

WHAT NEXT? UNPACKING ANTICIPATORY EEG OSCILLATIONS IN AUDITORY,
TACTILE AND VISUAL MODALITIES: RELATIONS WITH BEHAVIOR AND
EXECUTIVE FUNCTION IN CHILDREN AND ADULTS

A Dissertation
Submitted to
The Temple University Graduate Board

In Partial Fulfillment
of the Requirements for the Degree of
DOCTOR OF PHILOSOPHY

by:
Staci Meredith Weiss
August, 2020

Examining Committee members:

Dr. Peter J. Marshall, Advisory Chair, Department of Psychology
Dr. Nora Newcombe, Department of Psychology
Dr. Jason Chein, Department of Psychology
Dr. Kathryn Hirsh-Pasek, Department of Psychology
Dr. Johanna Jarcho, Department of Psychology
Dr. Elizabeth Gunderson, Department of Psychology

©

Copyright March 13 2020

Staci Meredith Weiss

All Rights Reserved

ABSTRACT

Anticipation refers to preparation for upcoming events in the environment (Clark, 1998; Ondobaka & Bekkering, 2007; Allen & Friston, 2016). The ability to anticipate – as manifested in the preparatory actions and neural activation in expectation of an upcoming target stimulus – may play a key role in the development of cognitive skills. In the current study, cognitive skills are specified as the execution of stimulus-relevant, goal-directed actions (as indexed by reaction time) and individual differences in the ability to use goals to direct action (as indexed by executive function measures). A cross-sectional investigation was conducted in 40 adults and 40 6- to 8-year-old children to examine the association of neural correlates of anticipatory attention to visual, tactile and auditory stimuli with inter- and intra-individual variation in executive function (EF) abilities. Consistent with prior findings (Weiss, Meltzoff, & Marshall, 2018), the sensorimotor mu rhythm in the alpha range of the EEG signal was suppressed in the contralateral hemisphere during anticipation of tactile stimulation, with the extent of this suppression being related to children's performance on EF tasks. Within-subject relations were also found between lateralized EEG modulation and single-trial reaction time responses to target stimuli. This relation was evident for visual and tactile stimuli (but not auditory stimuli) and was more prominent in adults than children. Further, these relations were responsible for significant variance in executive function scores using a multi-level model. Results indicated that inter-individual differences in anticipatory sensorimotor mu modulation (not visual alpha or auditory tau rhythms) contributed to the significant association with executive function variability. I discuss anticipatory EEG oscillations as an empirical, quantifiable indicator of stimulus prediction, advancing anticipation as a bridge concept embedded in neuroscientific, behavioral, computational and developmental science.

DEDICATION

I dedicate my dissertation to families who made my research visions come to life with their participation, generosity, and curiosity. I am extremely indebted to and appreciative of the outrageous, incredible superhero kiddos who infused my PhD journey with absolute joy. I hope that my science feeds back to enrich the lives of these families somehow, or at least that the children's 'supersensory powers' endure, leaving a lasting impression of lab visits.

Reveries of the future often prompt action, while memories of the past tend to pause action. My work on anticipation chases the moment in between impulsivity and paralysis, wherein prediction guides activity. As I defend my dissertation at the (hopeful) peak of COVID-19 pandemic on March 30th, it might seem counter-intuitive to think about anticipation as adaptive. It has never been more apparent that our expectations remain an ever-fluctuating figment of our imaginations. In fact, the weight of anticipation in shaping cognition and motivating action is perhaps best demonstrated by the crushing psychological toll the 'cancellation' of the next month has taken on some. For others, including my family, the frightening, visceral medical toll of COVID-19 has shattered our illusions of linear, predictable existence as we recover and adapt.

With my dissertation, I hope to call attention to the process and state of anticipation as a force for organizing action and mental life. Prediction of this kind may serve as a foundation for stability within dynamic, ever-changing activity. I sincerely hope by unearthing the neural processes underlying the anticipation, we can shed light on the optimal range of self-regulation and unearth contextual influences that define and defy the ability to predict what is forthcoming.

ACKNOWLEDGEMENTS

I first זכור, remember with gratitude, the generations of endurance and sacrifice that my degree rests upon. I share the privilege of this achievement with my family, who have nurtured my self-expression, compassion, and actualization. My mother serves as my inspiration for studying the principles of sensitivity, accommodation, and resilience, at the very core of human development. My father has the wisdom of a co-PI and the patience of saint, interrogating the meaning of the concepts outlined in this dissertation. My brother infuses levity, wit, and drama into my performance as an academic. He also served as my first participant in an infant neuroscience experiment (ask us!). My family are my anchor amidst the seas of activity within and beyond me.

The foundations of my aspirations were laid at Geneseo, which as an institution managed to actualize the lofty ideals of the liberal arts agenda. From my freshman year, my outstanding advisors, Dr. Joan Zook and Dr. David Forman, nourished my curiosity, imparted enduring quantitative skills and a sharp empirical lens which shaped continues to shape my perspective. I am also thankful for research opportunities provided by faculty who took a chance on me, despite little experience: Dr. Daniel Klein, Dr. Michael Lynch, Dr. Wendy Berry Mendes and the late, wonderful Dr. Tristram Smith. These early experiences – along with my summers at Loyaltown, an extraordinary living monument to the beauty of variability and diversity - solidified my lifelong commitment to developmental science.

My journey through 22 years of education would not be possible without my kindred spirits, from colleagues who provided refreshing insight to friends who provided refreshment-infused reprieves from academia. From the bottom of my heart, I thank my incredible cohort of peer boss

ladies, Michelle Rosie, Lillian Masek, and Molly Scott, who were my rock and resource during the ups and downs of graduate school. Other dear friends at Temple, Motunrayo Olaniyan and Michelle Chiu, provided intellectual and emotional support when I needed it most. I also thank Michael Haupt for sparring ideas across our symbiotic trajectories of development and encouraging my sense of adventure.

Within my lab, I acknowledge the support of my colleagues and collaborators, Jebediah Taylor, Javier Albayay, Guannan Shen, Nathan Smyk and Rebecca Laconi, and a host of wonderful undergraduates who made this work possible, keeping me sane and smiling during more than 300 EEG lab visits. I also thank Valentina Parma, who is the definition of goal-oriented, for her wise, calming council and detailed feedback on my dissertation slides amidst COVID-19 chaos.

My graduate education at Temple University proved to be a cognitive revolution. I am very grateful for the support, advice and assistance of Dr. Nora Newcombe and Jason Chein, who provided direction and enthusiasm for my dissertation. Dr. Kathy Hirsh-Pasek served as a role model, epitomizing the notion of broader impact: her ability to connect, communicate and inspire while conducting research of impressive scope and scale have left a lasting impression. I benefitted immensely from conversations with countless others in our department's warm, inclusive intellectual environment, under the leadership of my advisor, Dr. Peter Marshall.

