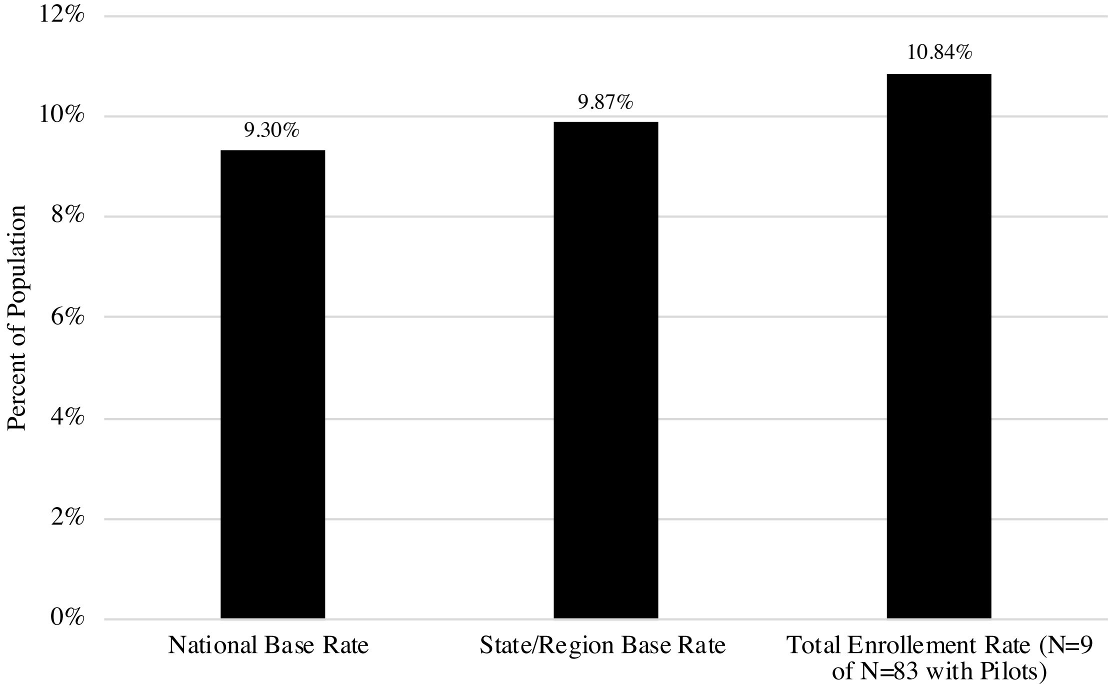


Figure 11. National base reporting for ADHD compared to the regional base rate for the state in which the current study was conducted, and the base rate for the total children enrolled in the study out of the current sample.

Children without the risk distinction had lower activity levels (*t*(68)=-2.732, *p*<.000) than those that did have the risk distinction. However, children without the risk distinction did not have significantly higher inhibitory control scores compared to the risk group (*t*(68)=1.922, *p*=.059). Children in the risk group were rated higher in high intensity pleasure (*t*(68)=-2.946, *p*=.004) and in surgency and extroversion (*t*(68=-2.798, *p*=.007) than children without the risk distinction. The risk group included children from both age groups, thus risk and age specific scores in temperament were not explored.

A Chi-squared test of independence was calculated comparing the frequency of risk distinction in 2.5-year-olds and 3.5-year-olds in the current enrollment sample (N=83). The interaction between risk distinction and age was not significant ($\chi^2(1) = .083$, p = .773) suggesting parents were not reporting symptoms more if they had a 2.5-year-old compared to a 3.5-year-old. Further, attentional focus (*t*(66)=-1.876, *p*=.065) and frustration (*t*(66)=1.797, *p*=.077) scores were not significantly different between the two age groups. However, inhibitory control (*t*(66)=-2.018, *p*=.048) was predicted by age. Younger children had lower attentional focus scores, higher frustration scores, and lower inhibition scores. Backward elimination regressions were run on all 15 temperament sub-scores and the three composite scores with risk and a significant regression equation as found (*F*(1,69) = 7.463, *p*=.008, r^2= .099) where activity level positively predicted risk above the other scores.

Temperament and Behavior

To test the relationship between temperament and performance in this battery of tasks, backward selection stepwise regressions were used with temperament scores (i.e., 15 sub-scales and 3 composite scores) as the predictors and behavior in each of the attention tasks as the dependent variable, separately. A significant regression equation was found (*F*(1,22) = 4.471, *p*=.011, *R*=.706) was found where impulsivity (β=-.303, *t*(22)=-3.446, *p*=.003), low intensity pleasure(β=-.171, *t*(22)=-2.025, *p*=.058), shyness (β=-.280, *t*(22)=-3.486, *p*=.003), and sociability (β=2.94, *t*(22)=3.092, *p*=.006) accounted for 49.8% of the variance in the Day/Night task. A significant regression equation (*F*(1,24) = 9.964, *p*=.004, *R*=.550) was found for snack delay performance (i.e., continuous score) where inhibitory control accounted for 30.2% of the variance in performance (β=-.853, *t*(24)=-3.157, *p*=.004). Impulse control (β=-.095, *t*(19)=-

2.412, p=.027) accounted for 24.4% of the variance in DCCS total scores (F(1,19) = 5.816, p=.027, R=.494). Activity level(β=.130, t(29)=3.392, p=.002) and impulse control (β=-.079, t(29)=-2.112, p=.044) accounted for 29.9% of the variance in total scores for the TC task(F(1,29) = 5.752, p=.008, R=.547). Activity level (β=.094, t(54)=2.270, p=.028) , attentional selectivity(β=.119, t(54)=2.482, p=.016), perceptual sensitivity(β=-.078, t(54)=-2.143, p=.037), and sociability (β=-.086, t(54)=-2.781, p=.008) accounted for 20.8% of the variability in percent correct scores during congruent trials in the Flanker task (F(1,54) = 3.275, p=.018, R=.456). Further, cuddliness (β=-.086, t(54)=-2.781, p=.008) accounted for 7.4% of the variance in incongruent trial performance (F(1,54) = 4.257, p=.044, R=.273). Finally, frustration (β=-.090, t(54)=-2.497, p=.016), motor activity (β=.099, t(54)=2.170, p=.035), perceptual sensitivity (β=-.094, t(54)=-1.978, p=.054), positive anticipation (β=.090, t(54)=2.358, p=.022), sadness (β=-.073, t(54)=-1.70, p=.096), and shyness (β=.062, t(54)=1.816, p=.076) accounted for 24.1% of the variance in percent correct scores on neutral trials in the Flanker task (F(1,54) = 2.534, p=.033, R=.490)

No one trait was predictive of IOWA performance in two out of three of the composite scores, thus backward elimination regressions were used on the IOWA composite attention scores. Attentional focus(β=.320, t(57)=2.777, p=.008), attentional selectivity(β=-.350, t(57)=-2.905, p=.005), fear(β=.214, t(57)=2.477, p=.016), and positive anticipation (β=.261, t(57)=2.610, p=.012) accounted for 23.5% of the variance in facilitation scores (F(1,57) = 4.077, p=.006, R=.485). Positive anticipation (β=-.397, t(57)=-2.562, p=.013) and sociability (β=.314, t(57)=2.280, p=.027) accounted for 12% of the variance in interference scores from the IOWA task(F(1,57) = 3.752, p=.030, R=.346). Finally, distractibility (β=.111, t(57)=-2.131, p=.037) accounted for 7.5% of the variance in competition scores (F(1,57) = 4.541, p=.037, R=.274).

Relationships Among Behavioral Scores

Basic correlations were run between behavioral scores for each task. Facilitation scores in the IOWA were predictive of accuracy in neutral trials during the Flanker for all children (r^2=-.310, p=.03), and Day Night total score in 3.5-year-olds (r^2=-.466, p=.029). Competition scores in the IOWA were predictive of incongruent accuracy in the Flanker for all children (r^2=.344, p=.016), and Day Night chance performance in 3.5-year-olds (r^2=-.485, p=.022). Congruent accuracy scores in the Flanker were predictive of snack delay score (r^2=.487, p=.016) for 2.5-year-olds. Day Night and DCCS total scores were not significantly related (r^2=.461, p=.062). Previous work has linked continuous scores on the TC to performance in the DCCS (Kerr-German & Buss, submitted). However, the TC and DCCS tasks were not correlated (r^2=-.056, p=.814) in the current study. This is likely due to the small sample size and high attrition in the DCCS task. Further, the DCCS task in the current study was shortened even further from previous papers (Kerr-German & Buss, submitted) thus it is likely the total scores are not the most informative in the current study. Follow-up independent samples t-test were run on total scores in the TC with a grouping factor of perseverator and switcher, but results were still not significant (t(18)=-.133, p=.895). Another alternative is that the TC and DCCS association is not as stable in 3.5-year-olds as it is in 4.5-year-olds. Previous studies utilizing both of these tasks have looked at 3.5- and 4.5-year-olds together. This current study is limited in this way.

Due to high attrition in this study, each subsequent analysis will include as many children as there is viable data for the current analyses. Thus, from task to task different children may be included.

Resting-State Results

Behavioral

A total of 34 2.5-year-olds and 36 3.5-year-olds began the eyes-closed resting state tasks. Of the 2.5-year-olds, one child refused to wear the fNIRS cap during the tasks, one child was dropped for a medical condition reported in session, and four children were not on task (i.e., were afraid of the dark so would not close their eyes or continuously talked through baseline). Of the 3.5-year-olds, one child refused to wear the fNIRS cap, one child was dropped for diagnosed behavioral problems reported in session, and one child was unable to complete the tasks due to technical difficulties with the display monitor thus was given a pilot battery under the same IRB with a different monitor. A total of 28 2.5-year-olds and 33 3.5-year-olds were included in the final resting state analyses. For the eyes-open resting state task, the same children were dropped in the 2.5-year-old group except one of the children who was previously afraid of the dark was willing to watch the videos, thus a total of 29 2.5-year-olds participated in the eyes-open baseline task. Of the 3.5-year-olds, five additional children were dropped due to technical issues with equipment (i.e., videos freezing intermittently) during the task. These issues were resolved by upgrading presentation software.

fNIRS Analyses

Recent work with resting-state utilizing fNIRS in children employed a correlation analysis to map functional connectivity profiles for each child in a sample after pre-processing (e.g., Gallagher, Tremblay, & Vannasing, 2016; Li & Qiu, 2014; Wang, Dong, & Nui, 2017). However, the task procedures in these studies spanned from eyes-closed to non-descriptive states at rest. Thus, in the current study both eyes-open and eyes-closed baselines were obtained. First, eyes-closed baseline data will be discussed. Data was grouped into 2.5-year-olds, risk, and 3.5-year-olds. There was an even number of 2.5-year-olds and 3.5-year-olds in the risk group (N=8). Two children in the risk group, three children from the 2.5-year-olds group and one child from the 3.5-year-old group were dropped from these analyses after motion artifact was removed for not having enough remaining data for eyes-closed baseline. Only group level channel pairs with positive correlation coefficients were used to extract individual correlation coefficients from the correlation coefficient matrices for each channel for each individual (see Figure 12). There was an even number of 2.5-year-olds and 3.5-year-olds in the risk group (N=8) for eyes-open baseline. Two children in the risk group, two children from the 2.5-year-olds group and one child from the 3.5-year-old group were dropped from these analyses after motion artifact was removed for not having enough remaining data for eyes-closed baseline (see Figure 10 for final sample and figurative representations of correlation coefficient matrices).

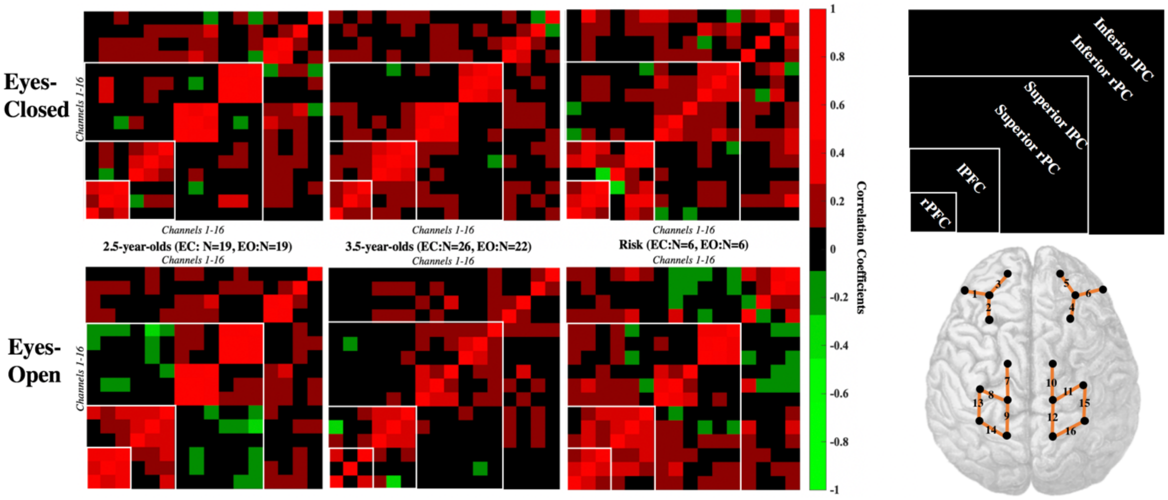


Figure 12. The above figure resting state depicts function connectivity (rFC) maps for 2.5- and 3.5-year-ols as well as children with the risk distinction. On the top is RFC during the eyes-closed baseline (45 seconds) and the bottom is RFC during the eyes-open baseline (2.5-minutes). In the middle are age groups, and sample size for eyes-closed (EC) and eyes-open (EO). Boxes in red represent channel pairs that are positively correlated at the .001 significance level. Boxes in black represent channel pairs that are not correlates and boxes in green represent channels that are negatively correlated at the .001 significant level. However, negatively correlated channels are not used beyond this step for further statistics.

Linking rFC and Behavioral Performance in the IOWA Task

Orienting, alerting, and regulated attention measures were hypothesized to predict resting-state connectivity in corresponding neural fronto-parietal attention networks. Multiple regression analysis was used to test if the strength of rFC during eyes-open baseline between fronto-parietal areas predicted participants' overall performance during the IOWA task (i.e., composite attention scores). First, shared channel pairs between 2.5- and 3.5-year-olds had to be distinguished (see Figure 11). Backward elimination methods were employed with multiple regressions on all shared channel pairs in each frontal cluster (i.e., left and right frontal cortex) channel pairs with posterior regions. That is all channel pairs from cluster 1 and 2 (i.e., left and right frontal with corresponding parietal region) were run as predictors for each of the three composite attention scores in the IOWA separately.

First the facilitation score (i.e., measure of alerting) was run in this regression analysis with shared channel pairs (see Figure 13) between eye-open resting state functional connectivity across all 2.5 and 3.5-year-olds regardless of risk criteria. These results were insignificant, thus supporting the null hypothesis. To test if any within-region channel pairs were instead predictive of composite attention scores in the IOWA task, all shared channel-pairs were included in the following analyses utilizing forward selection stepwise regressions (see Figure 11). These same channels were also found to be significant in the risk group when rFC analyses were run for them independently. A significant regression equation was found, R^2= .38, *F*(1,33) = 6.26, *p* =.002, where within region channel pairs in left parietal cortex (i.e., 15-16), β=.530, *t*(33)=2.47, *p*=.019, and right parietal cortex (i.e., 7-8), β=.756, *t*(33)=2.20, *p*=.036, were positively related to facilitation scores in this task while within region channel pair in left parietal was also negatively predictive of performance in this task (i.e., 8-13), β=-1.34, *t*(33)=-3.97, *p*<.001. Together rFC between these channel pairs accounted for 38.5% of the variance in facilitation scores. These data suggest that the stronger the functional connectivity within superior left parietal and inferior right parietal, and weaker connectivity between inferior left parietal, the more efficiently spatial cueing is facilitated.

Next, rFC was tested as a predictor of interference scores (i.e., orienting). A multiple linear regression was calculated to predict interference scores based on these channel pairs

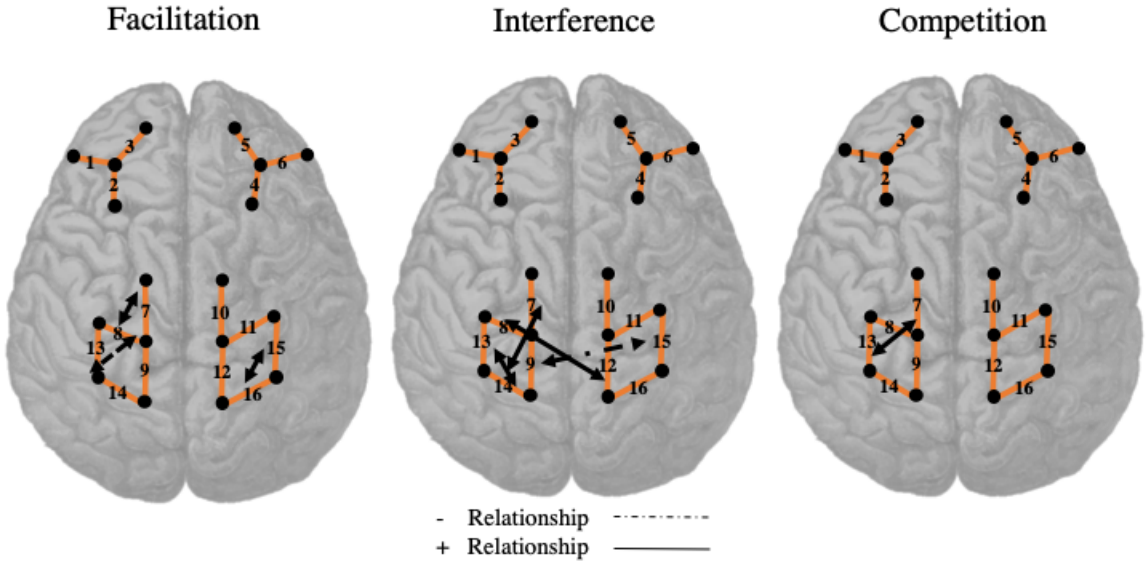


Figure 13. The above figure depicts the relationship between rFC during rest and performance in the IOWA task (i.e., composite attention scores).

A significant regression equation was found, R^2= .612, $F(1,33) = 6.31$, $p <.001$, where rFC channel pairs within left parietal cortex (i.e.,7-14), β=1.21, $t(33)=3.08$, $p=.005$, and between left and right parietal lobe (i.e., 8-12), β=1.15, $t(33)=3.08$, $p=.005$, were positively predictive of interference score whereas bilateral parietal (i.e., 9-15), β=-1.42, $t(33)=-4.07$, $p<.001$, and within regional left parietal cortex (i.e., 13-14), β=-2.06, $t(33)=-4.75$, $p<.001$, rFC was negatively predictive of interference scores. Together, these four channel pairs accounted for 61.2% of the variance in interference scores. Finally, within regional rFC in left parietal cortex, β=-.648, $t(33)=-2.22$, $p=.034$, accounted for 13.4% of the variance in in competition scores from the IOWA task, R^2= .134, $F(1,33) = 4.93$, $p=.034$.

Together these findings suggest that within and between posterior regional tuning might be more responsible for performance in a basic attention task such as the IOWA when accounting for long range connectivity from frontal to posterior regions.

Linking rFC and Behavioral Performance in the Flanker Task

The same shared pairs between 2.5- and 3.5-year-olds previously used in analyses with the IOWA task were used in the current analyses. Accuracy scores on each of the three flanker trial types were tested separately as dependent variables in a forward selection stepwise regression with channel pairs as predictors. A multiple linear regression was calculated to predict interference scores based on these channel pairs. A significant regression equation was found, R^2= .558, $F(1,35) = 9.768$, $p <.001$, where channel pairs from right frontal to right parietal (i.e., 4-10), β=.143, $t(35)=2.23$, $p=.033$, and from left frontal to right parietal (i.e., 2-15), β=.188, $t(35)=3.0$, $p=.005$, were positively predictive of congruent trial performance while two inter-regional channel pairs in left frontal (i.e., 1-3), β=-.159, $t(35)=-2.34$, $p=.026$, and right parietal (i.e., 10-11), β=-.325, $t(35)=-3.97$, $p<.001$, were negatively associated with performance during congruent trials. Together, these channel pairs accounted for 55.8%of the variance in congruent trial performance. This suggest that stronger long-range connections and weaker short-range connections might lead to better selective attention.

Next, rFC channel pairs were used to predict performance on neutral trials. A significant regression equation was found, R^2= .591, $F(1,35) = 11.2$, $p <.001$, where channel pairs from right frontal to right parietal (i.e., 4-11), β=.198, $t(35)=3.12$, $p=.004$, and within right frontal cortex (i.e., 4-6), β=.190, *t*(35)=2.66, *p*=.012, were positively predictive of neutral trial performance (see also Figure 14). Two channel pairs were negatively associated with neutral performance in this model; one between right frontal and parietal cortex (i.e., 4-12), β=-.273, *t*(35)=-3.37, *p*=.002, and the other within right parietal (i.e., 10-11), β=-.329, *t*(35)=-3.60, *p*=.001. These data suggest that a lateralized network might be involved in responding in this task, that is pushing the left or right button associated with the correct direction of the only animal on the screen, in comparison to a more bilateral network of cortical areas needed to selectively attention to the middle animal while also making the appropriate response in this task. Although flanking items during congruent trials do not provide competing information in this task, their presence might serve as a distractor generally for children.

Finally, rFC between right frontal and left parietal cortex (i.e., 5-7), β=-.223, *t*(35)=-2.60, *p* =.013, is negatively predictive of accuracy on incongruent trials R^2= .154, *F*(1,35) =6.749, *p* =.013, and accounts for 15.4% of the variance in performance during for this trial type.

Linking rFC and 3.5-year-olds Behavioral Performance

For these analyses, all channels specific to 3.5-year-olds were assessed. Only channel pairs that had significant positive relationships and passed the above criteria were considered for these analyses. For the DCCS, a forward selection stepwise regression was used to isolate the channel pairs that best predicted performance in the DCCS (i.e., pass/fail). The traditional measure of performance in the DCCS task, that is passing or failing the post-switch phase, was used as the dependent variable in these regressions with channel pairs as the predictors. A significant regression equation was found, R^2= .946, *F*(1,12) = 35.0, *p* <.001, where one channel pair from right frontal to right parietal (i.e., 5-12) was positively predictive of passing the DCCS task while three channel pairs were negatively predictive of post-switch performance from left frontal to parietal (i.e., 2-14), β=-.685, *t*(12)=-2.82, *p*=.023, from right frontal to parietal (i.e.,5-12), β=-.899, *t*(12)=-5.57, *p*=.001, and right frontal to left parietal (i.e., 6-9), β=-1.66, *t*(12)=-8.28, *p*<.001.Together these channel pairs accounted for 94.6% of the variance in performance.