Peter embodies the optimal balance of scaffolding and autonomy of an ideal mentor: as a student, he treated me as a collaborator and contributor. Peter nurtured the seeds of my ideas to allow them to grow into projects grounded in the literature, yet ambitious and innovative in their reach,

allowing me to flourish as a budding scholar. My time working with Peter and our collaborator Dr. Andrew Meltzoff infected me with aspirations to tackle meaningful, theoretical questions accompanied by high standards for empirical approaches. Above all, Peter's spirited, rigorous, and optimistic approach to scientific inquiry is contagious, setting a high precedent I hope to follow for how to enact meaningful knowledge through developmental science.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
DEDICATION	iv
ACKNOWLEDGEMENTS	v
LIST OF TABLES	x
LIST OF FIGURES	xi
CHAPTER	
1. INTRODUCTION	1
Developing Anticipation: Foundations in Infancy.....	4
Attention and Executive Function in Childhood	8
Measurement of Executive Function in Childhood	11
Linking Selective Attention and Executive Function	13
Linking Neural Indices of Selective Attention to Cognitive Skills	15
Linking Neural Indices of Anticipatory Attention to Executive Function.....	18
Variability in Reaction time and Executive Function.....	20
Neural Indicators of Anticipatory Attention.....	21
Occipital Alpha Rhythm: Anticipation in the Visual Modality	26
Tempoparietal Tau Rhythm: Anticipation in the Auditory Modality.....	28
Cross-modal Audio-Visual Anticipatory Attention	30
Sensorimotor Mu Rhythm: Anticipation in the Somatosensory Modality	32
Prior Investigation: Executive Function and Anticipatory Mu ERSP in Children	33
2. CURRENT STUDY	36
Participants.....	38
Methods	40
Target Stimulus Parameters	44
EEG Acquisition and Processing.....	45
EEG Analyses	46
Cognitive Skills Battery.....	47
Statistical Analyses	48
3. STUDY RESULTS.....	51
Behavioral Analyses	51
Anticipatory Alpha ERSP Analyses	53
Visual Alpha	53
Sensorimotor Mu	53
Auditory Tau.....	54

Multi-level Analyses: Behavioral Outcomes by Alpha ERSP, Modality and Group.....	58
4. DISCUSSION.....	63
Interpreting Study Finding.....	64
Specificity of Effects and Study Limitations.....	67
Anticipatory Attention to the Body: Modality-Specific or Mu-Specific?	70
Broader Implications: Applications for Malleability of Selective Attention.....	74
Future Directions: Anticipation as a Framework for Cognitive Development.....	78
Conclusion: Anticipation as a Bridge in Developmental Science	81
REFERENCES	82

LIST OF TABLES

1. <i>Descriptive statistics for behavioral measures</i>	52
2. <i>Repeated measures ANOVA of anticipatory α ERSP by cue, hemisphere & age group</i>	57
3. <i>Multi-level mixed effects model of behavioral measures by neural measures</i>	61

LIST OF FIGURES

1. <i>Schematic of the selective attention protocol</i>	42
2. <i>Scalp maps of mean ERSP</i>	55
3. <i>Bar graphs of Alpha ERSP by modality, development and hemisphere</i>	56
4. <i>Anticipatory alpha ERSP by sensory modality, presented by age group and lateralization</i>	62

CHAPTER 1 INTRODUCTION

“The future is uncertain, ephemeral, non-existent (It hasn’t happened yet!)

How can we talk about a nonevent?

How do we think about brain processes that represent events that have not yet occurred?”

Marshall Haith, 1991

Anticipation serves as a foundational biological construct that bridges basic perceptual processes and higher-order cognition, allowing an agent to predict its future from prior experience (Clark, 1998; Ondobaka & Bekkering, 2007). Anticipation is a multifaceted phenomenon that encompasses cognitive processing, phenomenological experience, and physiological changes, accompanied by changes in brain and bodily activity as the individual prepares for predicted events (Butz, Sigaud, & Gérard, 2004; Allen & Friston, 2016). Using a Bayesian predictive coding framework, anticipation is indicated by biological and behavioral changes which optimize perception (Feldman and Friston, 2010) by integrating *prior knowledge*, such as expectations about upcoming events, with likelihood information from the immediate environment (Clark, 2013). Our understanding of anticipatory attention is defined by observable actions and activity, separating it from expectations, which serve as a cooccurring cognitive and affective state.

In 1994, a collection of developmental scientists including Marshall Haith proposed a ‘call for action’ that placed anticipation as a frontier ripe for investigation in developmental science (Haith, Benson, & Roberts, 1994). The authors challenged investigators to fulfill the following challenges: 1) to trace the trajectory of anticipation from infancy through adulthood; 2)

to identify the role of anticipation in nudging development and contributing to variability in behavior, 3) to interrogate anticipation future-oriented processing with as thorough and nuanced scope as has been dedicated to memory and past-oriented processing (Haith, Benson, & Roberts, 1994). This call has largely gone unanswered within developmental science, though the body of work on memory development has expanded exponentially (Ngo, Newcombe & Olson, 2018; Reynolds & Romano, 2016). Recent advances in neuroscience and cognitive science have come closer to tackling this challenge, with a literature focused on adults, intelligence and computational understandings of cognition (Clark, 2015; Pezzulo, 2012; McKinney & Euler, 2019). Here, we aim to fulfill the 25-year old call, by integrating these approaches to anticipation with relevant theory, literature and data in developmental science.

The ability to anticipate events and outcomes can be seen as central to cognition itself. From such a perspective, cognitive development becomes the process through which the individual acquires an increasing capability for prediction and self-regulation, defined as the prospective control of action (Vernon, 2014). The development of these prospective capabilities can be traced from the processes coordinating ocular control, bodily orienting responses and manual actions in infancy (Fausey, Jayaraman, & Smith, 2016; O'Regan & Noe, 2001), eventually cascading into variability in measures of cognitive and social development, including action imitation, language, and social interactions (Zukow-Goldring & Arbib, 2007; Yu & Smith, 2013). Here, it is posited that the emergence of these cognitive abilities involves improvements in anticipation, via its role during voluntary selective attention and action (self-)regulation. At a broad level, self-regulation can be considered an *allostatic* process that involves a system adjusting to impending events in a prospective manner. An anticipatory, allostatic mode of self-

regulation can be contrasted with a reactive, *homeostatic* mode that involves the sensing of changes in environmental conditions and responding to them (Vernon, 2014).

The goal of this document is to interrogate the role of stimulus prediction as a constitutive cognitive process, and to identify its contribution to variability in stimulus response within individuals and cognition ability across individuals (Howdy, 2013; Clark, 2017). One key premise of this document is that electroencephalographic (EEG) indices are particularly useful for their temporal specificity – necessary to separate neural activity before and after a target event – and as an index of modality-specific sensory anticipation and attentional deployment (Murphy, Foxe, & Molholm, 2016; Sadaghiani & Kleinschmidt, 2016). This connection is further bolstered by findings from a cross-sectional developmental investigation that scrutinized the relevance of anticipatory neural responses to the ‘control of action’. The control of action was assessed in two ways: (i) in a task-relevant, immediate context, codified by single-trial fluctuations in reaction time responses to target stimuli and (ii) as a functional, decontextualized individual difference, codified by executive function abilities, measured on a standardized cognitive battery. Executive function is the ability to plan, organize, and monitor the execution of goal-directed actions (Stuss, 1992; Zelazo et al., 2013). Operationalization of executive function tends to decontextualize it from its defining tenets: a) goal-oriented action, the preparing and directing of the body to achieve an envisioned end; and b) self-regulation, the exertion of internal will on the external environmental (Dick & Overton, 2009). Subsequent analyses scrutinize the development differences in the reciprocity embedded in the relation of executive function and anticipation.