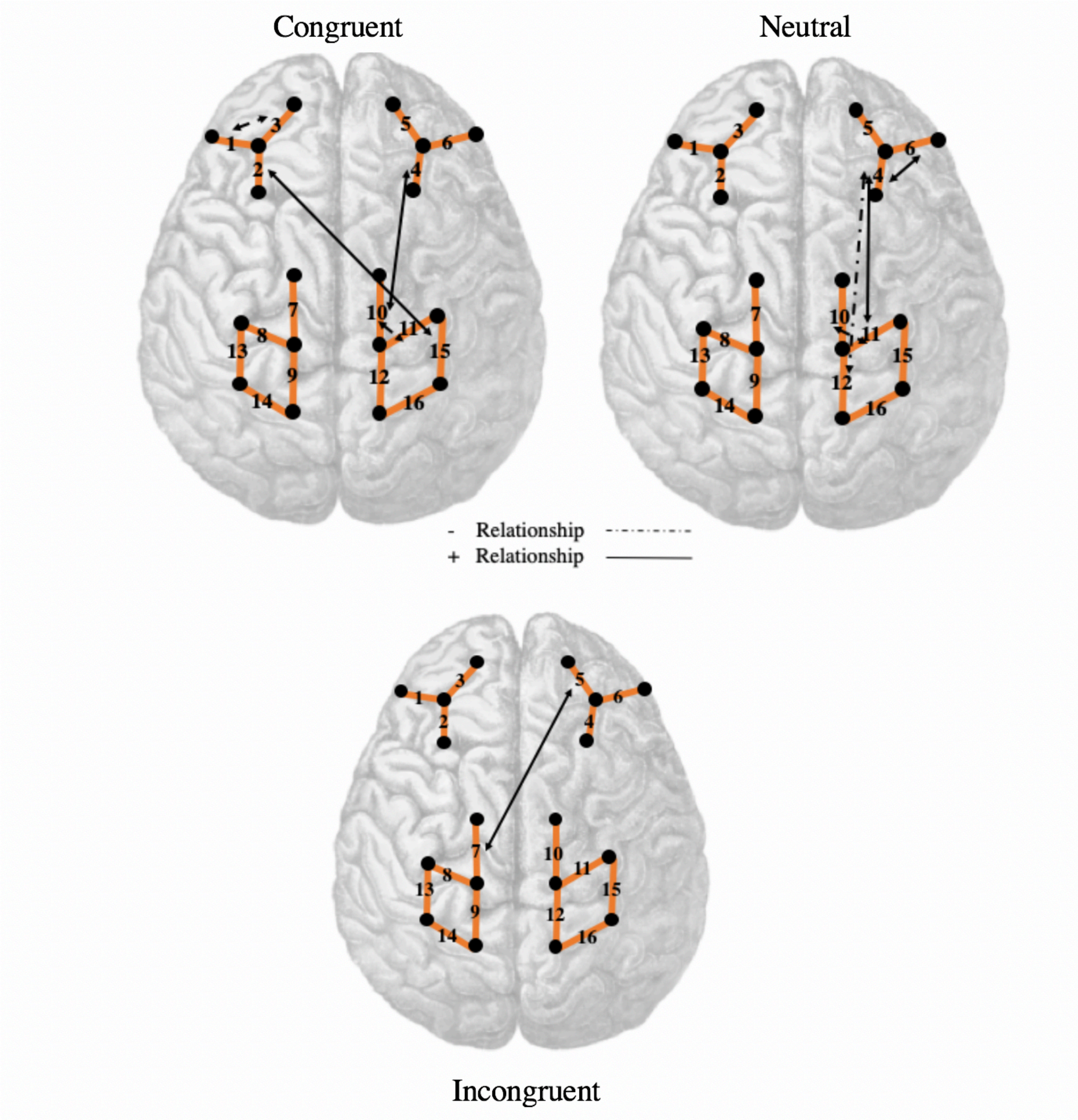


Figure 14. The above figure depicts the relationship between rFC during rest and performance in the Flanker task (i.e., accuracy during congruent, neutral, and incongruent trials).

Similar to the DCCS, the TC task only had one channel pair between right frontal and parietal cortex (i.e., 4-12) , β=.175, *t*(16)=2.18, *p*=.045, that was positively predictive of performance (i.e., TC total score), R^2= .241, *F*(1,16) = 4.76, *p* =.045. Further, the TC task did not have any negative predictors. Finally, the same regression was run with a dependent variable of Day Night performance grouped into passing and failing based on who performed above chance level. A significant regression equation was found, R^2= .364, *F*(1, 12) = 6.31, *p* =.029, where one channel pair (i.e., 3-10), β=.-1.27, *t*(12)=-2.51, *p*=.029, between left frontal and right parietal was negatively predictive of above or below chance performance in this task and accounted for 36.4% of the variance in performance (see Figure 15).

Task Specific Results

IOWA Results

Behavioral and Eye-Tracking Results

A total of 59 (2.5-year-olds: N=28; 3.5-year-olds: N=30) children completed the IOWA task. Behavior in this task was recorded via eye-tracking and video recordings taken of the session. One child was dropped for having a bad calibration. Of the remaining children, exclusion criteria were applied. Children had to have at least six trials contributing to each of the five conditions to be included in the following analyses. A total of 54 children remained after these inclusion criteria. Group RT data was first analyzed by conducting a 2 x 5 repeated measures ANOVA, with age as a between-subject factor and condition RT (valid, invalid, double, tone only, and no cue) as within-subject factors. There was no main effect of condition, *F*(4,49)=1.657, *p*=.175, η_p^2 =.119, nor was there a condition by age effect, *F*(4,49)=.019, *p*=.999, η_p^2 =.002 (see Figure 16).

Next, group accuracy was analyzed by conducting a 2 x 5 repeated measures ANOVA, with age as a between-subject factor and condition accuracy (valid, invalid, double, tone only, and no cue) as within-subject factors. Results revealed main effect of condition, *F*(4,49)=5.96, *p*=.001, η_p^2 =.327, but no interaction between age and condition, *F*(4,49)=.543, *p*=.705, η_p^2 =.042 (see Figure 17).

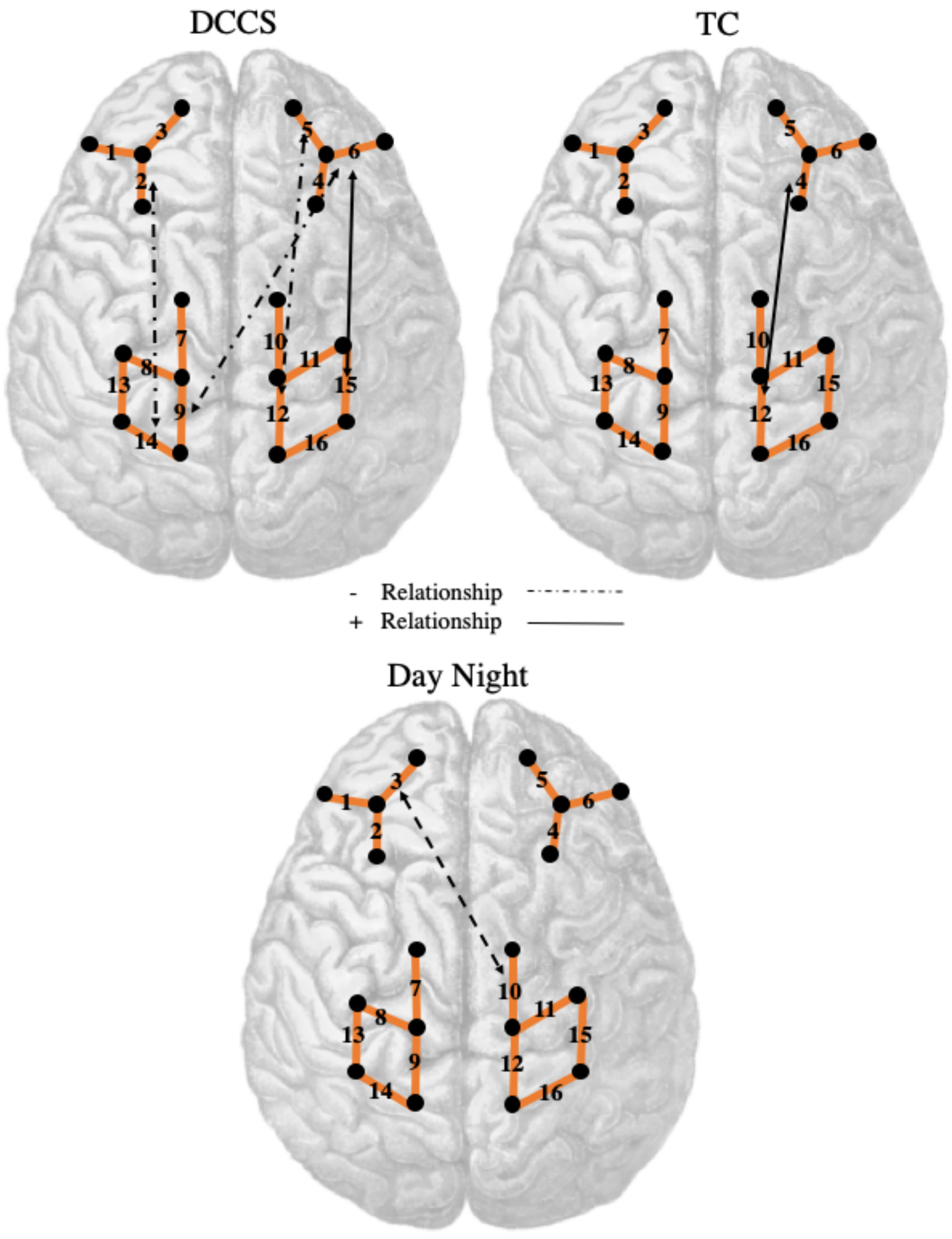


Figure 15. The above figure depicts the relationship between rFC during rest and performance in the DCCS task, TC task, and Day/Night task.

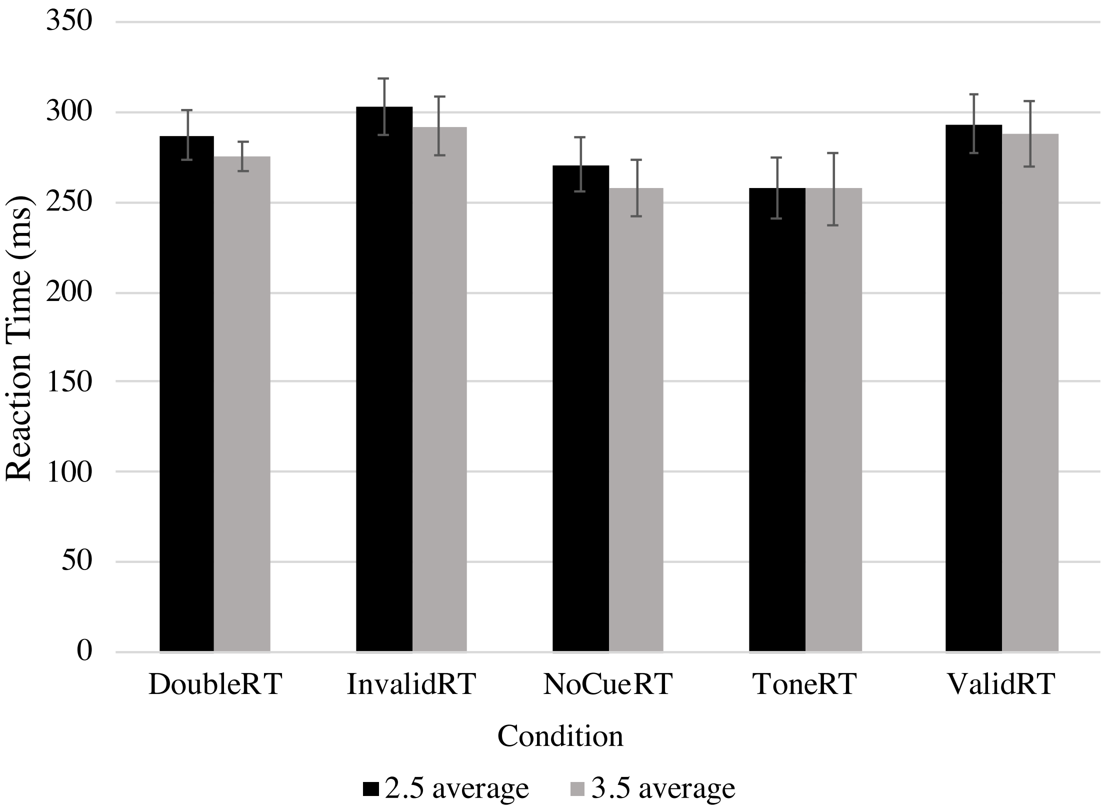


Figure 16. RT for accurate trials during different conditions in the IOWA task.

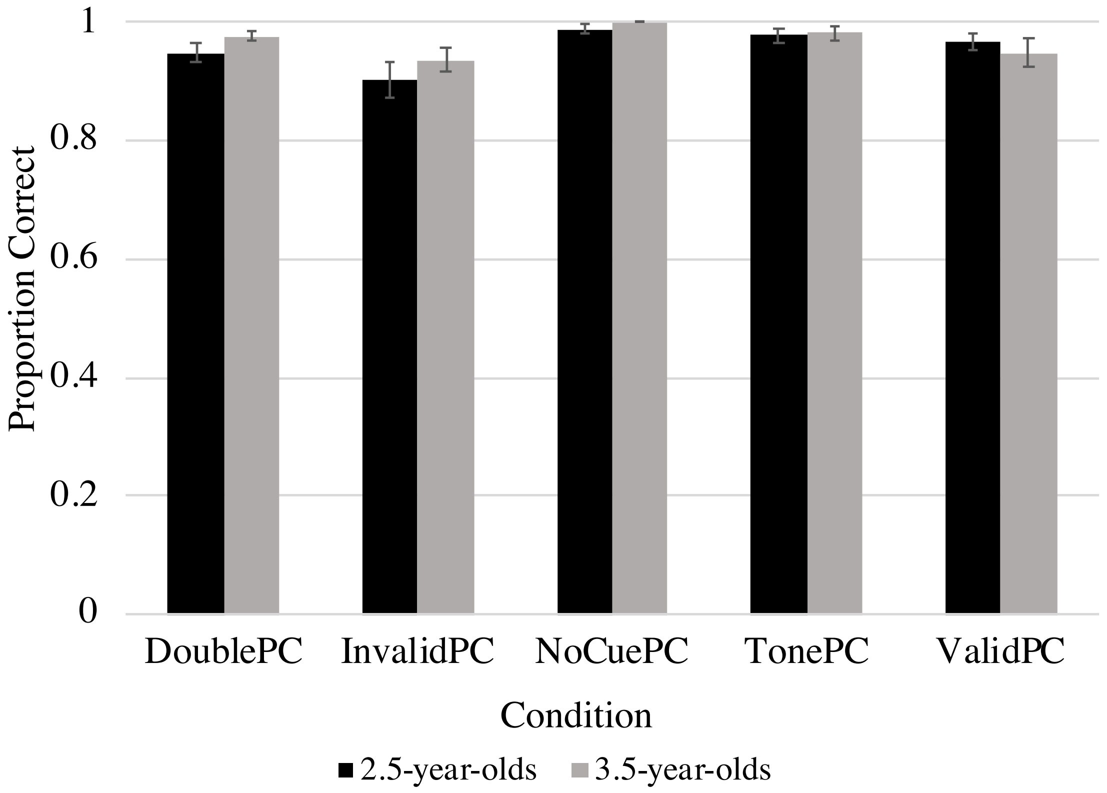


Figure 17. Accuracy during different conditions in the IOWA task

Bonferroni corrected follow-up paired samples t-tests revealed participants were more accurate in the no-cue condition compared to both the invalid condition, $t(53)=-3.76$, $p<.001$, and the double condition, $t(53)=-3.02$ $p=.004$. Further, participants were more accurate in the tone condition than in the invalid condition, $t(53)=-2.99$, $p=.004$.

Next composite attention scores were explored via a mixed 2(age: 2.5-, 3.5-year-olds) x 3(attention score: facilitation, competition, interference) repeated measure ANOVA with age as a between-subject factor and attention score as a within-subject factor. There was a significant main effect of attention score, $F(2,51)=6.4$, $p=.003$, $\eta_p^2=.201$, but no interaction between attention score and age, $F(2,51)=.226$, $p=.799$, $\eta_p^2=.009$. Bonferroni corrected paired-samples t-test demonstrated a significant difference between facilitation and interference scores, $t(53)=-3.60$, $p=.001$, facilitation and competition scores, $t(53)=-3.38$, $p=.001$, and interference and competition scores $t(53)=3.235$, $p=.002$ (see Figure 18).

Finally, error rates were compared between 2.5- and 3.5-year-olds but running a 2(age) by 2(error rate) mixed repeated measure ANOVA with a within-subject factor of error rate and a between-subject factor of age. There was no main effect of error rate, $F(1, 52)=3.99$, $p=.051$, $\eta_p^2=.071$, or interaction between error rate and age, $F(1,52)=1.69$, $p=.200$, $\eta_p^2=.031$ (see Figure 19).

IOWA and Risk for ADHD

These same analyses were run with a between-subject factor of risk instead of age. Due to an imbalance in sample size for each group these results should be interpreted with caution. There was no interaction between condition and risk, $F(4,49)=1.31$, $p=.281$, $\eta_p^2=.096$. For accuracy there was no interaction between condition and risk, $F(1,52)=.098$, $p=.983$, $\eta_p^2=.008$. For the composite attention scores, there was no interaction between risk and attention scores, $F(2,51)=.481$, $p=.621$, $\eta_p^2=.019$. Finally when comparing error rates, there was no interaction between risk and error rate, $F(1,52)=036$, $p=.851$, $\eta_p^2=.001$.

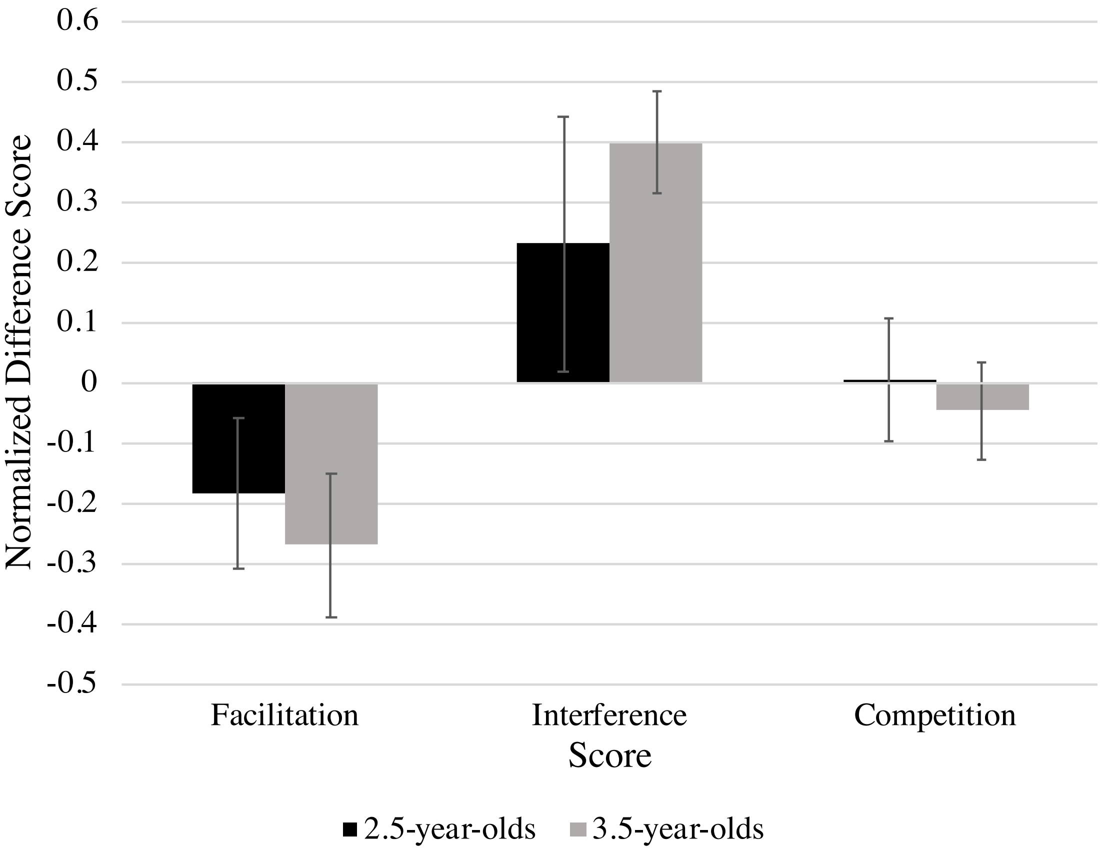


Figure 18. Composite attention scores by age in the IOWA task.

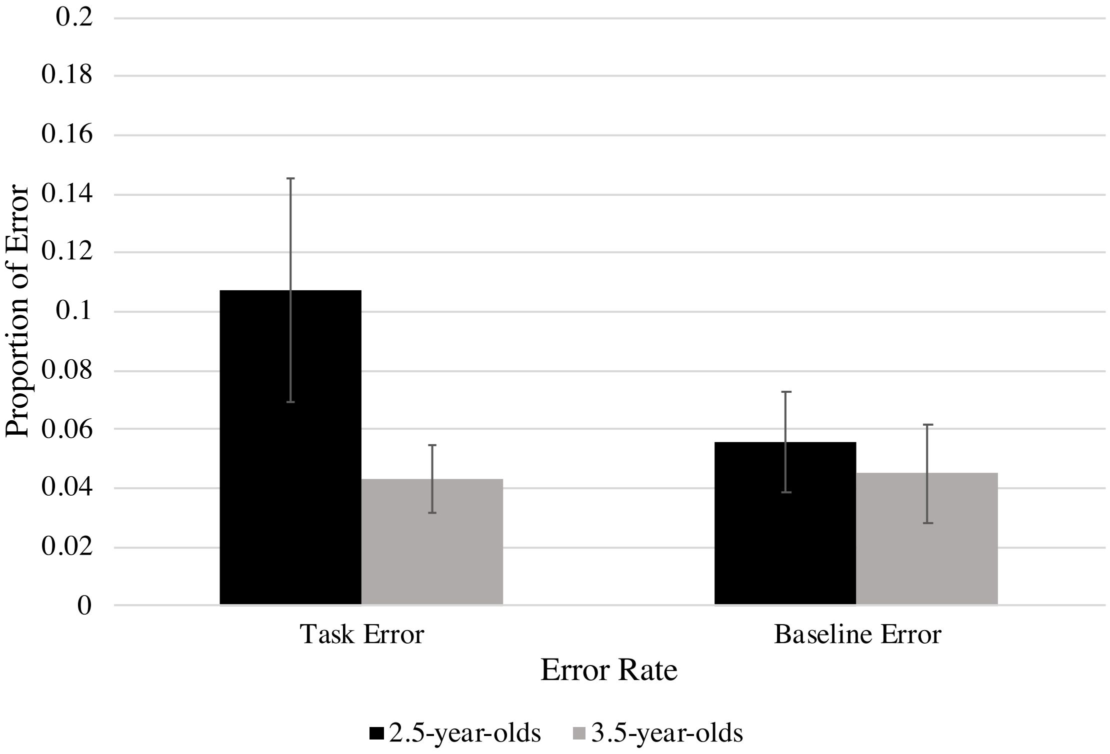


Figure 19. This figure shows error rates for 2.5- and 3.5-year-olds in the IOWA task.

IOWA fNIRS Event-Related Results

The same behavioral exclusions used in the previous analysis were implemented in the current analysis. Of the remaining 54 children, two 2.5-year-olds and one 3.5-year-old were excluded for refusing to wear the fNIRS cap during the task. An additional two children were excluded for noisy fNIRS data. Thus 48 children were included in the final fNIRS analysis, 24 2.5-year-olds and 22 3.5-year-olds. Data was first pre-processed as outlined in the methods section. Then data was divided into age groups and condition types. Only accurate trials were analyzed.

First, mixed 2 (chromophore: HbO_2 , HbR) x 5 (condition: valid, invalid, tone, no cue, double) repeated measures ANOVAs were run for each channel separately with within-subject factors of chromophore and condition. These results are highlighted in Figure 19. On channel 5 (i.e., right prefrontal cortex) there was a main effect of chromophore, $F(1,35)=5.87$, $p=.021$, $\eta_p^2=.144$. Follow-up paired samples t-test, where HbO_2 and HbR were averaged across condition types, revealed that HbO_2 ($M=.07$) was positive going and statistically different from HbR($M=-.007$) on channel 5, $t(35)=2.42$, $p=.021$ (see Figure 20).

Next, mixed 2 (chromophore: HbO_2 , HbR) x 5 (condition: valid, invalid, tone, no cue, double)x 2 (age: 2.5-years-old, 3.5-years-old) repeated measures ANOVAs were run for each channel separately with within-subject factors of chromophore and condition and between subjects-factor of age. These results revealed a significant interaction between chromophore and age on channel 15, $F(1,35)=5.64$, $p=.023$, $\eta_p^2=.142$. Follow-up independent samples t-tests with age as a grouping variable and where HbO_2 and HbR were averaged across condition types were run. These tests revealed that HbO_2 (2.5-year-olds: $M=.131$; 3.5-year-olds: $M=-.02$) was statistically different between 2.5-year-olds and 3.5-year-olds where younger children showed increases in HbO_2 and older children showed decreases, $t(34)=2.75$, $p=.010$. There was no difference in HbR (2.5-year-olds: $M=-.044$; 3.5-year-olds: $M=-.02$) values between these two age groups, $t(34)=-.291$, $p=.773$. Paired-samples t-tests on 2.5-year-old for channel 15 revealed that younger children showed activation on this channel, $t(12)=2.34$, $p=.037$, across trial types whereas older children did not (see Figure 21).

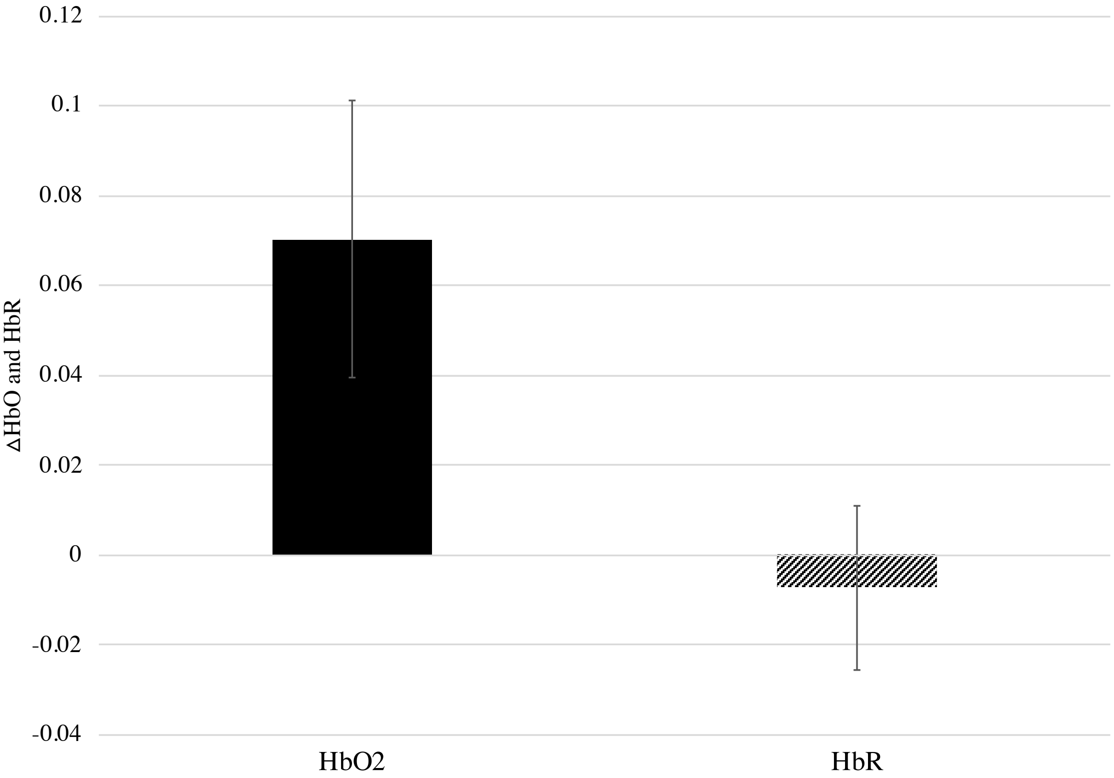


Figure 20. Group wide activation on channel 5 during the IOWA task, collapsed across trial type.

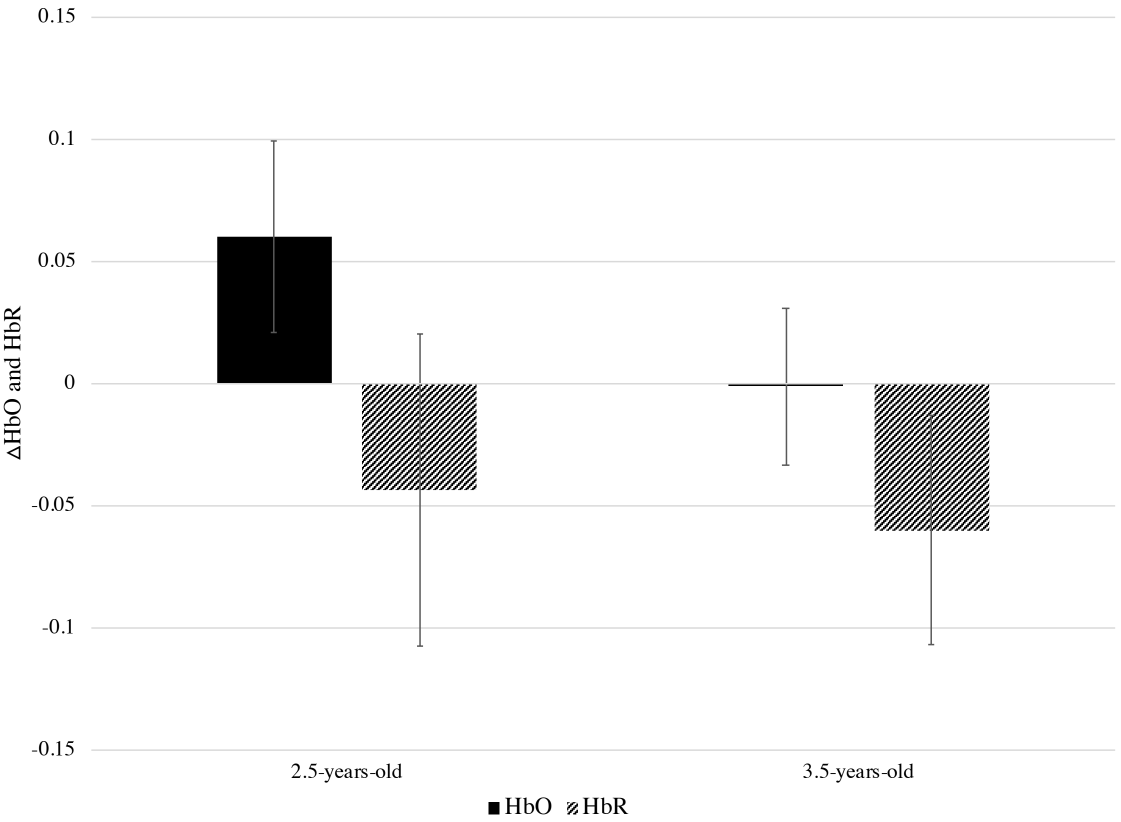


Figure 21. Age differences in activation across trial types in the IOWA task on channel 15.

One alternative approach to this data is to analyze hemodynamics with composite scores as a covariate and corresponding conditions as within-subject factors with chromophore to better isolate the underlying neural mechanisms as age is not related to performance in this task (see also Table 4).

To explore whether raw speed of orienting or alerting in this task predicted hemodynamics during those same trial types, mixed 2(chromophore) x 1(condition) x 1 (raw scores (RT): orienting, alerting) repeated measures ANOVAs with within-subject factors of chromophore and between-subject factors of either Tone Only RT (i.e., raw alerting speed) or No Cue RT (i.e., raw orienting speed). For alerting, channel 13 showed a significant interaction between Tone Only RTs and chromophore, $F(1,42)=6.89$, $p=.012$, $\eta_p^2=.141$. A main effect of chromophore was significant, $F(4,31)=3.33$, $p=.022$, $\eta_p^2=.300$, so correlations were done between HbO_2 and HbR with Tone Only RT (see Figure 8). Here, HbR was negatively associated with alerting speed during tone trials, $r^2=-.328$, $p=.030$. rFC involving channel 13 was predictive of all three attention composite scores in Section 2. No other channels during Tone Only trials were predictive of raw alerting speed except channel 13 (see Figure 21).

Next, these same ANOVAs were run for no cue trials to test if raw orienting speed was predictive of activation during no cue trials. Results revealed an interaction between raw orienting speed and chromophore on No Cue trials for channel 12, $F(1,37)=9.31$, $p=.004$, $\eta_p^2=.201$, with corresponding main effect of chromophore, $F(1,37)=9.90$, $p=.003$, $\eta_p^2=.211$. The same interaction was found on channel 13, $F(1,37)=5.85$, $p=.021$, $\eta_p^2=.137$, and main effect of chromophore, $F(1,37)=5.99$, $p=.019$, $\eta_p^2=.139$. Channel 14 had a main effect of chromophore, $F(1,37)=4.30$, $p=.045$, $\eta_p^2=.104$, but no interaction between raw orienting speed and chromophore, $F(1,37)=2.90$, $p=.097$, $\eta_p^2=.073$. HbR is negatively related to raw orienting speed on channel 13, such that as HbR decreases orienting speed increases, $r^2=-.329$, $p=.041$. Further, HbO_2 is negatively related to orienting speed on channel 13, such that as HbO_2 increases, orienting speed decreases, $r^2=-.367$, $p=.021$ (see Figure 22).

Table 4. Correlations between Age and IOWA Task Scores

		Age Group	Double RT	Invalid RT	NoCue RT	Tone RT	Valid RT	Mean RT	Double PC	Invalid PC	NoCue PC	Tone PC	Valid PC	Total PC	Fac.	Interf.	Comp.
Age Group	Pearson Correlation	1	-0.099	-0.065	-0.079	-0.001	-0.028	-0.051	0.203	0.122	0.205	0.029	-0.090	0.103	-0.065	0.095	-0.053
	Sig. (2-tailed)		0.465	0.629	0.564	0.996	0.838	0.706	0.130	0.364	0.130	0.828	0.513	0.443	0.630	0.478	0.695
	N	58	58	57	57	56	58	55	58	57	57	56	58	55	58	58	58

*. Correlation is Significant at the 0.05 level (2-tailed).
*. Correlation is Significant at the 0.01 level (2-tailed).
*. Comp. = Competition, Fac. = Facilitation, Interf. = Interference.

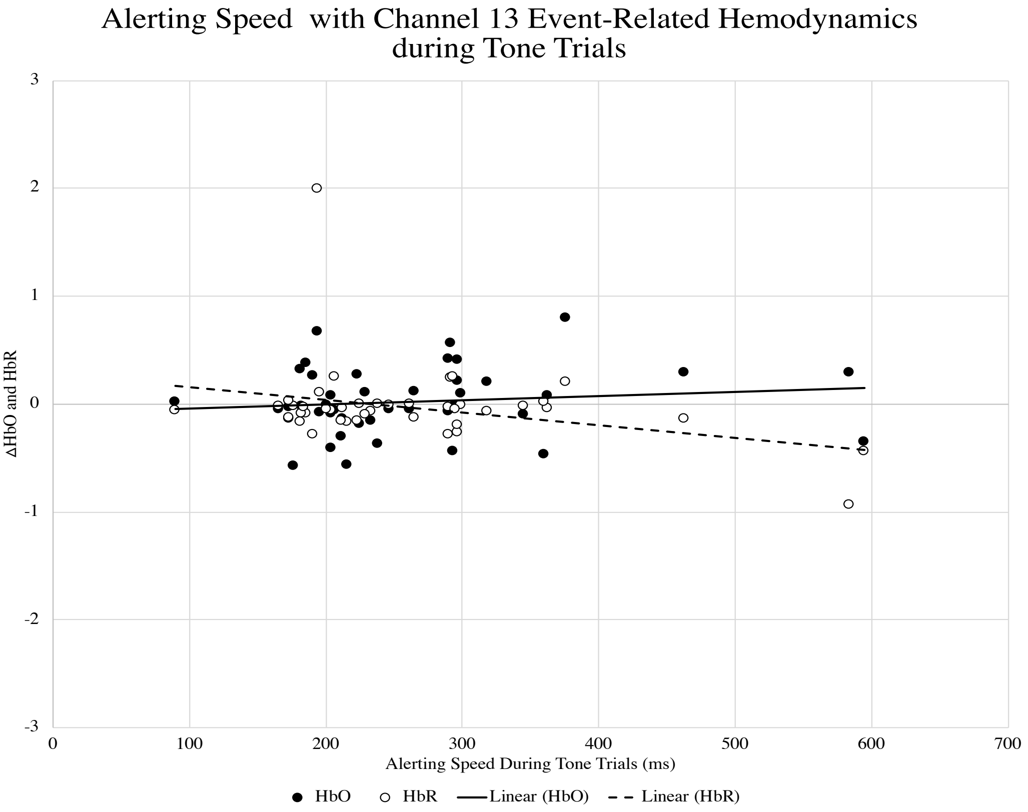
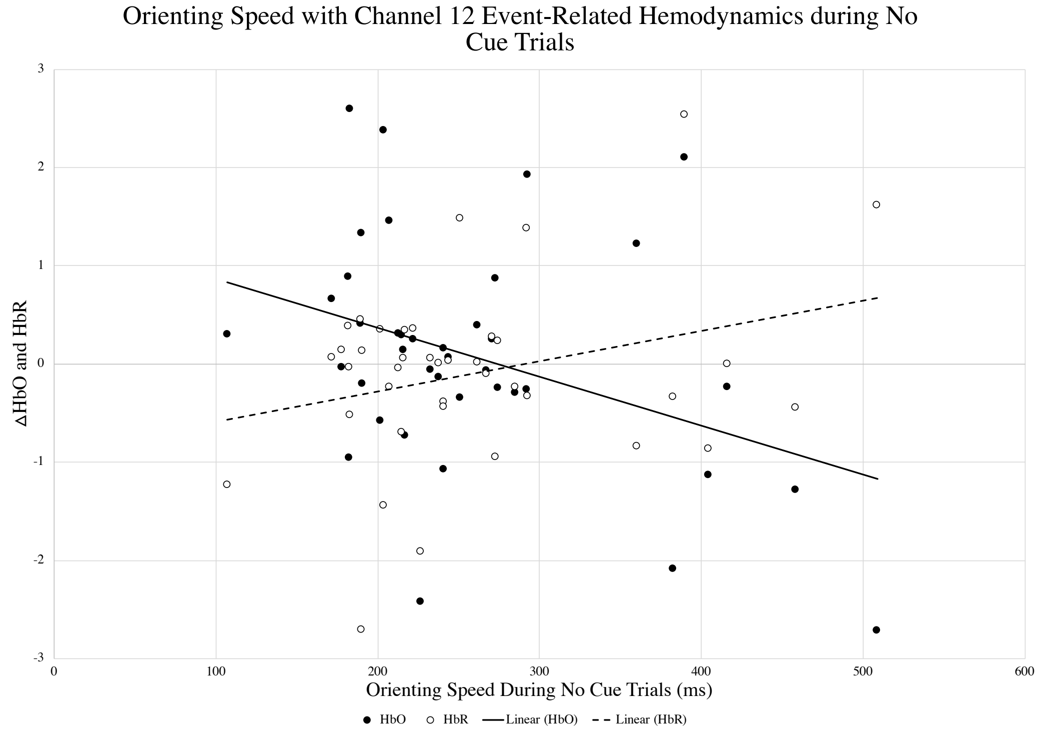


Figure 22. The top shows correlations between HbO_2, HbR levels, and raw alerting speeds during the IOWA task on Channel 13 during Tone trials. The middle chart depicts raw orienting speed on channel 12 with HbO_2 and HbR levels during No Cue trials. The bottom chart depicts HbO_2, HbR, and raw orienting speed on channel 13 during No Cue trials.



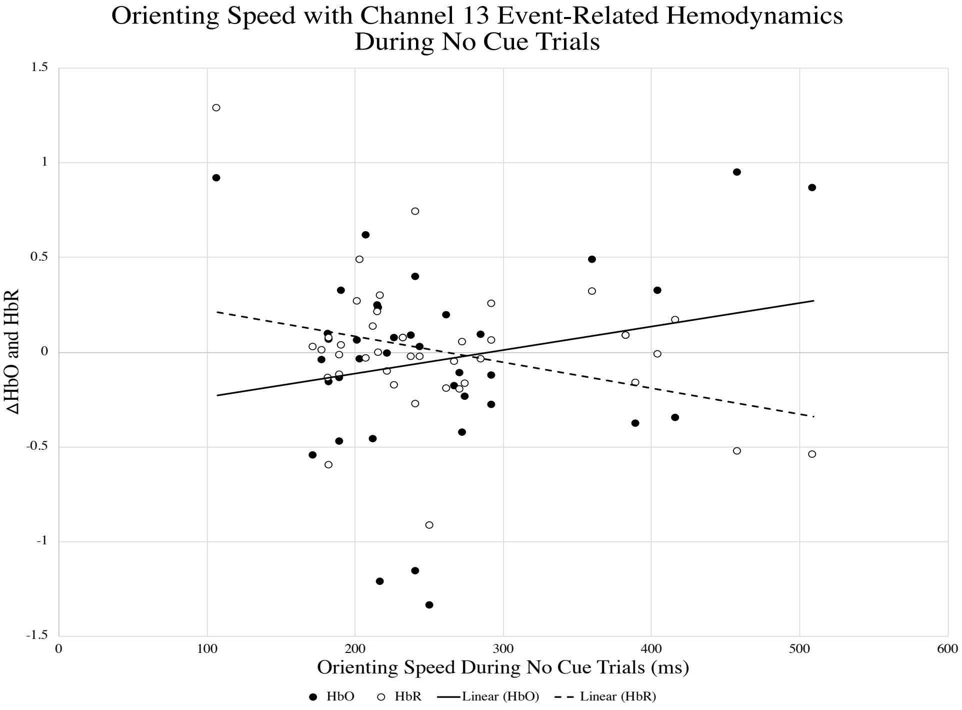


Figure 22. Continued.

Summary of IOWA Task Results

The current data demonstrate a clear relationship between rFC and event-related hemodynamics as predictors of behavior in the IOWA task. Children who have stronger interregional connectivity in bilateral parietal cortex at rest, do better in this task and tend to be less reactive as indicated by both accuracy and RT data. Further, bilateral parietal channels (i.e., 12, 13) were related to raw orienting and alerting speeds during tone and no cue trial types. These data suggest similar areas of cortex, in bilateral parietal love, are being utilized to orient and maintain alertness in this task. Younger children showed stronger activation on channel 15 (e.g., inferior right parietal cortex) compared to older children while overall children showed activation across trial types on channel 5 (e.g., right prefrontal cortex). Age was not correlated with any of the RT, accuracy, or composite attention scores in the IOWA task.

Flanker Results

Behavioral Results

A total of 55 children began the Flanker task. Three 2.5-year-olds and one 3.5-year-old did not complete at least half of the task. A total of 51 children were then included in these final behavioral analyses. Of these, 23 children were 3.5-year-olds and 28 children were 2.5-year-olds. Children were then given an accuracy score across all three trial types (congruent, incongruent, neutral), scored as a percent correct (see Figure 23).

Multiple regression analysis was used to test if age significantly predicted participants' overall performance during the Flanker Task as well as trial specific performance. The results of the regression indicated that age, β =.635, $t(50)$=5.76, p<.001, explained 40.3% of the variance and predicted overall performance (i.e., total percent correct collapsed across trial types) in the Flanker task, R^2= .403, $F(1,50)$= 33.140, p<.001. Further, these same multiple regression analyses were run for accuracy on individual trial types which revealed that age, β =.018, $t(50)$=.129, p=.897, did not predict incongruent trials, R^2<.001, $F(1,50)$<1, p=.897. However, age, β =.322, $t(50)$=7.13, p<.001, did predict accuracy on neutral trials, R^2= .508, $F(1,50)$=50.792, p<.001. Further, age, β =.236, $t(50)$=4.83, p<.001, predicted accuracy on congruent trials, R^2= .321, $F(1,50)$=23.277, p<.001. Although age predicted performance in this

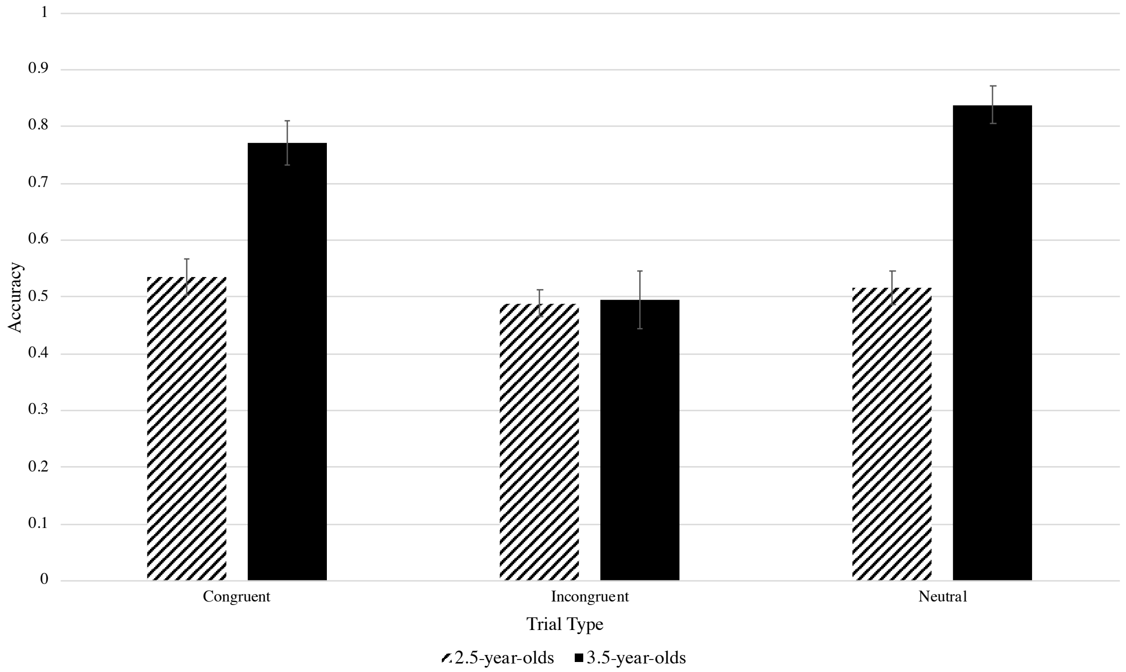


Figure 23. Accuracy during the Flanker Task for 2.5-year-olds and 3.5-year-olds across trial types.

task, some 2.5-year-olds were able to succeed and perform similarly to 3.5-year-olds (see Table 5). Further, age was only predictive of neutral and congruent trial performance and not incongruent trial performance. Mean RTs were calculated by first excluding trials that exceeded two standard deviations above the mean RT for all participants across both age groups within each trial type to explore generally how long children were taking to respond in this task for each trial type, regardless of accuracy. Next, mean RT was calculated in the same way for only accurate trials (see Figure 23). A repeated measures ANOVA was run with trial type and score as within subjects factors and revealed that these two RTs were significantly different across all three trials types with a main effect of scoring type, $F(1,50)=22.6$, $p=<.000$, $\eta_p^2=.302$, and trial type, $F(2, 49)=8.71$, $p<.001$, $\eta_p^2=.148$, and an interaction between scoring and trial type, $F(2,49)=3.92$, $p=.023$, $\eta_p^2=.073$. Both RT scores were calculated due to variability in accuracy scores for each trial type across both age groups to explore how quickly children were responding in this task generally. However, traditional RT scoring, where means were calculated from only accurate trials, were adopted (see Figure 24) and used for testing the Flanker Effect in the following analyses.

The Flanker Effect was tested by running a paired samples t-test comparing congruent and neutral trials to incongruent trials across all participants. Results revealed there was a significant difference between RTs on neutral trials ($M=2408$, $SD=2363.07$) compared to incongruent trials ($M=2987.43$, $SD=2526.37$), $t(50)=2.61$, $p=.012$, but not between congruent ($M=2868.74$, $SD=2645.93$) and incongruent trials, $t(50)=-.561$, $p=.577$. These data suggest that the Flanker Effect is best characterized by the relationship between neutral and incongruent trials across these two age groups. Next, independent samples t-tests were run for RT on all three trial types with a grouping variable of age. Children in the 3.5-year-old group were faster on congruent, $t(49)=5.67$, $p<.001$, incongruent, $t(49)=4.31$, $p<.001$, and neutral trials, $t(49)=7.75$, $p<.001$, compared to 2.5-year-olds.

To explore changes in cognitive demands between the three different trial types, conflict scores were calculated for both RT and accuracy scores. Conflict scores for RT were first calculated by taking the difference between mean RT scores during incongruent trials and subtracting mean RT for congruent trials and neutral trials separately. An independent samples

Table 5. Here, frequencies of above mean performance by age are shown. Children who performed above the mean for each trial type were grouped by age and trial type and those new group averages for accuracy were reported as well as the frequency of children who fell within those categories.