An initial review seeks to connect a multi-level, multi-modal and multi-method understanding of anticipation to the existing literature on executive function development. First,

anticipation, typically defined by its embedding within contemporary cognitive science, is contextualized using evidence from its origins in developmental science. Literature linking the development of executive function to selective attention is then summarized. Next, the document reviews the anticipatory changes in oscillatory neural responses elicited during selective attention paradigms, in order to provide a candidate measure and task for assessing anticipation across development. The subsequent focus of the document shifts to a developmental investigation examining the fluctuations in the EEG oscillations immediately prior to child and adult participants receiving an auditory, tactile or visual target stimulus, following the orienting of attention by a spatially informative cue. As detailed below, anticipatory EEG signals following such a cue are sensitive to the salience and strength of the expected target stimulus and are predictive of subsequent perceptual report and stimulus processing speed (for review, see Luck & Kappenman, 2011; Frey, Ruhnau, & Weisz, 2014). Finally, it is argued further study of neural indices during anticipatory attention can inform understanding of how core cognitive abilities - processing speed and executive function - emerge, develop, and vary.

Developing Anticipation: Foundations in Infancy

Anticipation is a central pillar of the developmental process: Improvements in anticipatory capabilities and in the prospective control of actions are defining features of ontogeny and may be key to the development of self-regulatory capacities (Vernon, 2014). The ability to anticipate the result of self-directed movement begins to develop prenatally. Examining precursors of thumb-sucking using fetal ultrasounds, Reissland et al. (2014) found the proportion of anticipatory mouth openings evident *before* contact with the fetus' hand increased 8% with each week of gestational age, while reactive mouth movements decreased proportionally each week (Reissland, Francis, Aydin, Mason, & Schaal, 2014). Classic infant studies examined how

behavioral aspects of anticipation (e.g. ocular shifts, anticipatory looking) facilitate goal-directed actions (Haith, Hazan, & Goodman, 1988; Johnson, Posner, & Rothbart, 1991; Rochat & Hespos, 1996). In infants, children, and adults, a state of anticipation evoked by visual cues (preceding the presentation of visual targets) is associated with alterations in perceptual thresholds, in the detection of target stimuli, and in the extent of resistance to distracting stimuli (Posner & Rothbart, 2006; Markant & Ambroso, 2016; Short et al. 2013; Tenenbaum et al., 2011). Such evidence supports anticipation as foundational to the development of autonomous control of action, which is theorized to shift from largely reactive changes in an infant's immediate environment and bodily state, to the self-regulated attention evident in early childhood, in which children can act to exert deliberate, planned changes in their environment and to control or maintain their bodily state (Haith, 1998; Vernon, 2014; Aslin, 2014).

The use of a relevant preparatory cue preceding the presentation of a target stimulus allows behavior to be assessed during anticipation, prior to a response to the target. Infants exhibit indicators of anticipation by orienting their eyes, heads, hands and bodies in expectation of changes in their immediate environment, reflecting underlying alertness and attention (Amso & Johnson, 2006; Yu & Smith, 2016; Johnson, 2010). Measures of anticipatory attention in infancy are typically derived from video coding of overt actions (e.g., ocular shifts, anticipatory head turns, hand movements etc.) or eye-tracking measures of gaze fixation, with both being leveraged to understand the associations between predictive gaze and anticipatory adjustments of the body in preparation for action.

Early studies of anticipation focused on its role in perception and action (Haith, Hazan & Goodman, 1988; Johnson, Posner, & Rothbart, 1991; Rochat & Hespos, 1996). More recently, behavioral measures of anticipation in infancy have been used to predict the later development of

self-regulation, motor control, and temperament traits related to executive function (Papageorgiou et al., 2014; Reddy, Markova, & Wallot, 2013; Sheese et al., 2008). In newborns, duration of anticipatory gaze has been found to be sensitive to stimulus features, novelty preferences and prior learning (Gomes, et al., 2000). Individual differences in 6-month-olds' anticipatory gaze fixation appear related to childhood temperament traits involved in executive function (Papageorgiou et al., 2014). The ontogeny and concomitants of anticipation in modalities other than visual are not well-defined; correcting this omission is critical to understanding whether anticipation is in fact a multi-modal indicator of attention or whether acuity and reactivity in the visual domain alone account for these relations.

The importance of anticipation extends throughout domains of development, including social development: Children's ability to anticipate caregiver reactions to their own actions may be critical to facilitating high-quality parent-child interactions, engendering shared meaning (Truswell et al., 2016; Cartmill et al., 2013), joint attention (Hirsh-Pasek et al., 2015; Yu & Smith, 2013), and synchrony in the timing of actions (Feldman, 2012). There is abundant behavioral evidence that within the first year of life, infants adjust preparatory actions to reflect understanding of the goals of an actor (Brandone et al., 2014; Cannon & Woodward, 2012; Stapel, Hunnius, & Bekkering, 2015) suggesting that infants anticipate the consequences of their own and other's action sequences (Meltzoff, 1988). For example, infants can enact an intended, goal-directed action series rather than faithfully imitating an observed failed action (Brandone & Wellman, 2009; Repacholi et al., 2014; Hunnius & Bekkering, 2014). Infants as young as two months old exhibit significant anticipatory adjustments of their bodily position and posture in expectation of touch from caregivers compared to infant-directed speech from caregivers, but only four-month-old infants significantly directed their gaze towards parents' approaching hands

(Reddy, Markova, & Wallot, 2013). At three months of age, infants fixate longer on familiar objects rather than familiar locations in preparation for actions performed on the object (Sommerville, Woodward & Needham, 2004). Falck-Ytter, Gredeback, and von Hofsten (2006) measured anticipatory gaze via eye tracking in 6- and 12-month-old infants as well as adults. After watching videos of an adult placing a ball at a target location, adults and 12-month-old infants exhibited anticipatory eye movements towards a target location they observed a hand make contact with a ball, but 6-month-old infants did not. Prior experience with live demonstrations may differ from video observations for 6-month-olds; in a similar study (Kanakogi & Itakura, 2011), the grasping ability of 4- to 10-month-olds was assessed and compared with their anticipatory shifts in gaze when observing a human hand grasp a toy, an inanimate object grasp a toy, and a human hand making contact with toy without grasping it. In only the first condition, a gradual increase in goal-directed, anticipatory eye movement towards the toy *before* the hand made contact was observed in 6- to 10-month-olds infants and was correlated with infant's grasping abilities, while 4-month-olds exhibited minimal goal-directed anticipatory eye movements and grasping abilities (Kanakogi & Itakura, 2011). These findings are interpreted as evidence that prior experience with an action influences anticipatory behavior in infancy, with biases in anticipatory eye movement and action specific to goal-directed actions performed by humans (Csibra, 2008).

Taken together, this literature suggests that towards the end of the first year of life, infants can dynamically regulate their own actions to align with predictions. Though anticipation is a popular topic of study in infancy, its developmental trajectory through childhood and association with other aspects of cognition has yet to be elucidated. The early emergence of anticipatory capacities can be leveraged to study its potential role in facilitating later-developing

cognitive functions (e.g. executive function, theory of mind and language) and prospective control of goal-directed action, which are the hallmark of organized behavior in childhood (von Hofsten, 2004; Kraybill & Bell, 2013; Veer et al., 2017)

Attention and Executive Function Under Development

The identification of potential precursors of executive function abilities in childhood is an important area of investigation in developmental science (Garon, Bryson, & Smith, 2014; Markant & Amso, 2016; Hendry, Jones & Charman, 2016; Holmboe et al., 2017), in part because of findings that early executive function abilities are a predictor of health outcomes, social adjustment, and emotional well-being in later life (Moffitt et al. 2011). By comparison, less is known about the more basic functions and individual differences in foundational attentional abilities, including anticipation, on which higher-order executive abilities might depend.