Age	Sample	Trial Type		
		Congruent	Incongruent	Neutral
2.5	N	11	14	13
	>*M* Group Average	0.687	0.579	0.650
	% of Sample	39.2	50.0	46.4
3.5	N	12	11	11
	>*M* Group Average	0.904	0.708	0.977
	% of Sample	52.1	47.8	47.8

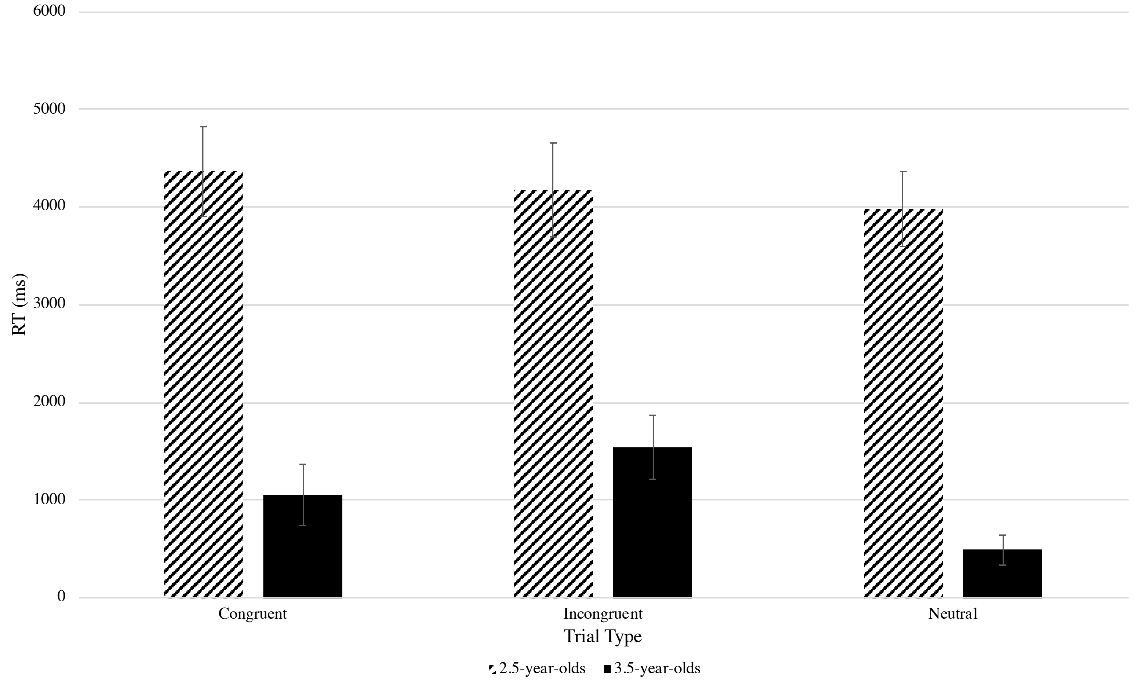


Figure 24. RT during accurate trials for 2.5- and 3.5-year-olds.

t-test with grouping factor of age was ran for these two difference scores to test if scores were different when considering age. Results revealed that for both conflict score 1 (i.e., incongruent-neutral RT) and conflict score 2 (i.e., incongruent-congruent RT) there was no significant difference between 2.5- and 3.5-year-olds, *t*(49)=-1.98, *p*=.054, and, *t*(49)=-1.63, *p*=.110, for conflict score 1 and conflict score 2 respectively. Finally, a paired-samples t-test was run to compare conflict score 1 and conflict score 2 across both ages. Results revealed that these two scores did not differ statistically, *t*(50)=1.86, *p*=.069, despite means suggesting they might be tapping into differences in response times for conflict score 1 (*M*=579.25, *SD*=1582.54) and conflict score 2 (*M*=118.69, *SD*=1510.74).

The first of these conflict scores is a composite score of how much slower or faster children were on incongruent trials compared to congruent trials. The second is how much slower children are due to either conflict and/or additional processing demands imposed by the presence of flanking items during incongruent trials juxtaposed to a single item with no conflict during neutral trials. For RT conflict scores, positive scores indicated children were faster on congruent and neutral trials compared to incongruent trials. However, if children are faster on incongruent trial types compared either neutral or congruent trial types (i.e., a negative score) on these two conflict scores then it may be due to impulsivity or lack of understanding during incongruent trial types. Interestingly, children who scores one direction for one of these scores did not always score in the same direction on the other (see Figure 25 for distribution of RT conflict scores across both ages).

Finally, these same conflict scores were calculated for accuracy to see how much costs children experienced in performance as a result of conflict and both processing demands and conflict. For accuracy conflict scores, negative scores indicated that children performed higher on either neutral or congruent trials compared to incongruent trials whereas positive scores indicated children scored higher on incongruent trials compared to neutral or congruent (Figure 12). Previously reported regressions suggest that age predicts performance in this task. However, to test if this relationship transfers to conflict scores from accuracy due to variability in performance across trials, an independent samples t-test with grouping factor of age was ran for these two conflict scores.

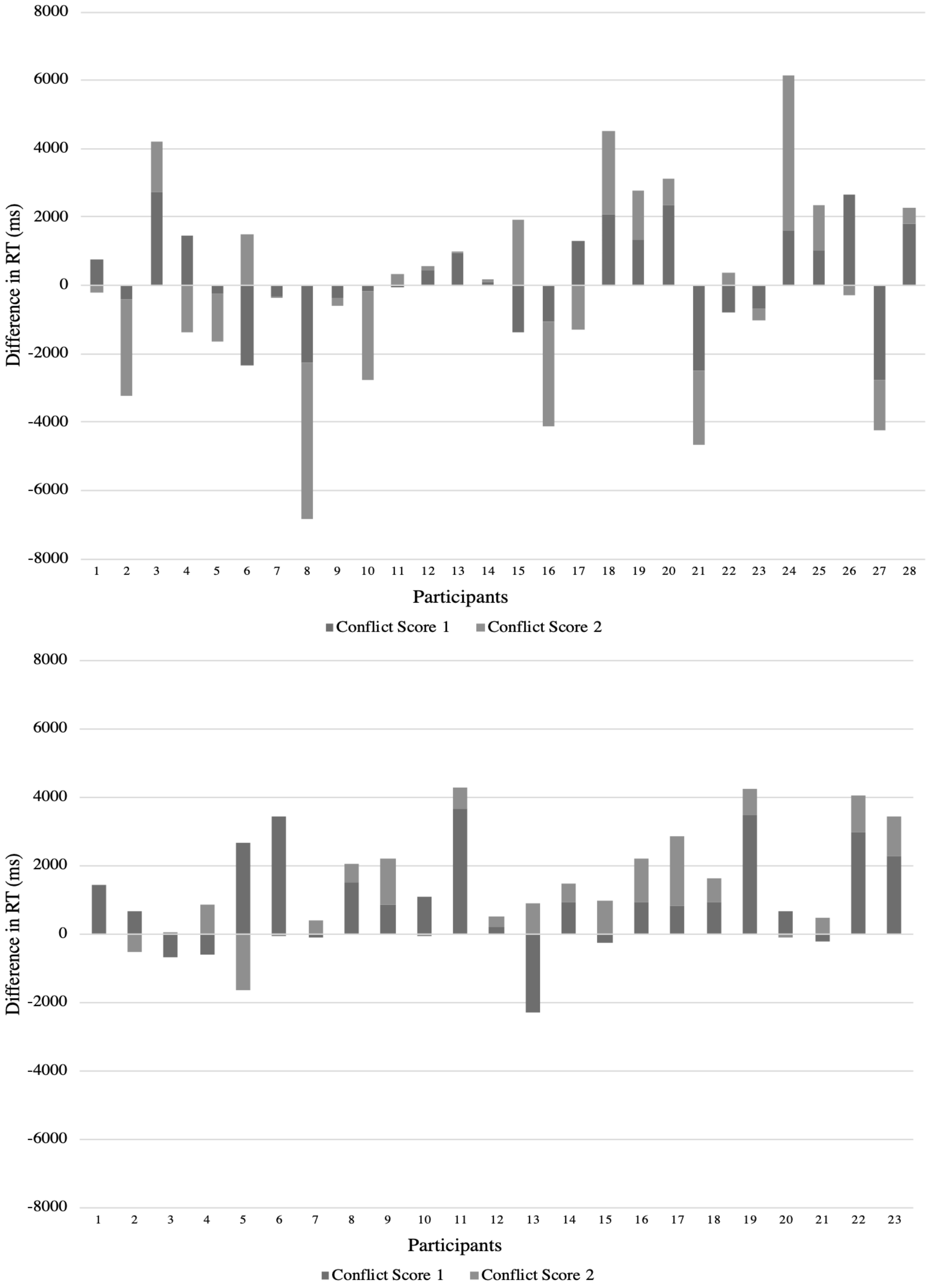


Figure 25. This figure depicts RT conflict scores for 2.5-year-olds (top) and 3.5-year-olds (bottom).

This test revealed conflict score 1 (i.e., incongruent-neutral accuracy) and conflict score 2 (i.e., incongruent-congruent accuracy) were different between 2.5- and 3.5-year-olds, $t(49)=4.52$, $p<.001$, and, $t(49)=5.67$, $p<.001$, for conflict score 1 and 2 respectfully. Younger children performed higher on neutral and congruent trials in comparison to incongruent trials, but only slightly for conflict score 1 ($M=-.0281$, $SD=.219$) and conflict score 2 ($M=-.0463$, $SD=.244$). Younger children were also less correct on neutral and congruent trial types in comparison to incongruent trial types when compared to 3.5-year-olds conflict score 1 ($M=-.343$, $SD=.278$) and conflict score 2 ($M=-.2750$, $SD=.281$). Younger children's RT and accuracy conflict scores (see Figure 3 and 4) are more variable and are both positive and negative going whereas older children in this task have more positive going RT conflict scores and more negative going accuracy conflict scores (see Figure 26 for distribution of accuracy conflict scores across both ages).

Eye-Tracking Results

A total of 51 children were included in the final behavioral analyses. Of these, 23 children were 3.5-year-olds and 28 children were 2.5-year-olds. The same behavioral exclusions were applied to the current eye-data analyses. Children were then excluded from eye-tracking analyses if they did not have enough eye-data, good calibrations, or if they refused to wear the tracking sticker or continually removed the tracking sticker. After these exclusions, 22 2.5-year-olds and 22 3.5-year-olds remained in the final analyses. Specifically, one 3.5-year-old was dropped for issues with the tracking sticker and two 2.5-year-olds were dropped for excessive movement resulting in less than half of trials contributing useable eye-data. The other four 2.5-year-olds that were excluded refused to wear the tracking sticker all together, excessively removed the tracker sticker, or had bad calibrations due to lack of compliance in tracking the black dot in the five-point calibration.

The same pre-processing was done with eye-data as it was with the behavioral data (i.e., removing practice trials and bad RT trials). From the remaining data, trials were grouped together by trial type and accuracy. For those who made it in to the eye-analyses, multiple regression analysis was used to confirm age significantly predicted participants' performance

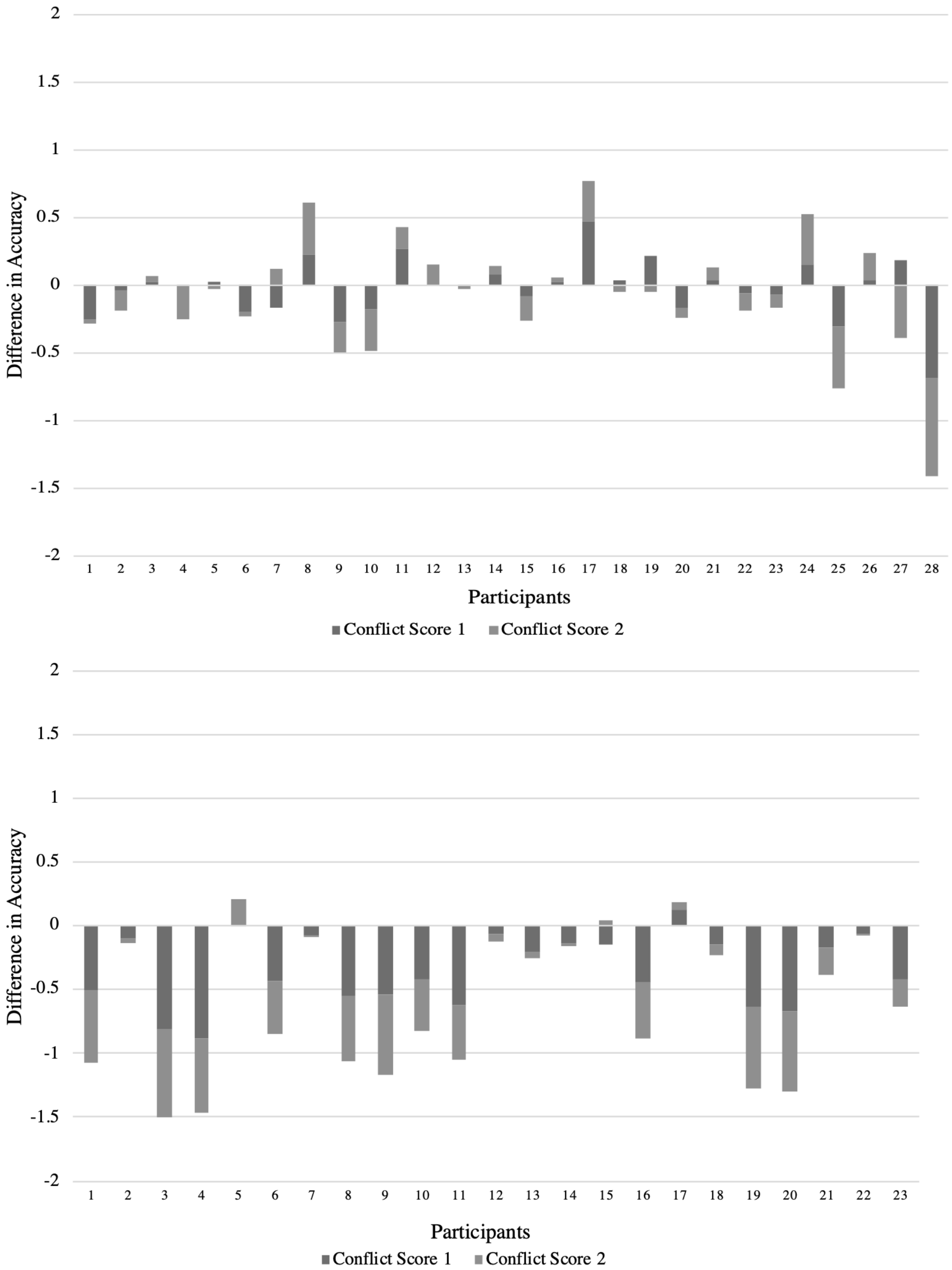


Figure 26. This figure depicts accuracy conflict scores for 2.5-year-olds (top) and 3.5-year-olds (bottom).

(i.e., accuracy) overall and during the three trial types during the Flanker task to ensure that additional exclusions made for eye-data analyses did not significantly change the sample population. The results of the regression indicated that age, β =.614, t(43)=5.04, p<.001, now explained 37.7% of the variance, R^2= .377, *F*(1,43)= 25.4, *p*<.001, in the total percent correct score. Further multiple regression analyses were run on accuracy for individual trial types revealing that age, β =.572, *t*(43)=5.52, *p*<.001, predicted accuracy on congruent, R^2=.327, *F*(1,43)=20.4, *p*<.001, trial performance. Further, age, β =.308, *t*(43)=5.71, *p*<.001, predicted 43.7% of variance in neutral trials, R^2=.437, F(1,43)=32.6, *p*<.001. Finally, age, β =-.289, *t*(43)=-.289, *p*=.774, still did not predict incongruent trial performance, R^2<.001, F(1,43)=.083, *p*=.774.

Next, Scores were calculated for total time spent fixating on the screen, and individual stimuli, and fixating on stimuli generally were calculated across all trials for each trial type. Then, average fixation duration for each trial type during a single trial was calculated. These scores were calculated based on the time spent fixating on stimuli on the screen. Then, average fixation for each trial type were then broken into accurate and inaccurate trials. Next, proportion of time looking at different stimuli (i.e., center verses flanking items) out of total time on screen were calculated, as well as further broken down in to sub-groups of accurate and inaccurate trials. These scores were used to run the following statistics.

First, repeated measures ANOVAs were run for total time spent fixating during a trial with a within-subject factor of trial-type collapsed across accurate and inaccurate trials and a between-subject factor of age. Age did not impact looking total time spent looking at the screen in this task, *F*(2,41)=2.53, *p*=.093, η_p^2=.110. Thus, children were collapsed across age and performance level to assess how children generally looked during this task. This same repeated measures ANOVAs was run without a between-subject factor of age, revealing a main effect of trial type, *F*(2,42)=34.2, *p*<.001, η_p^2=.443. Follow-up paired-samples t-tests demonstrated a significant difference between neutral and incongruent, *t*(43)=7.008, *p*<.001, as well as neutral and congruent trial types, *t*(43)=7.03, *p*<.001. This suggest that children are looking during neutral trials less than they are during congruent and incongruent trials, regardless of accuracy on those trials, which is likely due to the number of stimuli on the screen between congruent/incongruent and neutral trials.

To test whether different aged children made longer fixations during different trial types, and if these durations varied based on accuracy, repeated measures ANOVAs were run for average fixation duration with within-subject factors of trial type and accuracy and a between - subjects factor of age. There were no significant main effects of accuracy, $F(1,35)=2.54$, $p=.120$, $\eta_p^2=.068$, interaction between trial type and accuracy $F(2,34)=2.72$, $p=.080$, $\eta_p^2=.138$, trial type and age, $F(2,34)=.191$, $p=.827$, $\eta_p^2=.011$, accuracy and age, $F(1,35)=1.12$, $p=.298$, $\eta_p^2=.031$, nor an interaction between all three, $F(2,34)=.207$, $p=.814$, $\eta_p^2=.012$.

To test if age predicted fixation durations for each trial type when variance from performance (i.e., percent correct) for that trial type was considered, regressions were run for age and performance (i.e., percent correct on congruent, neutral, and incongruent trial types) as predictors and average time spent fixating on each trial type (i.e., average fixation duration for congruent, neutral, and incongruent) as the dependent variable. These regressions were insignificant.

Next, repeated -measures ANOVAs were run for the proportion of time spent looking at the five stimuli on the screen with within-subject factors of accuracy (incorrect/correct), trial type (congruent, incongruent), and location(middle/flanking) to test the looking strategies children might be using to make a decision in this task. Neutral trials were excluded for these analyses because children spent the majority of the time looking at the middle for both accurate (i.e., 83.43%) and inaccurate trials (i.e., 83.53%). These tests revealed a main effect of location, $F(1,35)=10.4$, $p=.003$, $\eta_p^2=.228$, but no interaction between accuracy and location, $F(1,35)=3.16$, $p=.084$, $\eta_p^2=.083$, or between trial type and location, $F(1,35)=1.33$, $p=.258$, $\eta_p^2=.036$, nor an interaction between all three, $F(1,35)=.548$, $p=.464$, $\eta_p^2=.015$. Bonferroni's test of post-hoc multiple comparisons were run as a follow-analyses for this ANOVA and means revealed that children looked more to the flanking items in comparison to the middle item regardless of trial type or accuracy (see Table 6).

Together, these data suggest that children are attending to both flanking and middle items in this task and that this is likely an indicator flanking items create for children similarly on congruent and incongruent trials regardless of age. Further, accuracy on all three trial types was not predictive of time spent fixating on that trial type suggesting children are likely spending the

Table 6. Proportion of Time Looking During Congruent and Incongruent Trials

Trial Type	Location	*M*	*SD*
Congruent Correct	Middle	.429	.149
	Flanking	.571	.149
Congruent Incorrect	Middle	.470	.171
	Flanking	.530	.171
Incongruent Correct	Middle	.408	.220
	Flanking	.592	.220
Incongruent Incorrect	Middle	.413	.146
	Flanking	.587	.146

same amount of time extracting information from the visual task space and that the resolution of conflict in this task is happening at the cognitive level.

Flanker fNIRS Event-Related Results

The same behavioral exclusions used in the previous two analyses were implemented in the current analysis. Of the remaining 51 children, two 2.5-year-olds and one 3.5-year-old were excluded for refusing to wear the fNIRS cap during the task. An additional three children were excluded for noisy fNIRS data. Two of these children were also dropped for excessive movement during eye-tracking analyses which likely explains the poor signal in their fNIRS data. Thus 45 children were included in the final fNIRS analysis, 23 2.5-year-olds and 24 3.5-year-olds. Data was first pre-processed as outlined in the methods section. Then data was divided into accurate and inaccurate trials for all trial types. Children were also grouped by performance and age for these analyses to explain the complex relationship between behavior and hemodynamics within and across these two age groups.

First, participants were collapsed across age groups as there were successful performing 2.5-year-olds and 3.5-year-olds. To test if different attention networks were involved in success during the three trial types, mixed repeated measures ANOVAs were run for each trial type with a within-subject of chromophore (HbO_2 , HbR) and covariate of performance (i.e., percent correct) for that trial type(i.e., congruent, incongruent, neutral). These analyses were run separately for each channel in the current probe design and were only run with HbO_2 and HbR averages were taken from accurate trials only. First analyses from congruent trials will be reported. For channel 11 (i.e., superior right parietal lobe) there was a main effect of chromophore, $F(1,38)=10.3$, $p=.003$, $\eta_p^2=.213$, and an interaction between chromophore and percent correct on congruent trials, $F(1,38)=10.4$, $p=.003$, $\eta_p^2=.215$. Follow-up correlations were run between both chromophore types and percent correct revealing HbO_2 during correct congruent trials was negatively related to overall percent correct on congruent trials, $r^2=-.395$, $p=.012$. However, both HbO_2 and HbR levels were negative for this channel suggesting deactivation of this region might be associated with better performance. For channel 16 (i.e., inferior right parietal lobe) there was a main effect of chromophore, $F(1,40)=4.59$, $p=.038$, $\eta_p^2=.103$, and an interaction between chromophore and percent correct on congruent trials, *F*(1,40)=4.24, *p*=.046, $\eta_p{}^2$=.096. Correlations between chromophore types and performance revealed that HbR was negatively associated with accuracy, r^2=-.363, *p*=.018, where children who performed better in this task also had lower HbR levels (see Figure 27).

Next, results involving incongruent trial types will be reported. For channel 7 (i.e., superior left parietal lobe) there was a marginal interaction between chromophore and percent correct, *F*(1,39)=3.41, *p*=.073, $\eta_p{}^2$=.080. On channel 8 there was also a marginal main effect of chromophore, *F*(1,40)=3.33, *p*=.076, $\eta_p{}^2$=.077. These affects may be due to low amounts of trials contributing to HbO_2 and HbR averages during incongruent trials across all children as this trial type had the lowest percent correct, thus the least amount of trials contributing when selecting for only accurate trials compared to other trial types.

Finally, results involving neutral trials are reported. Channel 3 (i.e., superior prefrontal cortex) had a significant main effect of chromophore, *F*(1,39)=4.76, *p*=.035 $\eta_p{}^2$=.109, and a marginal interaction between chromophore and percent correct on neutral trials, *F*(1,39)=3.35, *p*=.075, $\eta_p{}^2$=.079. On channel 4 (i.e., inferior right prefrontal cortex) there was a marginal main effect of chromophore, *F*(1,38)=3.94, *p*=.055, $\eta_p{}^2$=.094.

Additional mixed ANOVAs with within-subject factors of trial type and chromophore and a between-subject factor of age were run on all channels to test if age influenced hemodynamics. Channel 5 (i.e., right superior prefrontal cortex) had a significant interaction between chromophore and trial type, *F*(1,40)=12.4, *p*<.001, $\eta_p{}^2$=.386. Paired samples t-test revealed that both age groups had activation (i.e., significantly higher HbO_2 than HbR where HbO_2 is positive going) for correct congruent trials, *t*(41)=3.3, *p*=.002 (see Figure 27), but not during incongruent or neutral trials, *t*(41)=-.911, *p*=.368, and, *t*(41)=-.806, *p*=.425, for incongruent and neutral correct trials respectively. On channel 12 (i.e., right superior parietal cortex) there was a significant main effect of chromophore, *F*(1,40)=11.4, *p*=.002, $\eta_p{}^2$=.221. Follow-up paired samples t-test revealed activation on this channel for correct incongruent trials, *t*(41)=2.80, *p*=.008 (see Figure 28).

Summary of Flanker Task Results

Overall, children in this task performed relatively poorly on incongruent trial types. However, some 2.5- and 3.5-year-olds performed well on this task suggesting there is a developmental shift

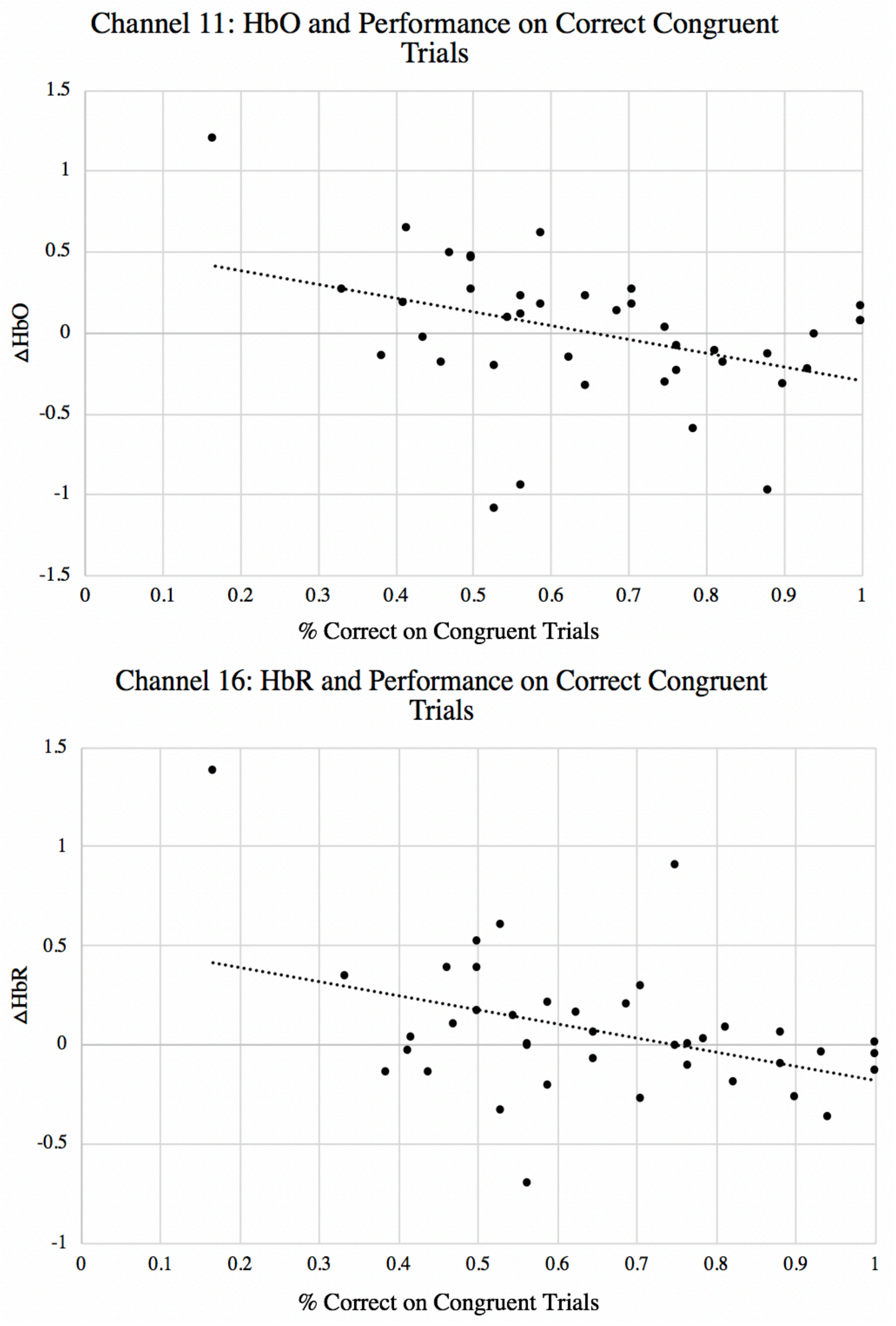


Figure 27. (Top) depicts the relationship between HbO_2 during correct congruent trials and percent correct on congruent trials in superior right parietal cortex. (Bottom) depicts the relationship between HbR and during correct congruent trials and percent correct on congruent trials in inferior right parietal cortex.

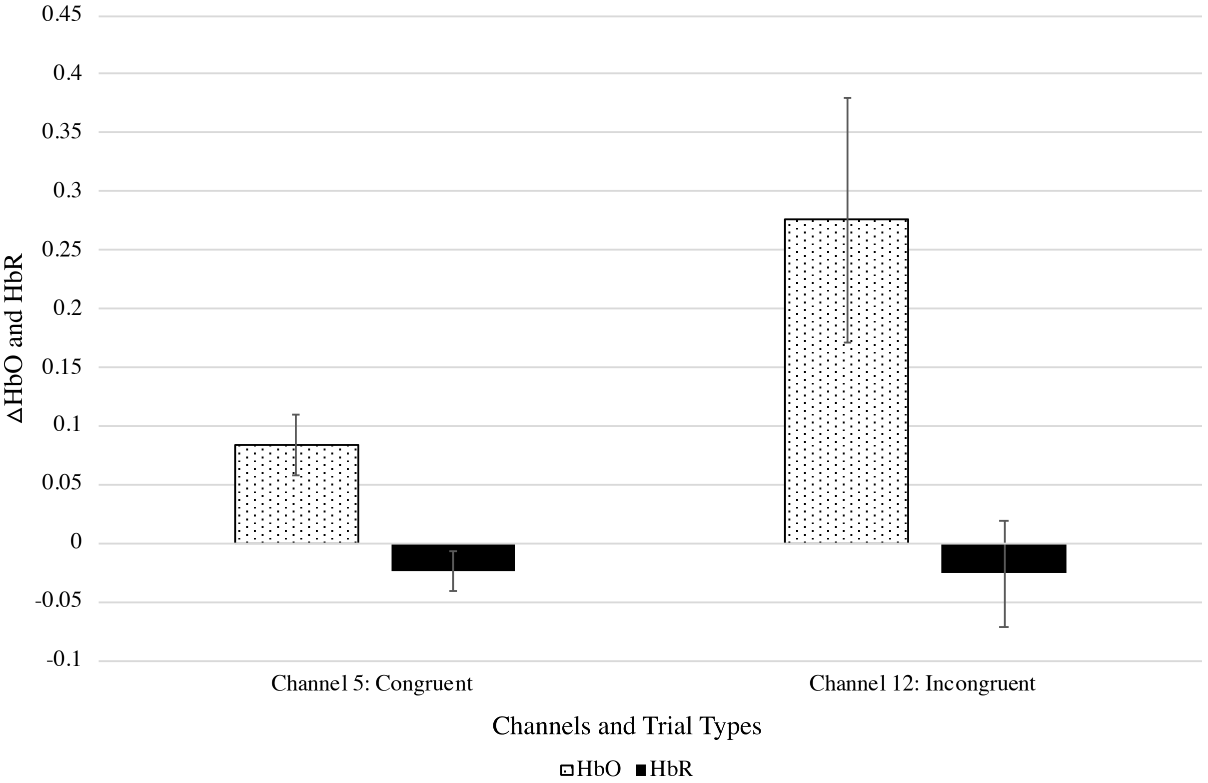


Figure 28. Activation in right superior prefrontal cortex and right superior parietal cortex during correct congruent and correct incongruent trials across both age groups during the Flanker Task.

in abilities for the Flanker occurring during this age range specific to conflict resolution. Further, hemodynamics suggest different regions of the brain might be contributing uniquely when children must focus on the middle item in the presence of flanking items (congruent trials) verses when children must make a decision when flanking items create conflict (incongruent trials). Finally, rFC was related to event-related hemodynamics and performance in this task suggesting both methods together could be used to assess the status of a specific neural network in children when they are converging. Event-related data suggest selective attention (i.e., use of a right lateralized attention network) might be driving correct responding on trials where flanking items are present.

Snack Delay Results

Behavioral Results

This task was administered at the end of the attention battery for 2.5-year-olds. Despite this, all 26 children who started the task finished it. Children were able to choose which snack they wanted from a choice of gummy snacks (N=15) and goldfish (N=11). Snack choice did not significantly change behavioral outcomes, $t(24)=-.097$, $p=.924$ (see Figure 29).

A total of eight children scored a three or above in the task indicating that they waited until at least the second half of each trial to touch the snack or the clear cup covering the snack. Of these, five children waited until the experimenter rang the bell at the end of the trial before touching or eating the snack. The remaining 18 children scored below a three indicating that on the majority of the trials they touched or ate the snack before the experimenter picked up the bell half way through the trial. Children were grouped into high (>3) and low (<3) performance groups and then performance in each of the five trials was averaged for those groups to see the proportion of children that failed at each time interval (see Figure 30).

First the relationship between behavioral performance and temperament scores was tested by running correlations between attentional focus, attentional shifting, and snack delay performance scores. In the current study, attention focus, $r^2= -.013$, $p=.951$, was not related to snack delay performance whereas attentional shifting, $r^2= -.421$, $p=.032$, was predictive of overall performance in the snack delay task.

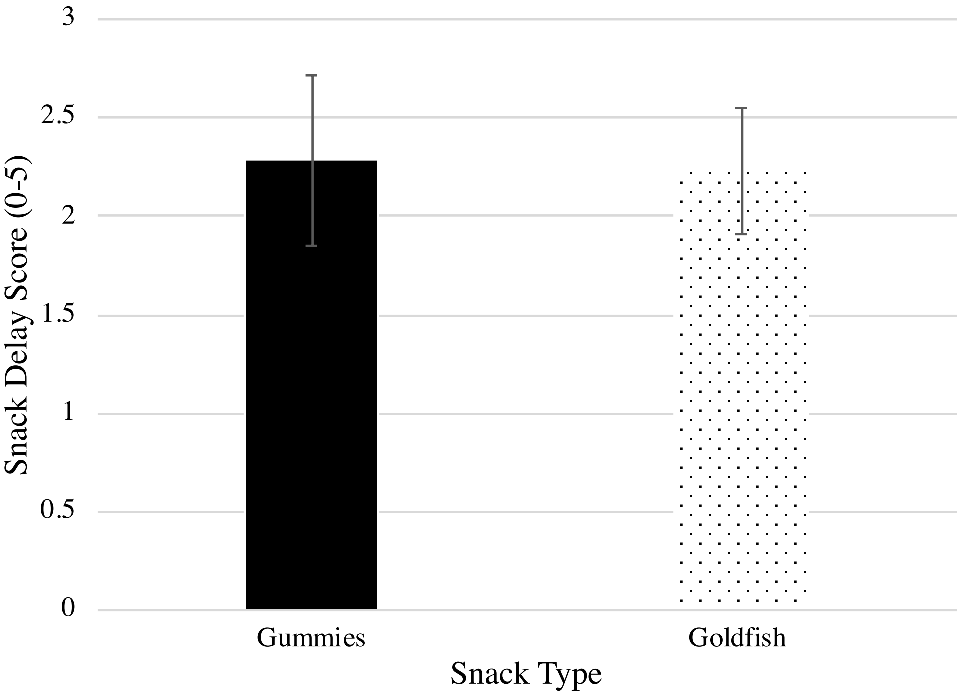


Figure 29. Group averages for snack delay scores across snack choice.

Children who scored higher in attention shifting tended to do worse in the snack delay than children who scored lower. In addition to this, snack delay scores were not correlated with the composite effortful control score, r^2= -.188, p=.359.

FC During the Snack Delay

Of the 26 children who completed this task, only 22 children were included in the final functional connectivity (FC) analyses. One child was dropped due to refusing to wear the fNIRS cap through the entire battery and three children were dropped for excessive movement during the task. Of the remaining 22 children, seven were high performers and 15 were low performers. Children's data was pre-processed in the same way as resting state data. Trials were further broken into pre- and post-bell periods labeled first- and second-half for ease. Although performance group (i.e., high verses low) is likely interacting with FC during this task, differences in FC as a factor of performance could not be addressed due to the small sample size. Thus, children were analyzed together. Channel-paired that passed the selection criteria for correlation coefficients, as in the resting state analyses, were considered in the final analyses. Once these channel-pairs were identified, forward selection step-wise regressions were used to isolate the channels that together predicted whether or not children would succeed in the task based on FC during the first half of the trial.

A multiple linear regression was calculated to predict snack delay performance based on channel pairs. A significant regression equation was found, R^2= .964, F(1,21)= 43.9, p< .001, where eight channel pairs accounted for 96.4% of the variance in snack delay performance (i.e., continuous score). Channel-pairs within parietal cortex bilaterally on the right (i.e., 10-15), β =1.70, t(21)=6.06, p<.001, and left (i.e., 12-14), β =1.82, t(21)=5.48, p<.001, as well as laterally on the right from right frontal to right parietal cortex (i.e., 2-13), β =.894, t(21)=4.11, p<.001, laterally on the left from left frontal to left parietal cortex (i.e., 5-16), β =.596, t(21)=2.24, p=.043, and cross-hemispherical from right frontal to left parietal (i.e., channel 4-7), β =.773, t(21)=2.29, p=.040, were positive related to performance in this task. Suggesting that the stronger the functional connectivity between these regions during this task in the first half of each trial the more likely children are to perform well in this task. Three channel-pairs in this model were negatively associated with performance in this task from left frontal to

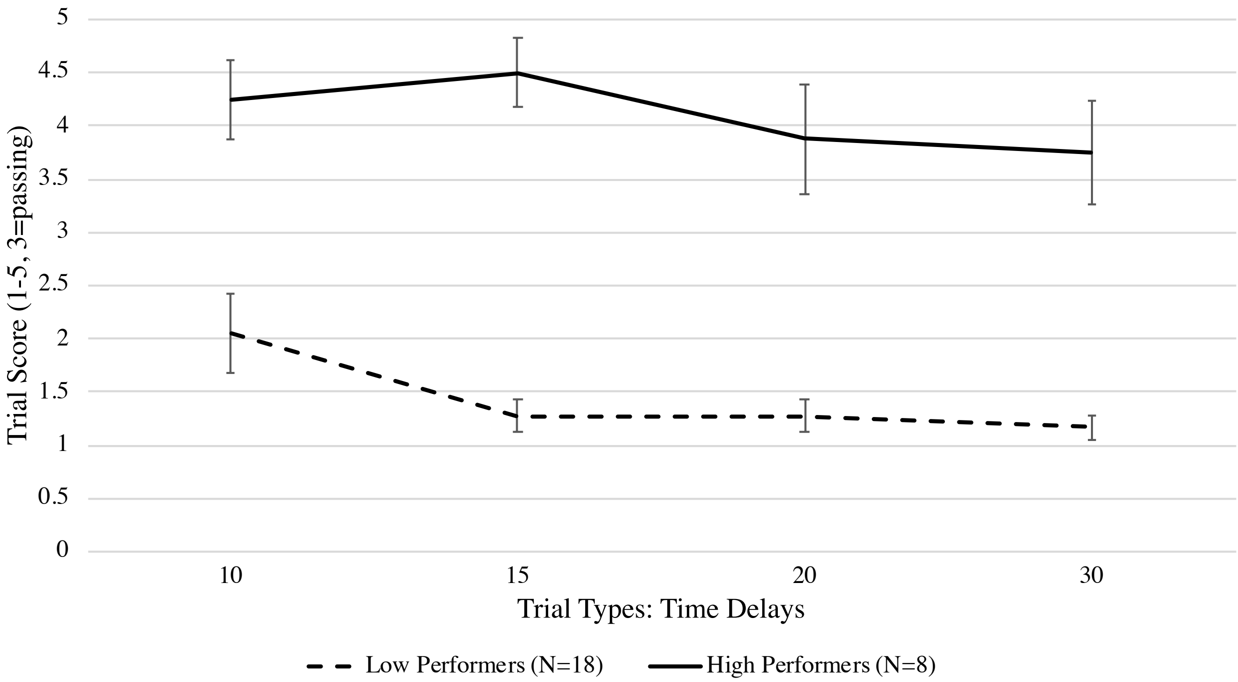


Figure 30. Average scores for each trial based on performance group in the Snack Delay. Here, low performers are represented by a dashed line and high performers are represented by a solid line.

parietal (i.e., 3-9), β =-2.66, $t(21)$=-8.25, p<.001, right frontal to parietal (i.e., 6-11), β =-2.65, $t(21)$=-11.5, p<.001, and right frontal to inferior right parietal (i.e., 6-13), β =-1.22, $t(21)$=-4.59, p<.001 (see Figure 31).

Forward selection step-wise regressions were used to isolate the channels that together predicted whether children would succeed in the task based on FC during the second half of the trial. Note, all children's data are used for these averages in the second half of the trial, although not all of them were still waiting for the trial to end. Those that failed were likely already were eating the snack during this time. Only two children waited on all trials until the end without touching the snack or the cup. Thus, only considering perfect scores in the second half of the trial analyses was not possible. A multiple linear regression was calculated to predict snack delay performance based on channel pairs during the second half of each trial. A significant regression equation was found, R^2= .755, $F(1,21)$ =9.91, p <.001, where five channel-pairs accounted for 75.6% of the variance in snack delay performance (i.e., continuous score). Channel-pairs between left and right frontal cortex (i.e., 2-4), β =3.05, $t(21)$=4.61, p<.001, cross-hemisphere channel pair from left frontal to right parietal (i.e., 2-15), β =1.77, $t(21)$=3.53, p=.003, and between left and right parietal cortex (i.e., 14-15), β =1.27, $t(21)$=2.53, p=.022, were positive related to performance in this task. Suggesting that the stronger the functional connectivity between these regions the more likely children are to perform well in this task. Two channel-pairs in this model were negatively associated with performance in this task between right frontal and left parietal (i.e., 6-8), β =-3.25, $t(21)$=-5.43, p<.001, and left frontal and parietal (i.e., 2-14), β =-1.77, $t(21)$=-2.96, p=.009 (see Figure 30).Together, these results suggest that FC during the first half of the trial is more predictive of performance than FC during the second half of the trial. These results are intuitive based on the behaviors observed during each half of the trial.

Day/Night Results

Behavioral Results

To be considered in the final analyses, children had to first demonstrate that they had learned the contingencies of sun and day and moon with stars and night prior to starting the task. Next, children had to demonstrate on the two training trials and the following two practice trials that they could utilize the new opposite game rules. One child out of 25 children could not

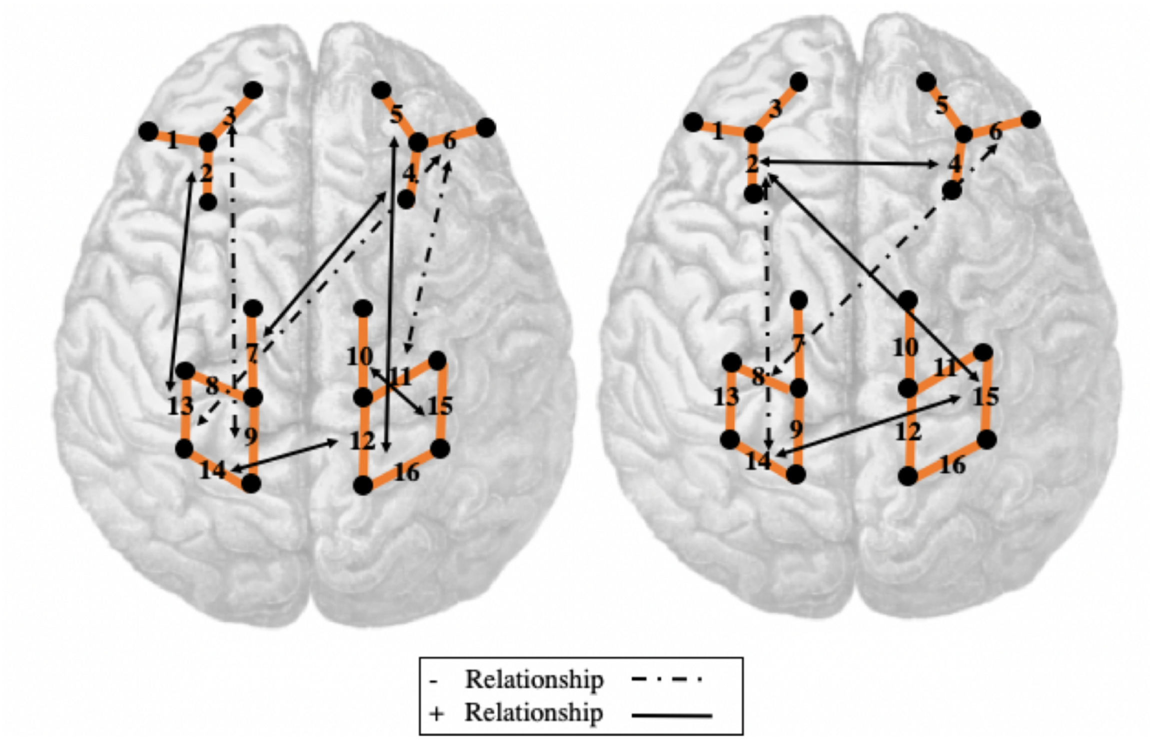


Figure 31. This figure depicts the relationship between FC and performance in this task during the first half of the trial (left) and the second half of the trial (right).

demonstrate that they knew the constancies or that they could use the new opposite game rules (i.e., refusing to verbally respond in the game). Of the remaining 24 children, one child quit the task right before the end. The remaining 24 children were included in the final analysis. Of these, 11 children performed above chance in the standard task and 13 children performed below chance. These results are typical of what is seen in the literature during the standard task (e.g., Diamond, 2002; see also Figure 32).

If children responded with labels or phrases that were similar in meaning to “day” and “night” they were counted as correct (i.e., night-night, daytime, nighttime, morning time, or dinner time). Most children did not use these phrases and were able to say “day” and “night” consistently. However, it is worth noting that children understood the opposite contingency and interchanged other opposites fluidly that similarly indicate the day and night during this task.

Day/Night fNIRS Event-Related Results

Data was preprocessed in the same way as the Flanker task. Hemodynamics in the Day Night task were first explored by running independent ANOVAs for each of the 16 channels over bilateral frontal and bilateral parietal cortex. To probe the relationship between performance and activation both oxygenated hemoglobin and deoxygenated hemoglobin were explored where activation is when oxygenated (HbO_2) hemoglobin was significantly greater and positive going in comparison deoxygenated (HbR) hemoglobin (reporting both HbR and HbO_2 changes, instead of only one of them, see Tachtsidis & Scholkmann, 2016). Mean concentration levels for oxygenated and deoxygenated hemoglobin were calculated from a 0-8 second time window after the presentation of the target objects. Two children were dropped from this analysis for refusing to wear the hat for the entire battery. Thus, 21 children were included in the current analyses. However, due to children not having as many correct trials in the below chance group and children not having many incorrect trials in the above chance group there was significant loss in power when comparing one or the other trial type in these ANOVAs.

Mixed 2 (chromophore: HbO_2, HbR) x 1 (performance) repeated measure ANOVAs were run with a between-subject factor of chromophore and a covariate of performance for all participants for correct trials. For correct trials, there was a main effect of chromophore on

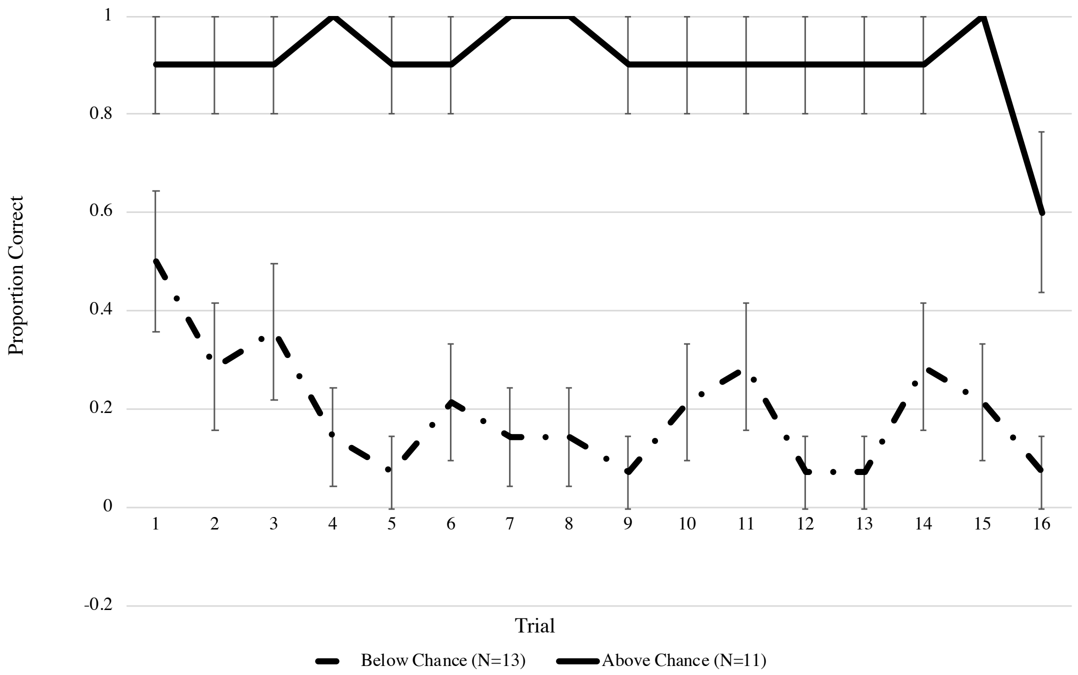


Figure 32. Proportion of children who answered correctly on each trial for the above chance and below chance performance groups during the Day Night task. Standard error bars are indicated on each trial for each group.

channel 3, $F(1,15)=4.97$, $p=.041$ $\eta_p^2=.249$, an interaction between chromophore and performance on channel 4, $F(1,15)=8.37$, $p=.011$ $\eta_p^2=.358$. Follow-up paired-samples t-tests on channel 3 were not significant, suggesting the variance from performance is what is driving this effect, $t(16)=1.53$, $p=.146$. Follow-up correlations between chromophore and performance on channel 4 revealed that as HbR levels decreased, scores on the Day Night increased (see Figure 33). Further, forward selection multiple regressions were run with HbO_2 and HbR levels for all channels during correct trials as predictors and performance as a dependent variable and a significant regression equation was found, $R^2= .407$, $F(1,10)=6.18$, $p=.035$, where only HbO_2 on channel 4, $\beta =-2.49$, $t(10)=.035$, $p=.035$, predicted overall performance in the task, accounting for 40.7% of the variance in overall performance in this task. Correlations revealed that HbO_2 was negatively associated, $r^2=-.520$, $p=.016$, with performance whereas HbR was positively associated with performance, $r^2=.412$, $p=.050$.