The attention network model (Posner & Petersen, 1990; Posner & Rothbart, 2007) is one prominent attempt to operationalize attention into its cognitive components, detangling the muddled concepts of executive attention, self-regulation and explicit memory in order to quantify the ability to “bring to mind” material for manipulation. This model describes three neural systems that dictate attention deployment and that develop sequentially from infancy to childhood (Johnson, Posner & Rothbart, 1991): (i) the alerting network, which maintains a level of cognizance ahead of incoming stimuli; (ii) the orienting network, which involves the ability to attend to information in a selective, focused, goal-directed manner, facilitating the updating and shifting of attentional priorities; (iii) the executive attention network, encompassing executive function abilities, involves the ability to resolve cognitive conflicts between competing

responses, to monitor and correct errors using internal reasoning and external feedback, and to plan and execute novel responses, tailored to environmental demands. The self-organized regulation of attention that is characterized as ‘orienting’ by 6 months of age relies on the experiences infants that accumulate in their first 6 months, which are marked by increases in infant awareness and arousal (‘alerting’); subsequently, the balance between bottom-up ‘alerting’ and top-down ‘orienting’ skills in the years of life contributes to the emergence of executive attention, in which goals directly influence the target of children’s focus. By the third year of life, goal-directed deployment of executive attention lends itself to the goal-direction action, measured by executive function. Executive function abilities involve the integration of predictions, preferences and prior experience with the immediate demands of the environment: Beyond active selection of certain features (executive attention), executive function involves the adaptive implementation of action in an organized, strategic manner, guided by the anticipated outcome and impact of planned action.

As summarized by the attention network model of Posner et al. (2012), which is accumulating empirical support (Veer et al., 2017), the development of higher-order executive function abilities relies on the successful orienting of attention in a focused, deliberate manner in infancy. Executive function, defined as the ability to plan, organize, and monitor the execution of goal-directed actions (Zelazo et al., 2013), supports the voluntary self-regulation of attention and behavior (Blair & Raver, 2015; Diamond, 2013). The central role of emerging executive function skills in early school achievement has been well-characterized (Diamond, 2013; Blair & Razza, 2007). Further, a critical body of work has documented how persistent disparities in executive function ability align with socio-economic status (SES) stratification (Raver, Blair, & Willoughby, 2013).

Executive function is understood as the constellation of cognitive skills involved in regulation of one's attention and actions in the pursuit of a goal. The planning, monitoring, and regulating of action skills foundational to executive function emerge gradually across infancy, becoming refined in early childhood (Nigg, 2017; Gottwald et al., 2015; Hendry et al., 2018; Ruff and Posner, 2006; Garon et al., 2008). By the preschool years, children demonstrate intentional actions and inhibition consistent with executive functioning (Carlson, 2005; Isquith, Gioia, & Espy, 2004; Blair, Zelazo & Greenberg, 2016). Variation in performance on early measures of executive function, particularly delay of gratification, has predictive value across multiple domains of development (Shoda, Mischel & Peake, 1990; Lin, Liew, & Perez, 2015; Zelazo, 2015). Executive function skills are critical for success in school, as children who are better able to regulate their behavior and attention are better equipped to adhere to classroom expectations and exhibit the focused attention conducive to information retention (Blair, 2002; Weiland et al., 2014; Zelazo, 2015). The literature holds that although executive function skills emerge during the preschool years (Garon, Bryson, & Smith, 2008; Diamond et al., 2013) and by age six years stably predict later cognitive skills and academic performance (Blair & Razza, 2007; Bull & Scerif, 2001; Fuhs et al., 2014), they remain an undifferentiated, unitary factor around age 10 (Miyake et al., 2000). Executive function difficulties are posited to be a source of cumulative risk for cognitive delay due to their predictive power across various developmental domains (Jacobson, Williford, & Pianta, 2011). However, executive function measures between the second and fourth years appear to have less reliability and less psychometric consistency across large samples, as compared to measures of executive function in later childhood (Wiebe, Espy, & Charak, 2008; Wiebe et al., 2011).

Measurement of Executive Function in Childhood

Executive function batteries in older children typically include assessments spanning multiple neurocognitive capacities, with facets of working memory, cognitive flexibility and inhibitory control (Miyake et al., 2000; Diamond, 2013) differentiated by latent measurement models in children older than ten years of age. Working memory refers to the ability to retain and manipulate information, while cognitive flexibility includes the sustaining or shifting in attention in response to different demands or to apply different rules in different setting, and inhibitory control dictates attentional priorities and restraint of impulsive actions (Miyake & Friedman, 2012). Executive function task batteries typically index multiple of these cognitive processes, particularly in children when they are overlapping, in order to quantify the latent variability shared across executive function abilities (Zelazo et al., 2013).

General executive function abilities can be indexed by “marker” tasks that involve the coordination of competing attentional priorities. For example, the task demands of the widely used Dimensional Change Card Sort (DCCS) involve all three domains of executive function (Frye, Zelazo, & Palfai, 1995; Beck, Schaefer, Pang, & Carlson, 2011; Zelazo, 2006). Directed to match the central test stimuli with one of two lateralized target stimuli by shape or color, child participants on the first block of the task sort the cards by one dimension, and on the next block sort the same cards by the other dimension. Younger and older preschoolers typically sort by the first rule without error, but when the dimension changes, only older preschoolers adjust their behavior accordingly, indicating flexible control of attention, task switching, and restraint of prior rule (Muller et al., 2006; Zelazo, 2006). Another widely used example is the Flanker task, in which participants indicate the direction of a central arrow that was presented between distractor or ‘flanker’ arrows. The direction of arrows is randomized by trial, such that the

flanking arrows are alternatively congruent or incongruent with the target central arrow.

Compared with the DCCS, the Flanker is considered a more specific ‘conflict’ task: it primarily indexes inhibitory control (Diamond, 2013), such that incongruent conditions are associated with slower reaction times, which is explained as participants reconciling the conflict between the target and distractor.

Similar to the inhibitory control component of executive function, effortful control involves the restraint of prepotent responses and is assessed by tasks demanding regulation of bodily actions, such as delay of gratification (Moffitt et al., 1990; 2011), Bear-Dragon, a derivative of Simon Says (Carlson, 2005; Garon, Smith & Bryson, 2014), and infant measures of motor control (Gottwald et al., 2016). In contrast to the cognitive accounts and neural concomitants associated with executive function during the school years (Miyake & Friedman, 2012), effortful control is typically studied as a core feature of temperament in toddlers and predictor of socioemotional development (for an excellent review, see Hendry, Jones & Charman, 2016). Accommodations in executive function, which make task demands appropriate for assessment of younger children’s self-regulatory capacity, often do so by invoking effortful control. For example, the classic Stroop test which is widely used to measure executive function in adults, is modified for participants under 3 by requiring children to override an existing association; children are asked to respond “Night” when shown an image of a sun, and “Day” when shown an image of the a moon (Carlson, 2005; Gerstadt, Hong, Diamond, 1994). It is speculated here that such measures of inhibitory/effortful control may build upon anticipatory abilities developed in infancy, as they involve the suppression of prior accounts of the environment in order to withhold impulsive actions in favor of novel or unintuitive actions. The early emergence of bodily awareness and control of goal-directed actions (which are implicitly

tested in most effortful control measures) may explain how these tasks capture meaningful, longitudinally-stable variation in self-regulatory capacity, ahead of formal development of executive functions (Dick & Overton, 2009; Pezzulo, 2012; Hendry et al., 2016).