Summary of Day/Night Task Results

Children were asked to do the standard speeded Day Night task. Behavioral performance in this task was typical of previous work with this age group, where the average across performance groups was right above chance. However, there were clear developmental differences between 3.5-year-olds who could and could not successfully switch naming the sun and moon by the new opposite contingency. Hemodynamic results suggest that deactivation on channel 4 is associated with both correct responding in this task and overall performance negatively. A larger sample size is needed to detect between group (i.e., performance scores) differences in this task.

Triad Classification (TC) Task Results

Behavioral Results

Thirty-one participants started the TC task. Of these, four participants did not complete at least half of the trials before refusing to go on. Due to the length of this battery, and the TC being presented fourth in a battery of seven tasks for 3.5-year-olds, some attrition is seen at this point in the battery. Twenty-seven participants went on to complete the TC task. Two participants were excluded because parental report of age was not accurate in our recruitment database and as

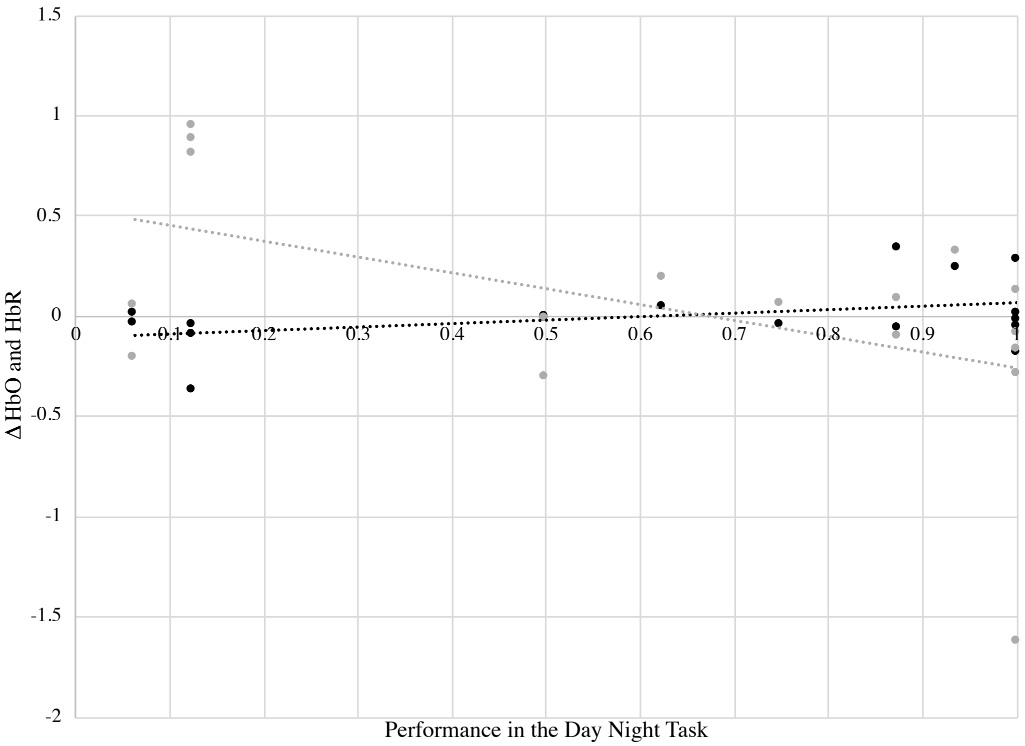


Figure 33. Here, chromophore and performance are plotted for channel 4 in the Day Night task. HbR levels are depicted in dashed black line while HbO_2 levels are depicted in a dashed light grey line.

a result the participants were run in the wrong paradigm (i.e., twin 2.5-year-olds were run as 3.5-year-olds). The remaining twenty-five participants were scored on accuracy for this task. The first score was percent correct and was calculated by taking the number of times they made a correct identity match out of the total number of trials. From this total score participants were grouped as passing (i.e., >60% identity matches) or failing (i.e.,<60% identity matches). Participants performed typically for their age group (e.g. Buss & Kerr-German, accepted; see also Figure 34) with 14 participants failing and 11 participants passing.

This task was presented after the IOWA in the battery for 3.5-year-olds. Additional participants were further excluded for a number of reasons in in the following sections on eye-tracking and fNIRS results. No RT pruning was done when analyzing the behavioral data for accuracy (*M*=8.424, *SD*=4.284, seconds). RT is calculated from the time the reference object appears to the time the child responds. Some additional error is likely in this particular iteration of the task because the experimenter uses a button press as the RT event when the child points to one of the two sorting locations (i.e., identity match or holistic match).

Eye-Tracking Results

Participants were first excluded based on the above behavioral criteria. Of the twenty-five participants remaining, one child's eye-data file was overwritten by a researcher, one child refused to wear the tracking sticker after the NIRS cap was placed, and an additional child did not have eye data due to noncompliance (e.g. putting feet on the eye-tracker and eating tracker sticker). Of the remaining twenty-two participants, two participants were excluded because they continually removed the eye-tracking sticker right before a trial or during a trial thus calibration became excessive and unreliable. None of the remaining participants were excluded due to bad RTs (i.e., >14 seconds) leading to excessive loss of eye data (i.e., >half of their trials). Most of the groups eye data remained after RT exclusions for each participant (*M*=.904, *SD*=.118). Loss of eye-data with populations that have excessive movement or are easily distracted such as young participants is typical in the eye-tracking literature (see Wass, 2016 for a review). Of the remaining participants (see Figure 35), 10 passed the TC (*M*=.762, *SD*=.112) and 10 failed the TC (*M*=.487, *SD*=.048).

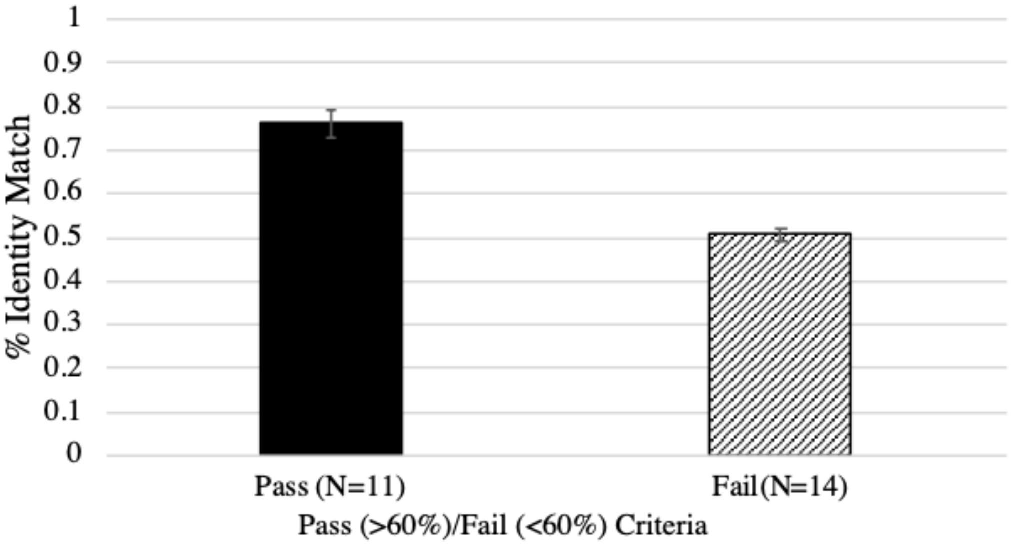


Figure 34. This figure depicts frequencies (N) of pass/fail performance in the sample population as well as group percent correct for these groups. Percent correct is calculated out of 40 trials and does not include the practice trials.

First, practice trials were excluded from the analyses. Data were analyzed and scored for average fixation duration, total fixation duration, and total number of fixations across trial types (correct, incorrect, shape, color; see Table 6). Scores were calculated based on data from when the reference object appeared, and the rules were repeated to the time the child made their response. Thus, RT inherently plays a role in these values.

These variables were calculated from fixations made to the screen (*M*=.782, *SD*=.01) as must all looks were made to one of the three stimuli in the task configuration (*M*=.618, *SD*=.168). Note, participants seemed to spend more time looking off screen for this task compared to the DCCS (results presented below). This may be due to the task being less engaging than the DCCS for participants in this age group. There was no difference in the amount of times participants looked at each of the three ROIs (reference, bottom left match, bottom right match) across all trials (i.e., 20.9%, 20.8%, 20.04%). To test the relationship between ROI and performance, a 2 (location: reference, match location) x 2(accuracy: correct, incorrect) mixed ANOVA was run for color trials and shape trials separately with a between-subject factor of performance (pass, fail). For color trials, there was a main effect of location, $F(1,15)=26.4$, $p<.001$, $\eta_p^2=.637$, but no interactions between location and performance, $F(1,15)=.177$, $p=.680$, $\eta_p^2=.012$, accuracy and location, $F(1,15)=.023$, $p=.881$, $\eta_p^2=.002$, or all three, $F(1,15)=.001$, $p=.973$, $\eta_p^2<.001$. Overall, children spent more time looking at the reference objects than the both ID and H objects. Thus, location as a variable was not explored further in this task as it was not related to performance or accuracy. Further probing of location with analyses on holistic vs. identity match objects are not presented here.

First, to test the relationship between performance and eye-movements generally, 2 (accuracy: incorrect, correct) x 2 (performance: pass, fail) mixed ANOVAs on total number of fixations for color and shape trials separately were run where accuracy was entered as a within-subject factor and performance as a between-subject factor. For color, there was both a main effect of accuracy, $F(1,17)=5.22$, $p=.035$, $\eta_p^2=.235$, and an interaction between accuracy and performance, $F(1,17)=13.0$, $p=.002$, $\eta_p^2=.434$. Follow-up independent samples t-tests revealed that participants who failed the TC made significantly more fixations during incorrect trials compared to those that passed, $t(17)=2.535$, $p=.021$. Further, participants who failed the TC

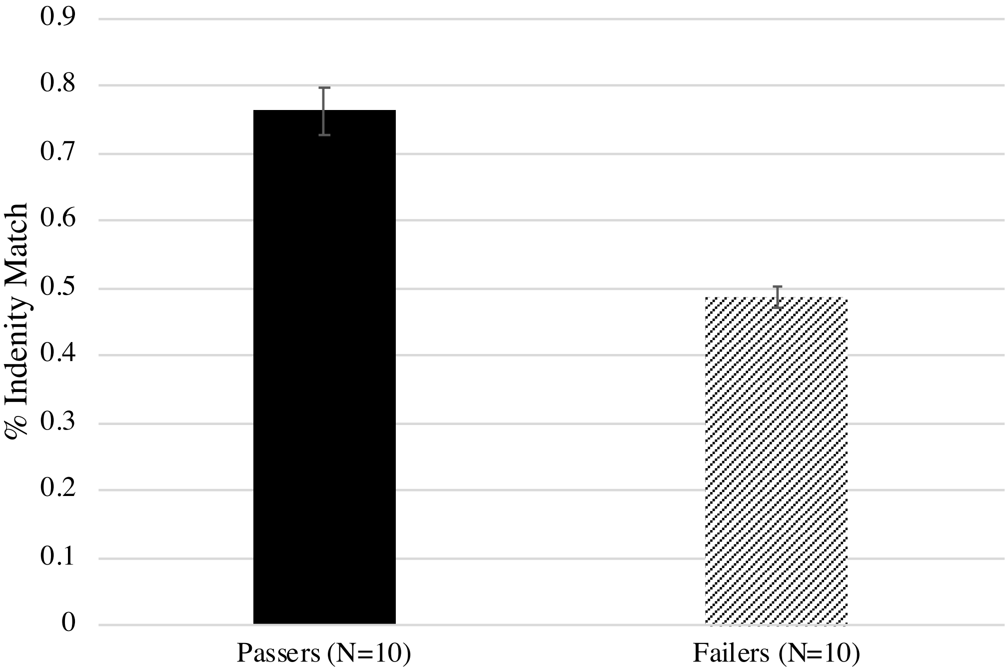


Figure 35. This figure depicts participants included in the eye-data analyses with the frequencies of passing and failing the TC as well as the corresponding group averages for total percent correct scores.

made significantly fewer fixations on correct color trials compared to participants who passed, $t(17)=-3.06$, $p=.007$.

For shape trials, there was a main effect of accuracy, $F(1,17)=4.86$, $p=.042$, $\eta_p^2=.222$, but no interaction between accuracy and performance, $F(1,17)=1.43$, $p=.248$, $\eta_p^2=.078$. A paired-samples t-test across performance for shape correct and shape incorrect trials revealed that overall participants made more fixations across correct trials in comparison to incorrect trials. However, participants who perform well on this task have more opportunities to make more fixations on correct trials compared to incorrect whereas participants who fail have fewer opportunities to make fixations. Thus, this interaction is likely due to an imbalance in trials rather than an actual effect. Thus, total fixation durations and total fixations for trial types by accuracy are not explored further and are not informative ways of looking at this data. Instead, average fixation durations and average fixation counts for these trials are used.

Next, the same 2 (accuracy: incorrect, correct) x 2 (performance: perseverate, switch) mixed ANOVA was ran on average number of fixations per trial. Neither the main effect of accuracy, $F(1,17)=.904$, $p=.355$ $\eta_p^2=.051$, nor the interaction was significant for color trials, $F(1,17)=.338$, $p=.569$, $\eta_p^2=.019$. Neither the main effect of accuracy, $F(1,17)=1.67$, $p=.213$ $\eta_p^2=.090$, or interaction, $F(1,17)=.919$, $p=.351$, $\eta_p^2=.051$, for shape trials was significant (see Table 7).

To test whether participants differed in how long they fixated overall on a trial based on the relevant dimension for that trial or their overall performance a 2 (dimension: shape, color) X 2(accuracy: correct, incorrect) x 2(performance: pass, fail) mixed ANOVAs with within-subject factors of dimension and accuracy and between subjects factors or performance were run. Results revealed there was no main effect of accuracy, $F(1,16)=.481$, $p=.498$ $\eta_p^2=.029$, or dimension, $F(1,16)=.551$, $p=.469$, $\eta_p^2=.033$, nor the interaction between accuracy and performance, $F(1,16)=.488$, $p=.495$ $\eta_p^2=.030$, dimension and performance, $F(1,16)=.060$, $p=.809$ $\eta_p^2=.004$, or interaction between all three variables, $F(1,17)=.254$, $p=.621$, $\eta_p^2=.016$.

Finally, to assess if average fixation durations differed across performance, accuracy, and dimension a 2(dimension: shape, color) x 2(accuracy: correct, incorrect) x 2(performance: pass,

Table 7. Average Fixation Count for Color Trials in the TC for ANOVA

Trial Type	Performance	N	*M*	*SD*
Color Incorrect	Fail	10	12.567	4.163
	Pass	9	14.370	5.513
Color Correct	Fail	10	11.425	4.829
	Pass	9	14.094	3.795
Shape Incorrect	Fail	10	12.374	2.421
	Pass	9	11.738	4.888
Shape Correct	Fail	10	12.715	2.677
	Pass	9	14.034	3.960

fail) mixed ANOVA was run with within-subject factors of dimension and accuracy and between-subject factors of performance. Results revealed no main effect of dimension, *F*(1,16)=.100, *p*=.756, $\eta_p{}^2$=.006, or accuracy, *F*(1,16)=1.30, *p*=.270, $\eta_p{}^2$=.075, nor an interaction between dimension and performance, *F*(1,16)=4.31, *p*=.054, $\eta_p{}^2$=.212, accuracy and performance, *F*(1,16)=.022, *p*=.883 $\eta_p{}^2$=.001, or all three variable, *F*(1,16)=1.18, *p*=.293, $\eta_p{}^2$=.069.

TC fNIRS Event-Related Results

Participants were first excluded based on the above behavioral criteria. Of the remaining twenty-five participants, two participants were excluded for refusing to wear the NIRS hat during the procedure. The remaining twenty-three participants had trials excluded based on a RT criterion (i.e., >14 seconds). All participants contributed at least half of their trials after this RT criteria. Participants were then divided into performance groups (pass, fail), where 11 participants failed the TC and 12 participants passed the TC. Hemodynamics in the TC were first explored by running independent ANOVAs for each of the 16 channels over bilateral frontal and bilateral parietal cortex. To probe the relationship between performance and activation both oxygenated hemoglobin and deoxygenated hemoglobin were explored where activation is when oxygenated (HbO_2) hemoglobin > and positive going in comparison deoxygenated (HbR) hemoglobin (reporting both HbR and HbO_2 changes, instead of only one of them, see Tachtsidis & Scholkmann, 2016). Mean concentration levels for oxygenated and deoxygenated hemoglobin were calculated from a 0-8 second time window after the presentation of the target objects.

To test this relationship, 2(chromophore: oxygenated, deoxygenated) x 2(accuracy: correct, incorrect) x 2(performance: pass, fail) mixed ANOVAs were run for color and shape trials separately. Chromophore and accuracy were used as within-subject factors and performance was a between-subject factor. For a summary of the significant results from these ANOVAs see Table 8.

Table 8. Brain and Behavior Results

Channel	Performance	HbO		HbR		Interaction				
1		*M*	*SD*	*M*	*SD*		*F*	*p*	η_p^2	*df*
Correct	Fail	0.095	0.416	-0.018	0.121	Accuracy x Performance	4.842	.039*	0.187	21
	Pass	-0.394	1.647	-0.240	0.708					
Incorrect	Fail	0.629	1.642	0.237	0.662	Chromophore x Accuracy x Performance	4.328	.050*	0.171	21
	Pass	-0.892	2.052	-0.408	0.799					
3										
Correct	Fail	-0.121	0.315	-0.025	0.130	Chromophore x Accuracy	4.672	.043*	0.189	20
	Pass	0.114	0.294	0.010	0.145					
Incorrect	Fail	-0.151	0.621	-0.067	0.235	Chromophore x Accuracy x Performance	5.359	.031*	0.211	20
	Pass	-0.404	0.765	-0.158	0.374					
11										
Correct	Fail	-0.217	0.182	0.057	0.060	Chromophore	7.664	.012*	0.287	19
	Pass	-0.082	0.389	0.049	0.158					
Incorrect	Fail	0.134	0.283	-0.023	0.055	Chromophore x Accuracy x Performance	5.968	.025*	0.239	19
	Pass	-0.400	0.615	0.020	0.242					
14										
Correct	Fail	-0.148	0.591	-0.009	0.130	Chromophore	4.120	0.055	0.164	21
	Pass	0.053	0.277	0.010	0.116					
Incorrect	Fail	-0.073	0.229	0.034	0.071					
	Pass	-0.164	0.429	0.064	0.211					

**significant ≤ .05

Summary of the Triad Classification Task Results

Behavioral data in this task demonstrate that 3.5-year-olds display a wide range of behavioral performances in this task. Percent correct was broken down into pass and fail criteria and then further probed across the remaining two methods. Overall, participants' behavioral performance did not predict how long they looked, where they looked, or how they looked at stimuli in the task. Together these eye-tracking data suggest that participants are extracting different information from their visual world in similar ways, regardless of overall performance in the task or relevant dimensional for a particular trial. Further, participants spent proportionally the same amount of time looking at left and right target items as they did the reference item. This suggest that participants expelled the same amount of energy looking at the target objects as they did fixate on the reference object. However, participants' performance in this task did predict their hemodynamic responses. Participants who failed the TC shows activation across correct and incorrect trials in anterior left prefrontal cortex while participants who passed the TC showed activation on correct trials only in left posterior prefrontal cortex. In right superior parietal cortex participants who failed the TC showed activation on incorrect trials while participants who passed the TC showed activation in left inferior parietal cortex during correct trials. Together these data suggest that participants might be using differential attention networks when performing these tasks. These activation patterns might lead to specific performance outcomes.

Dimensional Change Card Sorting (DCCS) Task Results

Behavioral

Twenty-six participants began the DCCS task. Participants were excluded if they did not complete at least 18 out of 28 mixed block trials. Two participants were excluded for this reason. This task was scored based on two performance criteria. The first was whether participants switched rules in the post-switch phase. Participants had to get 4/5 trials correct in the post-switch phase to be a switcher. The second score was an overall percent correct score, calculated as the percent of correct matches out of 38 trials (see Figure 36 for frequencies and group averages pertaining to these scores). Participants performed typically for their age group (e.g. Zelazo, 2006) with 10 participants perseverating with average percent correct scores reflecting

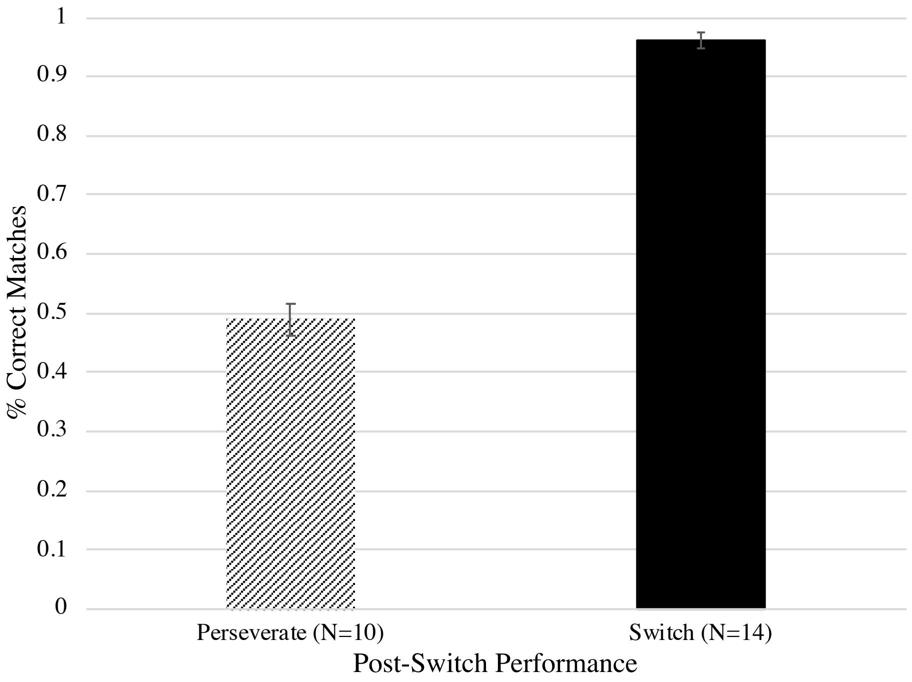


Figure 36. Frequencies (N) of post-switch performance in the sample population as well as group percent correct for post-switch performance groups (i.e., switchers, perseverators).

poorer performance (*M*=.49, *SD*=.09) and 14 participants switching with average percent correct scores reflecting better performance (*M*=.961, *SD*=.05).

This task was presented at the end of the fixed-order battery for 3.5-year-olds which led to high attrition and less participants being on task due to fatigue, thus additional participants were further excluded for a number of reasons in in the following sections on eye-tracking and fNIRS results. Average RTs were normal for switchers (*M*=5.704, *SD*=1.655, seconds) and perseverators, with most variability in RT coming from the first trial of the pre-switch and mixed block phases. No RT pruning was done when analyzing the behavioral data for accuracy. Figure 36 reflects the mean and standard errors for the raw data. RT is calculated from the time the test card appears to the time the child responds. Some additional error is likely in this iteration of the task because the experimenter uses a button press as the RT event when the child points to one of the two sorting locations (see Figure 37).

Eye-Tracking Results

Participants were first excluded based on the above behavioral criteria. Of the twenty-four participants remaining, two participants were excluded because their RTs were longer than 14 seconds. RT criteria excluded 24% of trials across remaining participants' data. An additional two participants were excluded for not having eye-data for 18 out of 28 mixed block trials. The percent of eye-data contributing from each block after these participants were excluded were as follows: pre-switch (85%), post-switch (86.7%), and mixed block (95.1%). For the current analyses, 20/26 participants who began the task were included in the final analyses. Of these, 7 participants failed the DCCS post-switch with mean percent correct scores that reflected poorer performance overall (*M*=.486, *SD*=.089). The remaining 13 participants passed the DCCS, with mean percent correct scores reflecting better performance overall (*M*=.962, *SD*=.051).

First, data were analyzed and scored generally for average fixation duration, total fixation duration, and total number of fixations across trial types (correct, incorrect, shape, color) and phase types (pre-switch, post-switch, mixed block) as well as broken down by the intersection of trial and phase where necessary (see Table 9). Scores were calculated based on data from when the target cards appeared, and the rules were repeated to the time the child made their response. Thus, RT inherently plays a role in these values.

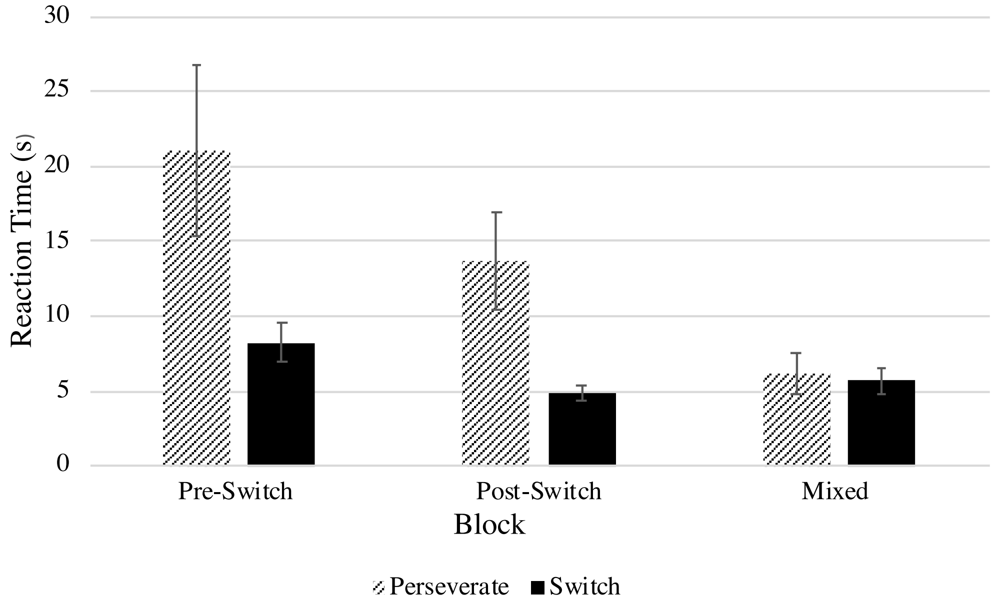


Figure 37. Depicts average RT based on experimenter-controlled trials.

Table 9. Average Fixation Durations and Count for Mixed Block Trials. Means and standard error for fixation durations and fixations counts during the mixed block. The following abbreviations are applied: SI=shape incorrect, SC=shape correct, CI=color incorrect, CC=color correct, Pass=Switchers, Fail=Perseverators.

	Fixation Duration								Fixation Count							
	SI		SC		CI		CC		SI		SC		CI		CC	
	Pass	Fail	Pass	Fail	Pass	Fail	Pass	Fail	Pass	Fail	Pass	Fail	Pass	Fail	Pass	Fail
Mean	389.0	274.5	321.9	225.5	316.1	535.5	268.3	304.5	73.1	122.7	97.5	55.4	31.4	30.5	59.8	78.3
Sterror	47.6	31.8	25.9	42.2	26.5	134.5	28.6	42.8	23.2	25.6	19.6	15.6	5.1	10.4	13.1	15.6

These variables were calculated from fixations made to the screen (*M*=.935, *SD*=.03) as must all looks were made to one of the three stimuli in the task configuration (*M*=.743, *SD*=.142). First, to test the relationship between performance and eye-movements, mixed block performance was assessed. To accomplish this, 2 (accuracy: incorrect, correct) x 2 (performance: perseverate, switch) mixed ANOVAs on total number of fixations for color and shape trials separately were run where accuracy was entered as a within-subject factor and performance as a between-subject factor. For both dimensions of color, $F(1,6)=.635$, $p=.456$, $\eta_p^2=.096$, and shape, $F(1,11)=.428$, $p=.526$, $\eta_p^2=.037$, the main effect of accuracy as well as the interaction between accuracy and performance for color, $F(1,6)=.333$, $p=.585$, $\eta_p^2=.093$, and shape, $F(1,11)=3.51$, $p=.088$, $\eta_p^2=.242$, were not significant. These results suggest that the number of fixations made during color and shape trials did not differ based on performers between switchers and perseverators. To test whether perseverators had more fixations than switchers during pre- and post-switch phases independent samples t-test were run on the total number of fixations during pre- and post-switch phases separately with performance as a grouping variable. There were no significant differences between switchers and perseverators during both pre-switch, $t(17)=-.311$, p=.760, or post-switch, $t(17)=.414$, p=.684, trials. Finally, to test whether participants looked differently during pre-switch vs. post-switch trials as a function of performance, a 2-way (Block: pre-switch, post-switch) mixed ANOVA was run with a between-subject factor of performance (switchers, perseverators). Results revealed there was not a significant main effect of block, $F(1,20)=2.13$, $p=.160$, $\eta_p^2=.096$, or interaction between block and performance, $F(1,20)=.296$, $p=.296$, $\eta_p^2=.054$. Since all participants received color for the pre-switch and shape for the post-switch in a fixed order, dimension could not be further explored for these phases of the task.

Next, we ran the same 2 (accuracy: incorrect, correct) x 2 (performance: perseverate, switch) mixed ANOVA on average fixation duration. Similar to the previous results, neither the main effect of accuracy, $F(1,11)=1.022$, $p=.334$, $\eta_p^2=.085$, nor the interaction, $F(1,11)=.006$, $p=.938$, $\eta_p^2=.001$, was significant for shape. Neither the main effect of accuracy, $F(1,6)=1.13$, $p=.328$, $\eta_p^2=.159$, nor the interaction, $F(1,6)=.166$, $p=.698$, $\eta_p^2=.027$, were significant for color.

Due to the imbalance in accurate and inaccurate trials within each dimension (e.g. several participants not having one or the other), follow-up 2-way (dimension: shape, color) mixed

ANOVAs with a between-subject factor of performance (switchers, perseverators) on accurate trials were run. These analyses revealed a significant interaction between dimension and performance, *F*(1,15)=11.56, *p*=.004, η_p^2=.435. Follow-up independent-samples t-tests with a grouping variable of performance was run for correct color and shape trials. Results revealed no significant difference between fixation durations during different dimensional trials based on performance, *t*(18)=-.724, p=.478. A follow-up paired samples t-test comparing correct shape trials to correct color trials for participants who switched rules revealed that participants made longer fixations during correct shape trials than they did for correct color trials during the mixed block, *t*(11)=3.15, *p*=.009. Thus, it is likely the high performing group is driving this interaction (see Figure 38). There were not enough participants with both correct shape and correct color trials in the group that perseverated to run this same t-test with this group, to confirm this.

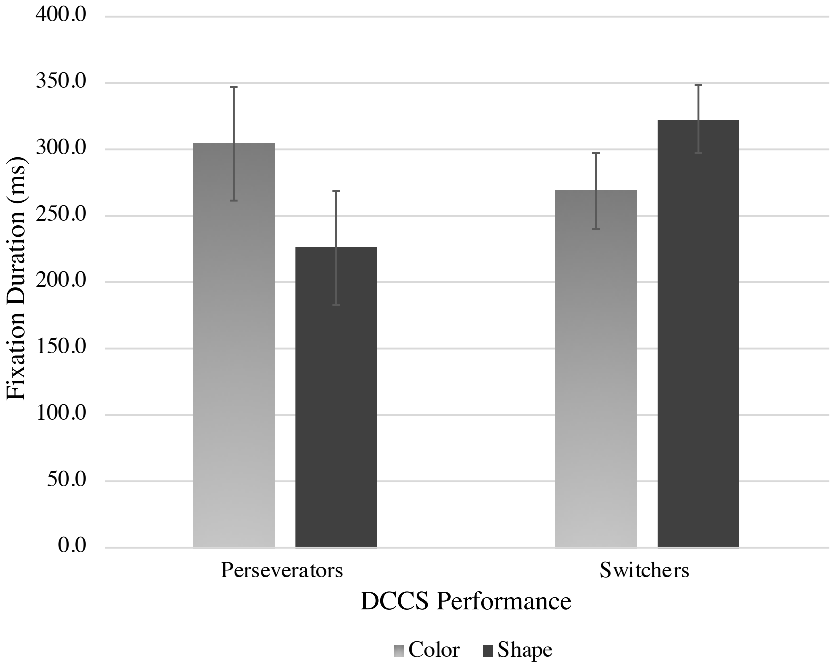


Figure 38. This figure depicts average fixation durations during correct color and shape mixed block trials for switchers and perseverators.

Together these data suggest there is likely a large amount of variation in fixation durations across performance groups in this task (see Table 10). Further, it seems that participants who switch rules in the post-switch tend to make longer fixations during shape trials compared to participants who perseverate whereas participants who perseverate in the post-switch tended to make longer fixations during color trials compared to those who switched. This interaction could likely be a result of how efficiently participants can extract the relevant meaningful information from different trial types.

One of the challenges of the DCCS task is that participants have switch rules from the pre- to post-switch blocks and generalize sorting rules to new sorting cards (i.e. total change of all card features) during the mixed block. Thus, one interesting question to ask is whether looking behaviors reflect the challenge presented by these transitional trials where attention to different visual information is needed to succeed. Further, does this behavior differ for participants who are successful in the task compared to those that are not? To achieve this, data from the first trials of each block (pre-switch, post-switch, and mixed) were analyzed via a mixed ANOVA on the total fixation duration data with DCCS performance as a between-subject factor. Results revealed a main effect of block type, $F(2,7)=8.37$, $p=.014$, $\eta_p^2=.705$, and no interaction between block and performance, $F(2,7)=1.07$, $p=.394$, $\eta_p^2=.234$. However, several participants did not have data in all three trial blocks due to RT criteria, and these trials in particular having longer reactions times compared to other trials in these blocks. Thus, this relationship was further probed with paired sample t-test on to increase power and reduce Type 2 error due to small sample size. There was a significant difference between the time spent fixating during the first trial on the pre-switch compared to post-switch, $t(11)=3.580$, $p=.004$.

Table 10. Mean Fixation Counts by Performance and Dimension.

Dimension	Performance	*M*	*SD*	*Sterror*
Color	Fail	55.40	41.332	18.484
	Pass	97.55	73.940	22.294
Shape	Fail	78.29	41.295	15.608
	Pass	60.92	49.050	14.160

That is, the first trial of pre-switch and the mixed block, *t*(12)=2.143, *p*=.053, were significantly different but not the 1st trial of the post-switch and the mixed block, *t*(13)=.297, *p*=.771. These data are severely limited by low sample size, largely due to RT. However, the means suggest there may be an interaction between trial and performance for the time spent fixating, though not revealed in the current statistics due to this limitation (see Figure 39).

DCCS fNIRS Event-Related Results

The current task was not optimized for traditional event-related analyses where channel by channel ANOVAs are used to assess the relationship between performance, response accuracy, and chromophore. The current sample is also limited due to sample size as the DCCS was the last task in the current battery thus it is unlikely effects will be detected via these traditional ANOVAs. However, more children were included in the rFC and DCCS behavioral performance analyses that isolated channel pairs likely involved in success during this task. Thus, block analyses were used for the current task and linked to rFC and behavioral performance. Specifically, pre-switch trials were analyzed separately. Post-switch as well as mixed-block trials were combined and collapsed across accuracy. To test if the strength of the hemodynamic

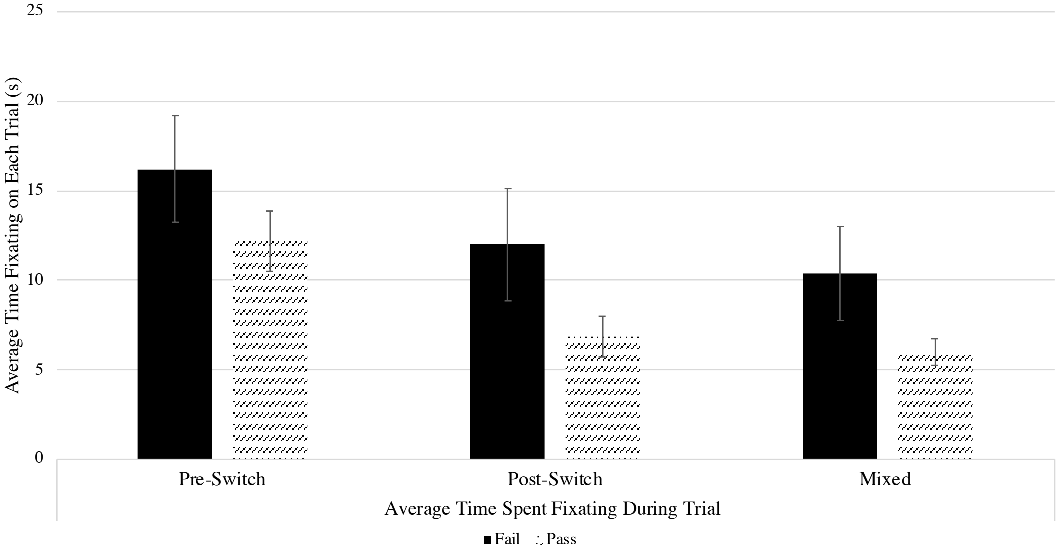


Figure 39. Group averages for time spent fixating on the first trial of each block.

response as well as the areas in frontal and parietal cortex varied as a function of performance, these averages were subjected to mixed 2(chromophore) x 1 (performance) ANOVAs where performance was calculated as post-switch performance (pass, fail).

For pre-switch trials, there was an interaction between performance and chromophore on channel 5, such that activation was seen for those that passed the post-switch whereas those that did not pass did not show activation, $F(1,18)=5.29$, $p=.034$, $\eta_p^2=.227$. Follow-up independent samples t-tests with a grouping variable of performance (pass/fail) were not significant for HbR (Pass: $M=-.046$, Fail: $M=.069$), $t(18)=-1.98$, $p=.063$, or HbO_2 (Pass: $M=.148$, Fail: $M=-.019$), $t(18)=-1.63$, $p=.122$, likely due to power. Paired samples t-test between HbO_2 and HbR for passers separately were significant $t(11)=2.44$, $p=.033$, where HbO_2 was positive going and significantly different than HbR. This same paired-samples t-test was run for failers and was not significant, $t(7)=-.962$, $p=.368$. On channel 9 there main effect of chromophore ($F(1,18)=5.356$, $p=.033$, $\eta_p^2=.229$), where HbO_2 ($M=.686$) was positive going and greater than HbR ($M=-.063$). On channel 12 (see Figure 40) there was a main effect of chromophore, $F(1,18)=4.85$, $p=.041$, $\eta_p^2=.212$, where HbO_2 ($M=.150$) was positive going and greater than HbR ($M=-.397$). These data suggest that all children are using posterior regions during this task, but that frontal activation during pre-switch is predictive of post-switch performance.

For post-switch and mixed block trials, there was a main effect of chromophore, $F(1,18)=8.52$, $p=.009$, $\eta_p^2=.321$, and an interaction between chromophore and performance, $F(1,18)=5.89$, $p=.026$, $\eta_p^2=.247$, on channel 2 (see Figure 41). Follow-up independent samples t-test with grouping variable of performance revealed that children who fail the post-switch have greater HbO_2 levels than those that pass the post-switch, $t(19)=2.402$, $p=.027$. Correlations between performance and HbO_2 levels are plotted in Figure 40, $r^2=-.493$, $p=.027$. While right frontal activation during the pre-switch predicts performance (pass, fail) in the post-switch phase of this task, activation in left frontal during the post-switch and mixed blocks is negatively associated with overall performance in this task. This suggest that children who are less flexible in this task have greater increases in frontal HbO_2 when switching is required whereas children who are more flexible are initially activating right frontal cortex but then decreases in activation in frontal cortex when switching is required.

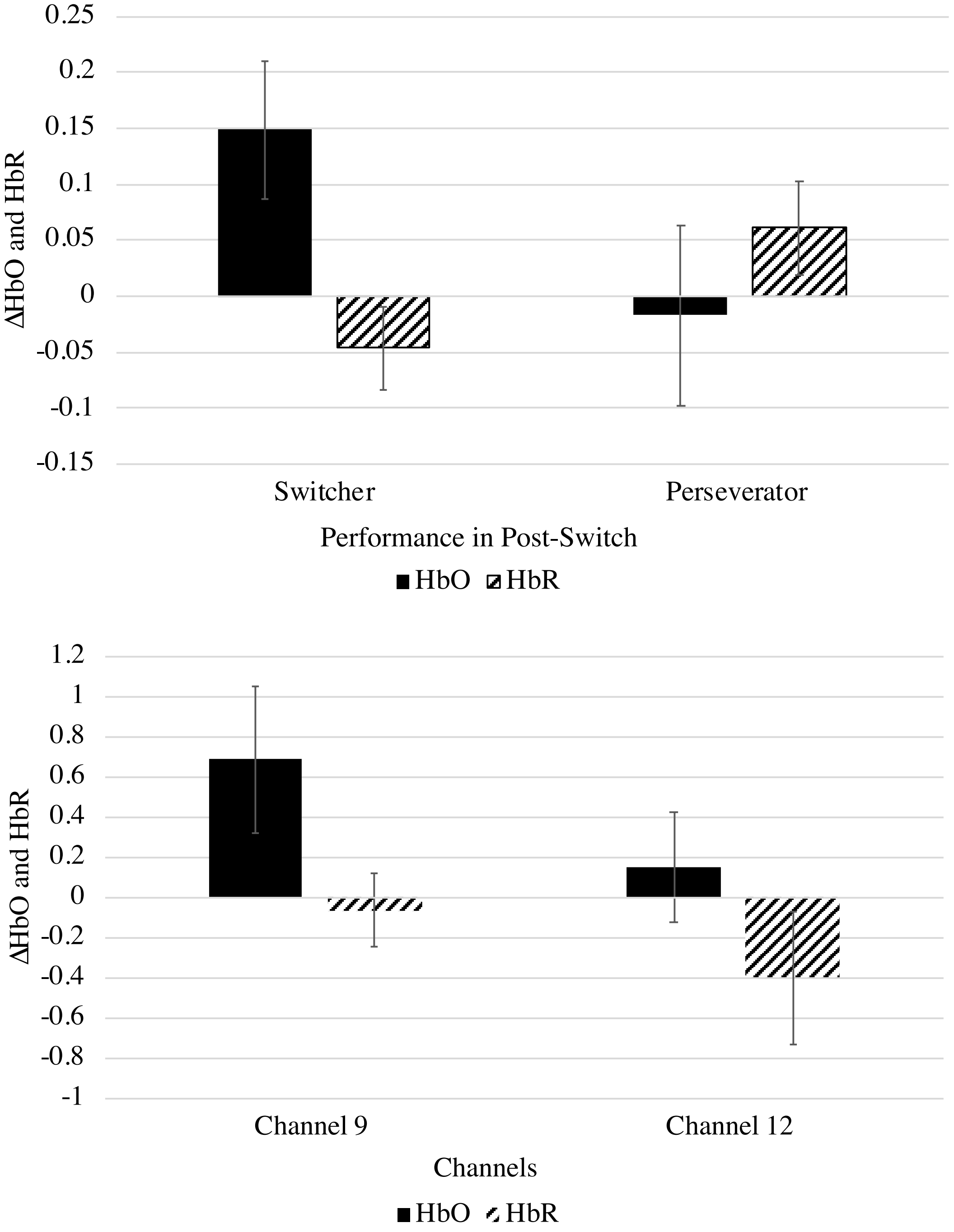


Figure 40. Activation during pre-switch trials. Frontal activation (top) is performance specific whereas posterior performance is group wide(bottom).

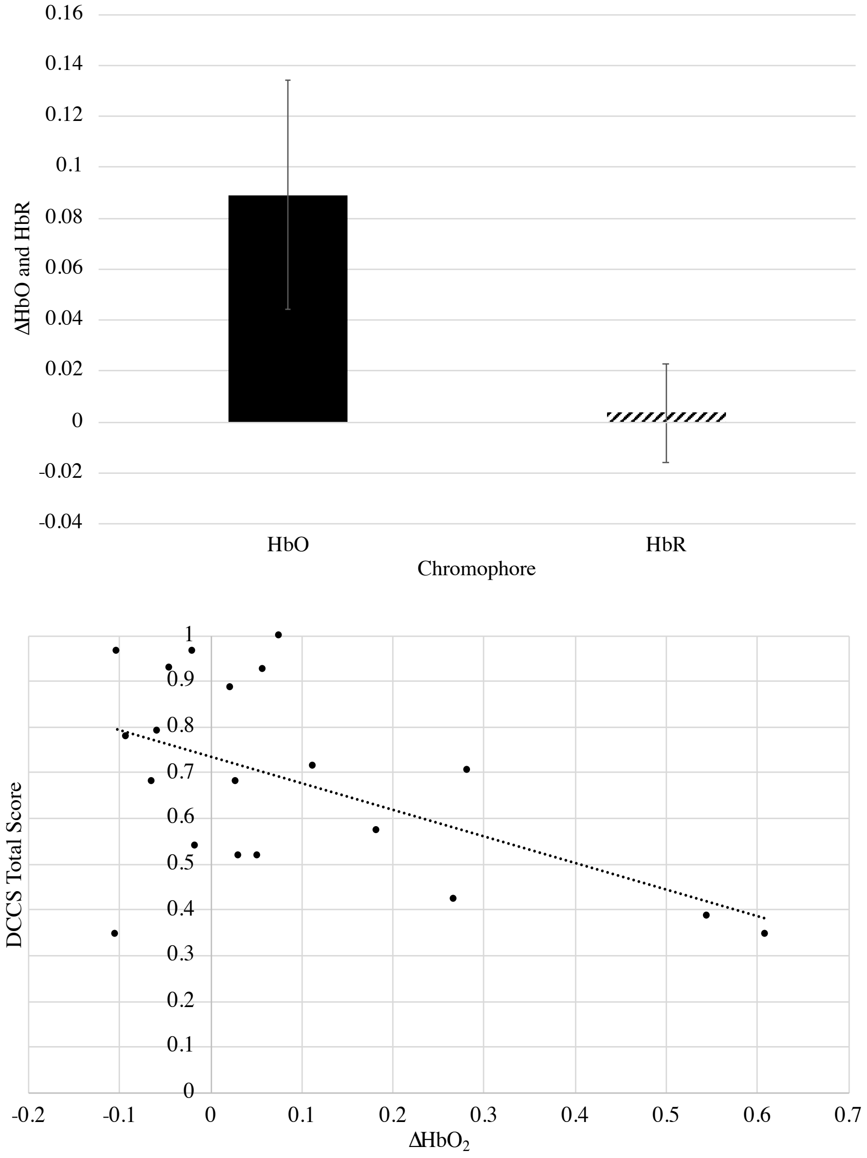


Figure 41. Group wide frontal activation during the post-switch and mixed block phases of the task for channel 2 (top) and correlations between HbO_2 levels and overall DCCS performance on channel 2 (bottom).

Backward elimination methods were employed with multiple regressions where channel 2, channel 9, and channel 12 HbO_2 levels during post- and mixed block trials were predictors and overall DCCS performance was the dependent variable. Results revealed that HbO_2 levels on channel 2 were most predictive of overall performance negatively during this task, $R^2 = .281$, $F(1,19) = 7.03$, $p = .016$. This same regression was run again with pre-switch HbO_2 levels added in for channel 5, channel, 9, and channel 12. The results of this regression analysis revealed that, even when accounting for pre-switch HbO_2 levels on these channels, post-switch and mixed block levels on channel 2 were still negatively predictive of overall DCCS performance, $R^2 = .281$, $F(1,19) = 7.03$, $p = .016$.

Summary of DCCS Task Results

Behavioral results in this task were typical of the age range tested. Eye-tracking data demonstrated that children were, similar to the TC task, looking at their visual environments similarly regardless of response accuracy across trials in the task. However, in this task, hemodynamics were able to uncover the neural regions that are engaged when successfully or unsuccessfully performing this task. Right prefrontal cortex was selectively activated during the pre-switch phase for those that switched rules in the post-switch, whereas those that failed the post-switch did not show activation. Further, group wide activation in left prefrontal cortex and bilateral parietal cortex were recruited across task blocks suggesting there may be a common mechanism child are utilizing to respond in this task. However, the relationship between HbO_2 levels in left prefrontal cortex were predictive across performance groups of overall scores on the DCCS. Lastly, regions during rFC that were predictive of behavioral performance in the DCCS, overlapped with regions demonstrating event-related activation in this task. These findings suggest rFC might be one way of tapping in to the developmental status of neural networks, specifically what regions might be more strongly connected than others and how that might manifest in the event-related, channel by channel, activation seen within a specific task. However, both rFC and task-related activation are required for making these types of claims.

CHAPTER IV:
DISCUSSION

The current study was the first to assess eye-tracking, hemodynamic responses, and behavior together in 2.5- and 3.5-yer-olds during this battery of attention tasks. The relationship between orienting, alerting, and executive attention were explored in relation to dimensional attention to examine how early developing aspects of the attention process influence later attentional performance in the context of executive functioning.