Similar to the sequential development of attention (Posner, 1990), the developmental cascade of executive function has been proposed to follow a specific sequence, paralleling the three-factor model evident in 10 year-olds and adults (Isquith, Gioia, and Espy, 2004; Miyake et al., 2000): from infant's capacity for inhibitory control, to adaptive shifting of behavior evident in toddlers, to pre-school children's precocious ability to manipulate items in working memory (Carlson, 2005; Hendry et al., 2016; Gottwald, 2016). Such a pathway has been offered to explain how executive function abilities transition from apparently 'offline' to 'online': these terms refer to the shift in child behavior from action-oriented responses to semantically-oriented 'representations' (Diamond, 2013; Best, Miller & Jones, 2009). However, it has also been noted that such accounts fail to fully consider the active role of the child in steering their own attention (Dick & Overton, 2009).

Linking Selective Attention and Executive Function

Selective attention, the prioritized processing of relevant features in the environment, is a key construct implicated in the development of higher-order cognitive skills (Posner & Rothbart, 2009; Amso & Scerif, 2015). Anticipatory activity, which can indicate a state of selective attention, is temporally constrained by its proximity to an imminent, expected event rather than orienting, which is defined by its proximity following a prior event (typically, a spatial cue). Children's performance on visual selective attention tasks at two years of age accounts for significant variation in their emerging executive function abilities at three years (Veer et al., 2017). Recent work suggests that cues are more effective at tailoring visual selective attention in

adults than children, with 5-year-old children showing greater recall of uncued non-target stimuli than adult participants (Plebanek & Sloutsky, 2017). In a seminal study, Goldberg, Maurer and Lewis (2001) found that by eight years of age, children's target discrimination accuracy on a visual selective attention task was comparable to adults when facilitated by a preparatory cue. However, when visual targets were presented in the cued spatial location alongside simultaneous visual distractors in the other visual hemifield, children's accuracy suffered. This study suggests that there may be discrepant trajectories between anticipation and distractibility, which appears to develop more gradually.

Furthermore, there is recent evidence that individual differences in selective attention accounted for variability in 4- to 5-year-olds task-switching ability, as indexed by a Card Sort task (Benitez et al, 2017). These authors suggest that cues enact both a focus of attention in expectation of upcoming stimuli and simultaneous inhibition of information to distractor information, explaining children's difficulty with the Card Sort task, since information matching the target is embedded within distractors. The authors identify the ability to manipulate, focus and refine the 'spotlight' of attention in childhood (Posner & Rothbart, 2009) as critical to the development of the self-regulation and cognitive flexibility indexed by the Card Sort task (and perhaps, executive function more broadly), explaining, "Flexible behavior may emerge, in part, from the same processes that underlie stability, including processes that narrow attention to a single source of information and processes that sustain attention on a single source of information." (Benitez et al, 2017, pg. 40).

Growth trajectories of children's cognitive abilities (Klenberg, Korkman & Lahti-Nuutila, 2002) have provided evidence for separable, sequential developmental trajectories of impulse control, attentional control and executive control, lending empirical support to the model

proposed by Posner et al. (1990; 2012). Klenberg, Korkman, and Lahti-Nuuttila (2002) suggest that the interrelations among these self-regulatory processes may be attributed to the reconciliation of the environment with top-down predictions (Muller et al., 2006).

In reviewing the literature on linkages between selective attention and executive function, we suggest anticipatory attention as one candidate precursor to executive function, such that individual differences in anticipatory abilities may account for common variability across domains of functioning. However, there is a dearth of research on anticipation in childhood, beyond infancy. Although anticipatory capacities are present very early in life, the fronto-parietal attentional networks that support the ability to selectively attend to information, particularly in the presence of distractors, continue to develop throughout childhood (Karns et al., 2015). We suggest that electrophysiological indicators of these relations can tease apart how endogenous, ‘top-down’ anticipatory attention from responses elicited by exogenous, ‘bottom-up’ attention during processing of stimuli contribute to ultimate control of behavior and action (Chica, Bartolomeo, & Lupiáñez, 2013; Macaluso et al., 2013).

Linking Neural Indices of Selective Attention to Cognitive Skills

Neural indicators of selective attention are associated with heightened sensory processing (Awh et al., 2000), and lower thresholds for perception of stimuli (Anderson & Ding, 2011; Posner & Driver, 1992). Accumulating evidence suggests that neural measures of selective attention account for significant variance in performance on cognitively demanding tasks (Posner & Rothbart, 2007; Gazzaley & Nobre, 2012), with focused attention regulating activity in primary sensory areas by enhancing target-relevant information and reducing target-irrelevant information (Iguchi, Hoshi, Tanosaki, Taira, & Hashimoto, 2005; Sarter, Gehring, & Kozak, 2006). Neuroimaging research suggests that this shift relies on the frontal-parietal attention

network, which modulates other brain areas in the service of task demands (Lepsien & Nobre, 2006). This leads to a narrowing of the attentional “spotlight” to a target (Posner & Raiche, 1995).

Coch, Sanders, and Neville (2005) studied EEG responses associated with selective attention in children aged 6-8 years using a dichotic listening task in which participants listened to different narratives presented to the right and left ear and were told to pay attention to only one story. The authors embedded identical target tones in the attended and unattended simultaneous auditory streams and studied the event-related potential (ERP) evoked in response to these auditory stimuli. They found a slow positive ERP component peaking around 150 ms, and reported that the indeed the amplitude of this component was greater in the attended auditory stream than the unattended auditory stream. In preschoolers undergoing the same paradigm, Isabel, Wray and Neville (2015) found that the amplitude of ERP responses to attended stimuli were related to children’s cognitive ability, such that only preschoolers with higher IQ scores differed in their brain response to tones in the attended stream, compared to the unattended stream. As indicators of auditory selective attention, it has been suggested that these ERP responses to target stimuli are malleable to intervention (Neville et al., 2013; Isbell et al., 2017). Similarly, in adults, the amplitude of the early sensory components and late ERP evoked during the dichotic listening task are related to measures of non-verbal working memory (Giuliano et al., 2014).

A relevant study by Ruberry et al. (2016) found that the magnitude of ERP components elicited by executive function tasks (specifically, a flanker task and a go/no-go task that indexes behavioral inhibitory abilities) accounted for significant variance in children’s performance on broad battery of executive function, beyond the effects of family income and demographic

factors. However, ERPs measured during executive function tasks have limited generalizability to behavior in that they are acutely sensitive to perceptual features of task stimuli, in contrast to EEG signals during selective attention, which can be tied to attentional state and attention deployment more broadly (Ruberry et al., 2016). Investigations of selective attention in childhood typically focus on EEG or behavioral responses *following* presentation of the target stimulus, with event-related responses compounded by the presentation of simultaneous distractors which compete for attention allocation (Markant & Ambroso, 2016; D'Angulli et al., 2008), or during a baseline period, when children fixate on a constant visual stimulus.

We now focus our attention to the neural measures elicited during selective attention paradigms, in which a spatial cue elicits anticipation of a singular stimulus. Individual differences in target stimulus response time as well as target stimulus detection accuracy are common behavioral measures of performance on selective attention and executive function tasks (Willoughby, 2018). It is speculated that variation in these measures may be partially attributed to individual differences in the ability to adaptively prepare for a stimulus as a function of trial-by-trial task demands. This builds on the proposal that anticipation as a key component process in determining the regularity with which participants filter and focus their attention to an upcoming stimulus. When compared across participants, anticipatory abilities may index how dynamic prediction (the strength of prior experience) informs perception of upcoming, cue-directed sensory events (Euler, 2018; Holmboe et al., 2018). However, there is limited work characterizing individual differences in behavioral and neural indices of anticipation in childhood or its potential relations with executive function and selective attention.