Orienting and Alerting

Basic attention functioning was examined cross-sectionally during the IOWA task. Neural data from the IOWA task demonstrate a clear predictive relationship between both rFC and event-related hemodynamics for behavior (e.g., eye-movements). Children who had stronger interregional connectivity in bilateral parietal cortex at rest, did better in this task and tended to be less reactive as indicated by both accuracy and RT data across trial types. Age however was not correlated with any of the RT, accuracy, or composite attention scores in the IOWA task. These data suggest that children's basic attentional abilities are based on the status of the neural system more than they are on the age of the child. Generally, 2.5 and 3.5-year-olds perform similarly in this task.

Executive Attention

During the Flanker task, children performed poorly on incongruent trial types. However, some 2.5- and 3.5-year-olds performed very well on these trials suggesting there is a developmental transition in the ability to both resolve conflict and selectively process stimuli in the face of competition being recruited in response to incongruent trials for toddlers and young children. This finding is not surprising. Much work has been done on these abilities in early childhood. Whether this transition is a result of increases in selective attention leading to better attention to directionality of the middle stimuli or more focused attention in the face of conflicting distractors remains unclear. Neural data during this task suggest different regions of the brain might be contributing uniquely to congruent and incongruent trials. Right superior prefrontal cortex was recruited when children had to focus on the middle item in the presence of flanking items (congruent trials) whereas right superior parietal cortex was recruited when children had to make a decision about what direction was relevant when flanking items created conflict (incongruent trials). Finally, rFC was related to event-related hemodynamics and performance in this task. Specifically, right prefrontal cortex was implemented as one region in the rFC data that was predictive of incongruent performance. These data suggest both of these methods together could be used to assess the status of a specific neural network in children when they are converging.

Linking Early Attention with Executive Function

First, basic attention functioning was examined cross-sectionally during the IOWA task and compared to attention in the context of executive functioning during the child Flanker task. Measures of in the IOWA were predictive of accuracy in neutral trials during the Flanker for all children. Previous work with infants suggests that facilitation effects of spatial cueing occur earlier in development than interference effects (Ross-Sheehy, Perone, & Kellen, 2015). The current work demonstrated that the extent to which children benefited from the cue was related to their performance on neutral trials, that is their selective attention to stimulus directionality when there are no distractors. Overall, children performed better during neutral trials compared to congruent and incongruent trials suggesting that children ability to benefit spatially from a cue is related to children's ability to correctly map the direction of the animal in the Flanker during neutral trials to the correct left or right spatial location corresponding with the two buttons on the serial response box. Competition scores in the IOWA were predictive of incongruent accuracy in the Flanker for all children suggesting that as children develop the attention skills to succeed in the Flanker task, they also show lower competition scores suggesting they can more quickly resolve the spatial conflict in the IOWA. Further, this competition score was predictive of whether or not children performed at above chance levels in the Day Night task for 3.5-year-olds and their overall accuracy in the task. These data indicate that early attentional control in a task that primarily tests space-based attention might also be predictive of better executive attention in a task where spatial information is not relevant and where object-based information is critical for success such as the Day Night task. Further, congruent accuracy scores in the Flanker were predictive of snack delay scores for 2.5-year-olds. This suggest that attentional regulation during the snack delay is also related to children's ability to succeed in the Flanker task during trials where flanking information is not in direct competition with the correct response but, as indicated by eye-tracking results, can still distract children from responding correctly.

Event-related hemodynamic results indicate that accuracy during congruent and incongruent trials was associated with activation in superior right prefrontal and parietal cortex. These same areas have been previously implemented for selective attention in a variety of tasks. In the current study, only superior right prefrontal cortex was related to performance in the IOWA task across participants. However, channel 4 showed age-related changes in activation where the vast majority of 2.5-year-olds did not show activation on this channel whereas 3.5-year-olds did for no cue and invalid trials. This suggest that the use of both frontal and posterior regions are necessary for success in the Flanker task whereas tuning of right prefrontal cortex, that is more widely distributed activation in younger children and more finely tuned activation in older children, in conjunctions with bilateral tuning within parietal cortex leads to better performance in the IOWA task. Individual differences in speed or orienting or alerting to target stimuli were predictive of activation in superior right parietal cortex and inferior left parietal cortex. The IOWA task in the current study was sensitive to the individual differences seen in brain activity while children performance the task within the same regions that were implemented in the rFC analyses. The use of multiple methods in the current study allow for much stronger claims concerning brain development and behavioral changes in performance than any one of these methods in isolation. That is, using rFC data to anchor even-related and FC findings within specific tasks and then further linking those with multiple response types (ocular-motor, motor, and verbal) has been demonstrated as incredibly useful as a practice in the current study.

Together, these data suggest that differential cortical regions are being utilize across two tasks as a factor of age, functional connectivity, and type of attentional function being recruited. Further investigation of these intricate interactions in both spatial and object-based attention tasks is warranted to better understand how these three variables interact. The current data do suggest that these basic attentional functions likely continually improve with development between 2.5- and 3.5-year-olds and are related to better or worse performance in executive functioning tasks such as the Flanker task. Thus, space-based attention in toddlers and preschoolers is related to their ability to attend to object-based information in executive functioning tasks where attention is one primarily process being recruited. These findings together provide insight into the developmental status of attention and executive function from 2.5- and 3.5-years-old.

Inhibition and Attention

In the current battery, two tasks were used to assess inhibitory control as one aspect of executive functioning that influences attentional functioning, the Snack Delay and Day Night tasks. Typically, the snack delay is done with pre-school aged children (e.g., Carlson, 2005). However, versions of this task have been used with children as young at 18-months-old (e.g., Spinrad, Eisenberg, & Gaertner, 2007). Gerardi-Caulton (2000) measured children’s sensitivity to spatial conflict between 24-36 months as well as other effortful control measures such as the snack delay and found that children performed relatively poorly on the snack delay prior to 30-months-old. Thus, scores on this task were not used for long term correlations prior to 30-months-old for later self-regulation outcomes in that study. Despite this, the snack delay task was found to be related to parental-report temperament measures of attentional focusing and attentional shifting. The current study presents data suggesting children at 2.5-years-old perform similarly poorly in this task, despite some children succeeding. However, attention focus in the current sample was not predictive of attentional focusing and was negatively related to snack delay continuous scores. Further, these behavioral scores were compared to performance in other tasks in the current study despite children performing poorly overall. In the current study, channel-pairs in executive attention networks were implemented as predictors of success in this task. These data suggest that success in the Snack Delay might be about more than inhibition, and likely involves the consistent engagement of attention to the goal at hand while also being able to inhibit the desire to eat the snack. The dynamic interaction between inhibitory networks and executive attention networks in the context of this task should be further explored. Morasch and Bell (2011) explored the relationship between inhibition and executive function in toddlers and demonstrated that tasks such as the crayon-delay and the A-Not-B task are related in 2-year-olds and that they are predictive of temperamental measures of inhibition. Further, this same study found that bilateral prefrontal cortex (i.e., Fp1:2, F3:4), parietal (i.e., P3:4), temporal (i.e., T3:4, T7:8), as well as occipital (i.e., O1:2) and central (i.e., C3:4) electrodes together predicted inhibitory control subscales on the temperament subscale. Longitudinal work should include Snack Delay performance in toddlerhood, regardless of poor performance scores, based on the presently presented neural data that suggest this task does capture developmental differences in attention and inhibition within this age group.

The current paper suggest that the snack delay is about more than inhibition, and likely captures executive attention abilities in toddlers. Juxtaposed to this task, the Day Night task is already widely debated in the literature for two reasons that mirror the evidence presented here for the snack delay. One is a disagreement on why children struggle in the task and the second is if it is a measure of inhibition or if it is a measure of executive attention (Diamond, Kirkham, & Amso, 2002; Gerstadt et al., 1994; Simpson & Riggs, 2005a, 2005b). One explanation of why behavior varies in this task is that children as young at 3.5-years-old are unable to inhibit their learned associations between day and sun and night and the moon and stars. Munakata (2013) proposed that children have difficulty holding on the relevant rule, similar to the DCCS task, over the course of the 16 trials. Diamond et al. (2002) suggested that, given more time to respond, children who succeed more in the task, and children did succeed at 89% given the extra time to think before responding while they performed at chance in the standard condition. This suggest that some level of conflict resolution occurs when children are preparing to respond. When rushed, children are unable to override their learned associations, but given time children are more successful in implementing the new “opposite” rule. In the current task, children were asked to play the “opposite” game where they were first taught the new association between sun and night and moon and stars with day. Considerable research has been on the concept of opposites and at what age children begin to understand what this word means as well as the concept that objects can have antonyms (e.g., Morris, 2003; Phillips & Pexman, 2015). However, these explanations are largely metalinguistic, suggesting children younger than 4-years-old might be able to implement the concept of opposite if first taught what that means and given examples as in the practice trials of the Day Night task in the current study. However, additional examples and alternative versions of the Day Night study should be explored in the future to test this.

The Day Night task has also been discussed in terms of whether or not it is a measure of inhibition, executive attention, executive function, or interference control (e.g., Montgomery & Koeltzow, 2010; Stievano & Valeri, 2013; Watson & Bell, 2013). Berwid et al. (2005) modified the task to be longer and used it as a sustained attention measure in children that were at risk for ADHD and typically developing and found that those at risk for ADHD performed poorly in his task not as a result of deficits in inhibitory control rather an inability to self-regulate state. The current study provided evidence for bilateral frontal regions being activated in this task during correct trials, where follow-up regressions revealed HbO_2 levels in right prefrontal cortex was predictive of overall performance in this task. This channel specifically was implemented in other selective attention tasks within this battery. Together, neural engagement of bilateral frontal areas in the current study provide evidence for the Day Night task being a measure of executive function (i.e., inhibition, selective attention, and flexibility). The current study uses the Day Night task as a proxy of children's executive functioning ability as well as their ability to both selective in their attention to the current rule, flexibly apply that rule as visual stimuli change randomly from trial to trial and inhibit proponent responses to the stimuli (day=sun, moon and stars=night).

Innovations, Limitations, and Conclusions

Previous theories have suggested that attentional functioning increases with age and becomes more efficient as the brain matures (Posner & Peterson, 2012). However, the current study is only partially in support of these ideas. In the IOWA and Flanker tasks for example, age was not predictive of performance but rather neural activation and rFC was. Complimentary theories posit that temperament is heavily tied to attention development beyond age and maturation (Rothbart, Posner, & Kieras, 2008). However, the current battery of tasks was not explained by temperament in isolation. Rather, the triangulation of hemodynamic, ocular-motor, and behavioral responses in the current study have provided a more in-depth examination of how the functional properties of the neural system give rise to behavioral and motor responses in a given set of attention tasks during the toddler and early childhood years. Despite these contributions, the structure of the current study also leant to high attrition rates and possible skewing of the date due to this attrition.

In the current battery, we failed to replicate previous findings that suggested dimensional attention, one type of object-based attention, is jointly assessed by both the Triad Classification and DCCS tasks. Due to attrition rates seen in this study due to both the length of the battery and the nature of coordinating multiple measurement modalities within a single paradigm, it is likely this correlation is due to the specific subgroup of children that made it to the end of the battery in the 3.5-year-old group. Thus, attrition in the current study limited the power of the current sample. Additional replications are necessarily to fodder this claim. The current study did however support the hypothesis that behavior would look similarly in these two tasks. That is, regardless of performance in the two-dimensional attention tasks, children looked at stimuli and responded to stimuli (i.e., RTs) similarly. rFC in these tasks showed overlap in right prefrontal and parietal cortex. Such that weaker connections between superior right frontal and parietal cortex were predictive of overall DCCS scores whereas stronger connections between channel inferior right frontal and superior right parietal cortex were related to better performance. The event-related data suggest that channel inferior right frontal cortex is involved in TC performance whereas inferior right frontal cortex and superior right parietal cortex are involved in the DCCS. In the Flanker task activation in this same lateralized network of right inferior and superior frontal cortex and right superior parietal cortex were implemented in successful performance. These three tasks recruit selective and flexible attention to objects in different ways. In the Flanker task, children have to be selective to the middle animal, but flexible in responding with the right or left button from trial to trial across trial types. In the DCCS, switching dimensional rules requires flexibility, whereas selectivity is required to attend to specific aspects of stimuli from trial to trail. Finally, the Triad Classification task requires flexibility and selectivity similar to the DCCS but without the presence of explicitly stated dimensional rules. Additional research should be conducted with longer versions of both the DCCS and TC to see if this relationship with the Flanker task changes at the neural level and to what extent variations in these task structures modulate performance in these tasks.

Across attention and executive functioning tasks, selective attention networks in right dorsal stream (e.g., Desimone & Duncan, 1995) seem to play a role in performance and vary as a function of developmental status and age. Further, right lateralization of activation during orienting, reorienting, and executive attention in indicative of typical attention development in controls whereas children with ADHD have been shown to recruit more left lateralized fronto-parietal areas during the Attention Network task (Konrad, Neufang, Hanisch, Fink, & Herpertz-Dahlmann, 2006). Children in the risk group had negative correlations between HbO_2 levels in superior right prefrontal cortex and superior right parietal cortex during both eyes-open and eyes-closed baseline tasks suggesting that these cortical areas were less connected for these children across 2.5- and 3.5-year-olds. These same channels showed activation during the Flanker task across age groups during accurate congruent and incongruent trial types. This suggest that perhaps children at risk for ADHD exhibit differential neural network development and recruitment to perform tasks where attention is used in conjunction with other higher-level cognitive process and that dysfunction in regulated attention might lead to later differences in lateralization, neural tuning, and behavioral performance deficits. Despite this possibility, any conclusions from this group have to be interpreted with caution because of the sample size. Despite the limiting sample size, it is interesting to note that these deviations in rFC across baseline tasks for right dorsal-lateral attention networks were present in the risk group as early as toddlerhood. Further, the current study suggests that early spatial attention might be predictive of later object-based attention in the context of executive functioning. It is possible then that one root of executive and attentional dysfunction seen in children with ADHD is a result of early dysfunction in alerting and selective attention, leading to downstream dysregulation of higher-order attentional processes involved in executive function.

Little work had been done on rFC in toddlers, particularly with regards to the targeted attention networks in the current study. However, rFC has become an increasingly popular method for infants that has provided unprecedented insight into the developing brain over the last decade (Mongerson, Jennings, Borsook, Becerra, & Bajic, 2017). This is in part due to limitations in feasible technologies for assessing hemodynamics in the developing brain. Now, fNIRS provides a unique opportunity to collect rFC from toddlers and young children.

Together these results are promising for addressing the extent to which early attentional processes effect later executive functioning. Further, simultaneously measuring behavioral, ocular-motor, and neural responses was demonstrated as a viable and beneficial way of addressing the study of attention in the toddler years.

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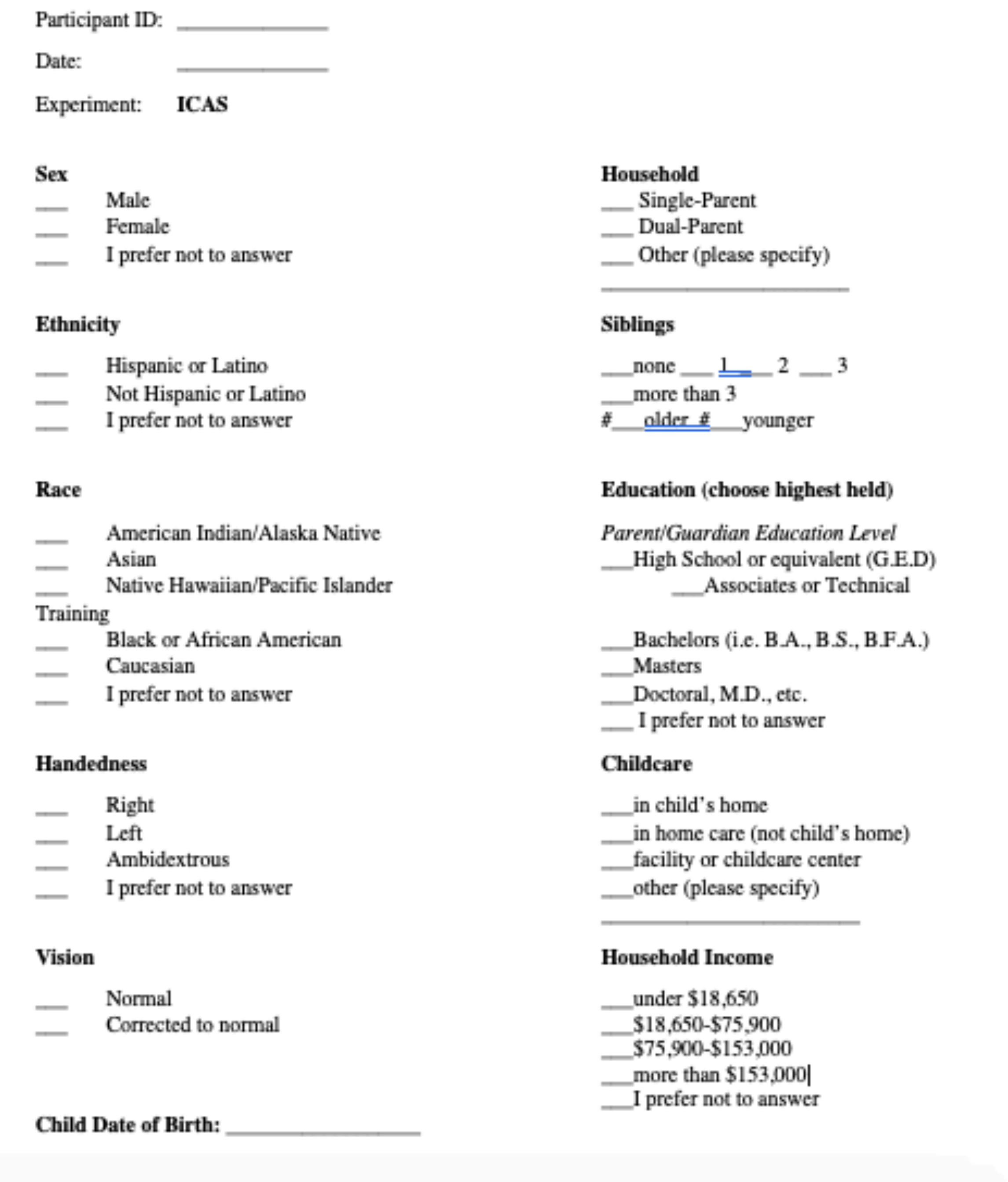
APPENDIX



Participant ID: ____________

Date: ____________

Experiment: **ICAS**

Sex

___ Male
___ Female
___ I prefer not to answer

Ethnicity

___ Hispanic or Latino
___ Not Hispanic or Latino
___ I prefer not to answer

Race

___ American Indian/Alaska Native
___ Asian
___ Native Hawaiian/Pacific Islander
Training
___ Black or African American
___ Caucasian
___ I prefer not to answer

Handedness

___ Right
___ Left
___ Ambidextrous
___ I prefer not to answer

Vision

___ Normal
___ Corrected to normal

Child Date of Birth: ________________

Household

___ Single-Parent
___ Dual-Parent
___ Other (please specify)
____

Siblings

___none ___ 1___ 2 ___ 3
___more than 3
#___older #___younger

Education (choose highest held)

Parent/Guardian Education Level
___High School or equivalent (G.E.D)
___Associates or Technical

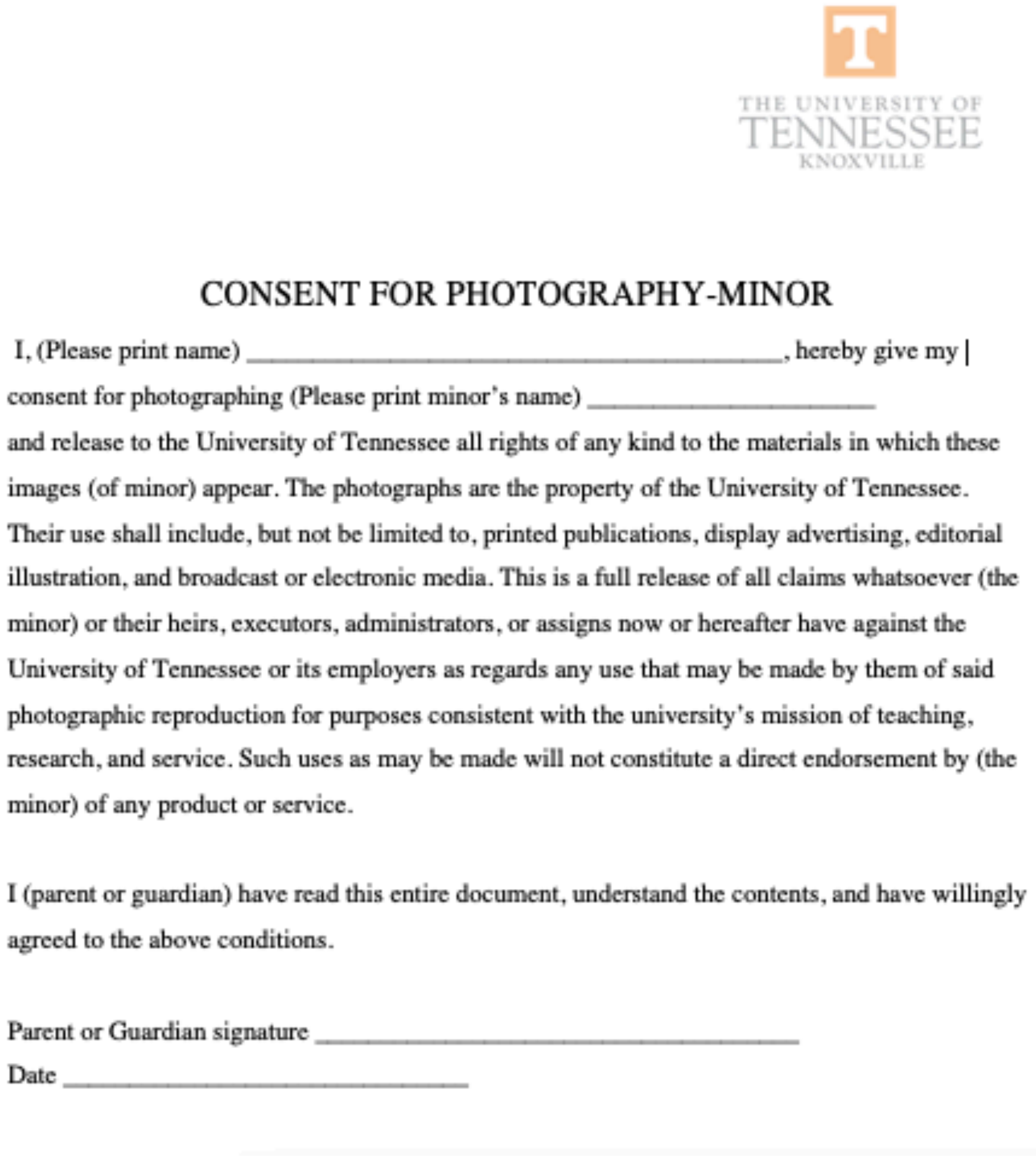
___Bachelors (i.e. B.A., B.S., B.F.A.)
___Masters
___Doctoral, M.D., etc.
___ I prefer not to answer

Childcare

___in child's home
___in home care (not child's home)
___facility or childcare center
___other (please specify)
____

Household Income

___under $18,650
___$18,650-$75,900
___$75,900-$153,000
___more than $153,000
___I prefer not to answer



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VITA

Anastasia Kerr-German was born in Snellville, Georgia and grew up in Sugar Hill, Georgia. Anastasia attended Sugar Hill Elementary School, followed by Lanier Middle School, and North Gwinnett High School in Suwanee, Georgia, where she graduated in May of 2010. She went on to attend Georgia College and State University in Milledgeville, Georgia, where she completed a Bachelor of Science degree in Psychological Sciences in May 2014. Following graduation, Anastasia began her graduate program in Experimental Psychology at the University of Tennessee in Knoxville, Tennessee, with a developmental concentration. Under the supervision of her graduate mentor, Aaron Buss, her graduate training and research focused on developmental cognitive neuroscience topics targeting the development of attention and executive function, as well as learning in early childhood. She received her Master of Arts degree in Experimental Psychology in December 2016 from the University of Tennessee and continued on there to pursue her Doctor of Philosophy degree in Experimental Psychology. Pending graduation, Anastasia plans to pursue a research career at Boys Town National Research Hospital in Omaha, Nebraska, where she will be starting an fNIRS based research program within a newly formed Early Childhood Neurobehavioral Research Group to continue exploring the development of attention in young children.