Linking Neural Indices of Anticipatory Attention to Executive Function

One suggestion arising from work in cognitive neuroscience linking selective attention and executive function is that “lower-level” indicators of attentional processing reciprocally influence “higher-level” cognitive abilities (Gazzaley & Nobre, 2012; Tarantino et al., 2017). One key to understanding this relation is to separate exogenous responses elicited by cue and target stimuli from endogenous activity that characterizes anticipatory attention. Classic neuroimaging work has revealed localized anticipatory biases in areas of human visual cortex that facilitate subsequent processing of a target stimulus (Kastner et al., 1999). Further research has shown that such biases are not simply sustained, static signals, with anticipatory neural activity more flexible, adaptive, and dynamic than previously assumed (Kok et al., 2012).

Selective attention tasks can invoke anticipation by incorporating a preparatory cue that conveys information (e.g., spatial location or modality) relevant to an impending target stimulus (Jensen & Mazaheri, 2010; Posner, 1980). One early study adopting such a paradigm found that the amplitude of a preparatory ERP component during anticipation of visual stimuli differed in children with ADHD and without ADHD, such that children diagnosed with ADHD did not exhibit an anticipatory negativity in expectation of a visual target (Perchet et al., 2001). To our knowledge, only one recent set of studies investigated the relations between *anticipatory* electrophysiological indices and higher-order cognitive functions in children. In 10-year-olds, Schimi and colleagues (2014; 2015) found that anticipatory ERP responses in the hemisphere contralateral to a visual cue were related to visual working memory capacity. They reported that children with greater working memory capacities exhibited greater ERP amplitude elicited by a visual cue (Schimi et al., 2015) followed by enhanced modulation of anticipatory negativity components (Schimi et al., 2014), which were significantly different in amplitude compared to children with lower working memory

performance. In contrast, adult anticipatory EEG responses in the ipsilateral hemisphere only were related to working memory performance and college GPA (Zanto & Gazzaley, 2009). However, these studies utilized cues and target stimuli in the same modality (visual), making it difficult to isolate exogenous shifts in neural activity evoked by the cue from anticipatory, endogenous activity related to the expectation of the target (Kouider et al., 2015). Another issue is that developmental work to this point has typically focused on EEG or behavioral responses following presentation of the target stimulus, and often involves the presentation of simultaneous distracting stimuli (Markant & Amso, 2016; Veer et al., 2017).

Increasingly, attentional control and maintenance are understood as arising from predictions, represented by anticipatory neural responses that are situated in prior experiences, actions and cognitive capacities (Engel, Fries & Singer, 2001; Clark, 2015). By leveraging EEG indicators of anticipatory attention, the current study aimed to extend the understanding of children as active agents in their own self-regulation, with anticipation serving as a potential demonstration of children's ability to integrate their attention with their behavior (Haith, 1998), rather than viewing anticipation as a reflexive response unique to the visual system (Aslin, 2014). With this goal in mind, the following section summarizes the literature on oscillatory EEG signals that are modulated both in anticipation of a sensation and in response to cognitive demands (Basar, 2012; Arnal & Giraud, 2012), in order to advance the position that neural responses during prediction of simple sensations are integral to (the development of) higher-order regulation of cognition and behavior (Foxye & Snyder, 2011; Scheeringa et al., 2009; Schimi et al., 2014).

Variability in Reaction time and Executive Function

Single trial reaction times index intraindividual variability and individual differences in general speed of processing, which contribute to – but are distinct from – EF skills (Willoughby et al., 2018). Unlike complex processing speed measures, reaction time measures do not make demands on executive processes (Cepeda, Blackwell, & Munakata, 2013). Coordination of actions in response to stimulus detection, in a task-relevant manner consistent with participant goals, experimenter instructions or tangible rewards, undergoes a protracted period of development, with prominent changes evident during early childhood (Kail, 1991, 2007; Kail & Ferrer, 2007). Developmental improvements in reaction time are attributed to changes in white matter (Chevalier et al., 2015; Scantlebury et al., 2014). Individual differences in reaction time and related processing speed measures that emerge in infancy and toddlerhood predict children's later performance on EF tasks (Rose, Feldman, & Jankowski, 2011, 2012). Consequently, reaction time may be an especially good candidate to serve as a control variable for inclusion in EF assessments of young children.

Furthermore, reaction time to stimulus detection has been consistently associated with adult preparatory neural responses during stimulus anticipation, following a spatial cue (Sauseng et al., 2009; Jensen & Mazaheri, 2010; Romei, Gross & Thut, 2010; Scheeringa et al., 2009); in children aged 7-10, there is less consistent evidence for such an association. The relation between reaction time to target stimulus detection and anticipatory alpha-range oscillations was not significant for visual (Vollebregt et al., 2015), auditory (Murphy, Moholm & Foxe, 2016) and tactile (Weiss et al., 2018) target stimuli. There may be greater intra-individual differences responsible for the failure to detect an effect in children, whereas adults may have a more consistent neural response in anticipation of stimuli. The association of stimulus reaction with

neural indicators of anticipation will be further explored in the next section, with a mind to implications for higher-order cognitive skills and development differences in this relation.

Neural Indicators of Anticipatory Attention

The human brain exhibits patterns of rhythmic oscillations, which occur at similar temporal and spatial scales across species (Buzsáki & Draguhn, 2004). Typical time-frequency decomposition methods apply Gaussian-curve sinusoidal signal processing methods to identify systematic changes in neural response. Neural oscillations have been clustered into frequency bands, including delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (15-30 Hz), and gamma (30-90 Hz). These bands roughly correspond to frequency ranges commonly observed in human electroencephalography (EEG). These oscillatory bands are believed to play an active role in neural communication (Fries, 2005; Lopez Da Silva, 2013) and functionally distinct roles in coordinating action and perception, as well as multi-sensory stimulus processing.

Anticipatory neural activity can be seen as bridging pre-stimulus attention and post-stimulus perception (Sebanz, Bekkering, & Knoblich, 2006), associated with top-down attention deployment and selective monitoring of environment (Engel, Fries & Singer, 2001; Arnal & Giraud, 2012). Electrophysiological studies have shown the modulation of EEG and ERP signals during anticipation of visual (Gazzaley & Nobre, 2009), auditory (Weisz et al., 2011) and somatosensory (Jones et al., 2010; Shen et al. 2017) target stimuli. Such modulation is evident when a preparatory cue is presented in a different sensory modality from that of the expected target, which allows temporal and spatial differentiation of anticipatory activity in the target sensory cortex from neural responses elicited by the cue and the target stimulus (Weisz et al., 2011; Mazaheri et al, 2013; Foxe & Snyder, 2011).

Paradigms that involve anticipation of visual stimuli have typically employed variations of the Posner paradigm, in which a central preparatory cue is displayed to direct the participant's attention to one visual hemifield that will contain a visual target; simultaneous presentation of visual targets to both hemifields invokes selective attention (Posner, 1980). Studies utilizing functional magnetic resonance imaging (fMRI) have found that preparatory cues in the Posner paradigm uniquely engage the intraparietal sulcus to apply a filter on attention, which is not active in subsequent processing of perception of target stimuli (Corbetta & Shulman, 2002). Dynamic causal models have implicated the fronto-parietal attentional network as also critical to visual anticipation, identifying functional connectivity between frontal eye fields to the ipsilateral parietal sulcus, and then feeding into activity in the occipital cortices (Bresler et. al, 2008). Source localization methods have identified generators of anticipatory EEG activity in the sensory cortices that encode *upcoming* target stimuli features, as well as in the fronto-parietal attentional network (Simpson et. al, 2011).

Fluctuations in attentional states are tracked by the modulation of EEG oscillations, which index rhythmic changes in the polarity of cortical tissue (Buzsáki, 2019). The oscillations apparent in the EEG signal are speculated to arise from fluctuations in polarity of cortical tissue, which reflect the shifting balance of postsynaptic potentials released by assemblies of pyramidal cells and inhibitory (GABAminergic) interneurons (Lopes da Silva, 2013; Cohen, 2016). The homeostatic balance of oscillatory activity during baseline or rest is disrupted by expectation or presence of a stimulus. Changes in amplitude, phase and frequency of oscillations evoked by a discrete event can be computed using event-related spectral perturbation (ERSP), in which sinusoidal wavelets are used to estimate the shift in amplitude and phase of the data in each successive, overlapping time window (Pfurtscheller & Lopes da Silva, 1999; Delorme &

Makeig, 2004). ERSP is theorized to track the temporal sequence of postsynaptic potentials discharged synchronously from a particular neuronal population (Klimesch et al., 1998; Pizzagalli, 2007; Lopes da Silva, 2013).

Analysis of EEG activity during tasks (as opposed to during “baseline” or rest periods) often focuses on changes in spectral power in specific frequency bands (Klimesch, Sauseng, & Hanslmayr, 2007), which are functionally dissociable. Recent years have seen continued interest in oscillatory activity in the alpha frequency range (8-12 Hz) in relation to various aspects of cognitive functioning (Zanto & Gazzaley, 2009; Klimesch, 1999; Sadaghiani & Kleinschmidt, 2016). For example, a simultaneous fMRI-EEG study observed increases in alpha-range ERSP relative to baseline while encoding visual stimuli to be later recalled on a working memory task; as working memory load increased, alpha ERSP linearly increased during encoding, which was associated with greater modulation of the hemodynamic response in the primary visual cortex and the middle temporal gyrus (Scheeringa et al., 2009). Sauseng et al. (2011) showed that the pairing of prior events with a cue was accompanied by stronger alpha synchronization at prefrontal and occipital regions, indicating functional coupling. These results suggested that increased frontal alpha power indicates the control of posterior cortical activation by anterior brain areas. This is one way in which fast-wave frontal activity could influence both top-down and bottom-up attentional control through Posner’s posterior attentional network (thalamus, superior colliculus, and parietal lobe; Banich et al., 1997)

As the most prominent oscillation in the EEG (Berger, 1932), the alpha rhythm was originally associated with an ‘idling’ state but is now seen as reflecting more active sensory and cognitive processes (Klimesch et al., 1998). Contemporary accounts of alpha-range activity are often grounded in the inhibition-timing hypothesis (Klimesch, Sauseng, & Hanslmayr, 2007;

Foxe & Snyder, 2011) which posits that increases in the amplitude of alpha oscillations arise from synchronized timing of cortical firing in an underlying neural population. Synchronization of the alpha rhythm is associated with the ‘gating’ or inhibiting of unnecessary features in the immediate environment, ‘turning the mind inward’ rather than sharpening perception (Jensen & Mazaheri, 2010; Romei, Gross & Thut, 2010; Scheeringa et al., 2009). From this perspective, decreases in alpha power are thought to reflect the deployment of attention to specific features of the environment, thus facilitating perception.

In preparation for, or in the wake of, a stimulus, the (default) synchronized state that characterizes rhythmic alpha oscillations is disturbed (‘desynchronized’) by the signal from a select group of neurons (i.e. those with spikes in polarity of extracellular membrane in wake of a postsynaptic potential). Hence, neural activity is biased to prioritize expected events in selective spatial locations and sensory modalities, which optimizes the processing of forewarned events (Banerjee, Snyder, Molholm, & Foxe, 2011; Lopes da Silva, 2013; Arnal & Giraud, 2012). Global *increases* in alpha power from baseline reflect inhibited sampling of sensory events, permitting concentrated cortical firing by neurons in the relevant sensory cortex. The resulting *decreases* of alpha power that reflect a ‘release from inhibition’ and adaptive adjustment in the sampling of sensory events to match the expected temporal and spatial presentation of an upcoming stimulus (Schroeder and Lakatos, 2009; Frey, Ruhnau, & Weisz, 2014). Thus, sequential, selective gating of neural activity supports effective prediction of and reaction to upcoming sensory events, resulting in its coupling with behavioral indicators of selective attention deployment, such the accurate detection and speed of responses following stimulus presentation (Schroeder et al., 2010; Klimesch, 2012).

In summary, changes in alpha oscillations are thought to reflect ‘top-down’ attentional control. Selective inhibition of neuronal excitation by interneurons results in global increases in the amplitude of alpha oscillations. These inhibitory processes give rise to conditions that allow the filtered (sensory-specific) and gated (lateralized) dynamics of cortical firing, such that a higher proportion of excitatory post-synaptic potentials can be released by pyramidal cells in the relevant primary sensory cortex. This reorganizes the sequential processing of information in a manner consistent with predicted sensory events, thus allowing ‘goals’ to orient sensory processing (Kerr et al., 2013; Buzsáki, 2006, 2019).

Examining fluctuations in alpha power has been particularly useful in the study of anticipatory attention: when attention is directed by a spatial cue to monitor one visual hemifield, one ear, or one hand in anticipation of stimulation of that location, there is a reduction of alpha power (also known as an event-related desynchronization or ERD) observed over the contralateral sensory cortex (Sauseng et al., 2005; Weisz et al., 2011; Zhang & Ding, 2011). Understood from the inhibition-timing hypothesis, lateralized alpha modulation is evident following a spatial cue – when a stimulus is expected but not yet presented – is the product of top-down attentional signals from frontoparietal attention networks (Clayton, Yeung, & Kadosh, 2015; Sadaghiani & Kleinschmidt, 2016; Jensen & Mazaheri, 2010). These modulations of EEG power mediate an increase in local sensory cortex excitability, which in turn increases the perceptual salience of incoming stimuli (Foxe & Snyder, 2011; Zhang & Ding, 2010). This pattern of anticipatory ERSP modulation is evident in visual, auditory, and tactile modalities across regionally specific alpha-range rhythms (Frey, Ruhnau, & Weisz, 2014; Arnal & Giraud, 2012; Shen et al., 2017) which in other contexts, exhibit dissociable properties and appear to operate independently (Mazaheri, Nieuwenhuis, van Dijk, & Jensen, 2009). There is speculation

drawn from unimodal or cross-modal studies that alpha modulation functions ahead of stimuli processing using a supramodal gating mechanism (Foxye & Snyder, 2011; Banerjee et al., 2011); to examine this account of anticipatory neural activity, the following section reviews alpha-range ERSP studies of visual, auditory, cross-modal and visuospatial-tactile stimuli, with a particular focus on studies investigating oscillatory alpha activity in relation to cognitive development.

Occipital Alpha Rhythm: Anticipation in the Visual Modality

It has been speculated that anticipatory alpha range activity over posterior scalp regions in preparation for visual stimulation is driven by a coordinated dorsal system that orients voluntary attention to the cued visual hemifield, while the ventral system monitors the uncued hemifield for unexpected stimuli (Capilla et al., 2012). This phenomenon is well characterized in adults, with lateralized desynchronization of the visual alpha rhythm over occipital sites following a cue to expect visual stimulation in the left or right visual field (Worden et al., 2000). Visual discrimination abilities are associated with anticipatory occipital alpha activity (van Dijk et al., 2008; Bengson et al., 2012). Transcranial magnetic stimulation has provided additional evidence for the causal role of anticipatory oscillatory alpha-range activity in actively shaping online visual perception (Romei, Gross, & Thut, 2010). The authors suggest that the state of anticipation modulates cortical excitability, such that biases in perception indexed by alpha oscillations reflect expectations about the timing and spatial specificity of stimulus content, rather than the feature content of incoming information (Rohenkohl & Nobre, 2011; Nobre & van Ede, 2017).

Reductions of alpha power are evident during visual attention within the first year of life (Stroganova et al., 1999), with significant modulation evident in 4-month-olds following the presentation of a face compared to periods of inattention (Michels et al., 2015). Xie, Mallin, and

Richards (2017) examined alpha desynchronization during fluctuations of infant attention, using variability in heart rate to discern between orienting, sustaining, and terminating states of visual attention in 6 to 12-month-olds. The authors reported significant alpha desynchronization associated with sustained attention in 10- and 12-month-olds, but not in younger infants. This study did not include an anticipatory component: indeed, anticipatory modulation of the occipital alpha rhythm has not yet been documented in infancy.

In older children, a prior study of unimodal visual selective attention in 7- to 10-year olds (Vollebregt et al., 2015) found that magnitude of posterior alpha-range ERD during anticipation was largely not associated with reaction time in target detection, except when the spatial cue was invalid, in which case children with greater alpha ERD were *less* flexible (exhibiting significantly slower reaction time) in adjusting the focus of their attention. The authors' interpretations conflict with the functional inhibition account of alpha-range modulation, stating that focus of attention (and greater alpha ERD) comes with the cost of less rapid adjustment to unanticipated changes in the environment.

A competing theory of attention-related fluctuations in alpha-range signals has been advanced by Handel, Haarmeier, & Jensen (2011), who found that adults with pronounced alpha lateralization were worse at detecting motion direction in the unattended hemifield. In contrast, lateralization did not correlate with visual discrimination in the attended visual hemifield (Handel et al., 2011). These findings emphasize the suppressive nature of alpha oscillations and suggest that processing of inputs outside the field of attention is weakened by increased alpha activity, particularly when participants must inhibit response to distractors. There remain questions open for investigation at the cellular level in explaining how prospective sensory predictions (that when accurate, facilitate subsequent perception) are manifested in desynchronization of rhythmic neural

activity (Arnal & Giraud, 2012). In some respects, this theory does not fully account for the *decreased power* (ERD) of alpha-range activity during deployment of attention, in the absence of competing distractors, which are seen in anticipation of stimuli across sensory modalities.

McKinney and Euler (2019) probed the association between higher-order cognitive functions, reaction time and lateralized alpha modulation using multi-level models separating within and between-subject variability in neural and behavioral measures. The authors employed a unimodal visual selective attention paradigm to identify the association of alpha modulation higher fluid intelligence but was mediated by reaction time and temporal anticipation (McKinney & Euler, 2019). There remain open questions regarding whether these anticipatory processes serve the same functions in a multi-modal cued paradigm in adults and if they explain differences in reaction time across development and stimulus sensory modality.

Temporoparietal Tau Rhythm: Anticipation in the Auditory Modality

The tau rhythm is an alpha-range EEG oscillation observed over temporal and posterior parietal electrode sites, fluctuating in response to and in anticipation of auditory stimulation (Weisz et al., 2011). Studies employing diverse stimuli including white noise or oddball tone paradigms have used magnetoencephalographic, transcranial magnetic stimulation and computational approaches to identify auditory cortex as the generator of post-stimulus tau rhythm responses, with electrophysiological responses manifesting in the superior temporal lobes (Lelta et al., 1997; Frey et al., 2014; Karhson et al. 2015). However, is notably difficult to elicit EEG tau rhythm modulation even in adult participants, with some evidence that tau oscillatory activity may not adhere to the inhibition-timing hypothesis of alpha-range modulations (Weisz et al., 2015; Mazaheri et al., 2014; Van Diepen et al., 2019). In contrast to lateralized modulation of

occipital alpha oscillations, ipsilateral increases in alpha-range tau power over temporoparietal sites have not been observed.

Mazaheri et al. (2014) examined tau rhythm responses in anticipation of speech sounds. Prior to auditory stimulus onset, increases in power were observed at temporal and parietal sites. The authors suggest that processing of auditory stimuli can be accompanied by spatially selective inhibitory increases in alpha to allow for more rapid motor responses, which resemble orienting towards stimuli location in preparation for action, rather than anticipating the processing of the stimulus in a concentrated, deliberate manner. Another study using patterns of white noise bursts presented at predictable intervals found anticipatory alpha-range modulation, which was generated in the auditory cortex sites contralateral to the expected spatial location of upcoming auditory stimuli, consistent with visual and tactile sensory processing (Weisz, 2011). Further, the magnitude of the contralateral anticipatory responses has been associated with the *expected* salience of an upcoming stimulus, even when stimuli delivered were identical (Hartmann, Schlee, & Weisz, 2012).

Studies in children have examined tau rhythm modulation evoked in response to (but not in anticipation of) auditory stimuli. An infant study by Fujioka, Moraud, and Trainor (2011) compared the properties of tau during exposure to sound and silence determined its developmental properties to be similar to sensorimotor mu (Marshall et al. 2002) and occipital alpha (Stroganova et al., 1999). This study suggested that the tau rhythm oscillates at a lower frequency range in early infancy, gradually increasing in frequency and becoming more topographically distinct during the first year of life. Alpha oscillations over temporoparietal sites, as recorded by Magnetoencephalography (MEG), indicated that by six years of age (Fujioka & Ross, 2008) the tau rhythm oscillates within an adult-like alpha range (8-13 Hz), with upper

limits of the signal (centered on 12 Hz) showing greater desynchronization evoked by complex tones compared to white noise.

Further evidence is provided by an EEG investigation of tau and verbal working memory in 10- to 14-year-olds. Using MEG, Krause, Pesonen, and Hämäläinen (2006) reported bilateral tau synchronization in response auditory stimuli presented during a verbal working memory task, with a linear association observed between increase in tau and demands on working memory. Increases specific to parietotemporal electrode sites ipsilateral to a spatial cue have not been observed in prior studies of tau rhythm in children and adults (Krause et al., 2006). Further, there is no EEG study of characterizing the features of a unimodal *anticipatory* tau rhythm modulation in younger children.

Cross-modal Audio-Visual Anticipatory Attention

One limitation of the existing visual work is that anticipation is difficult to isolate in a unimodal paradigm, where changes in alpha oscillations due to cue, target anticipation and target perception occur over the same scalp region. Presenting a preparatory cue in a different modality from the target stimulus allows temporal and spatial differentiation of anticipatory activity (over sensory cortex relevant to the target) from neural responses elicited by the cue (Foxye & Snyder, 2011; Mazaheri et al., 2014; Slagert et al., 2016). For example, Frey et al. (2014) cued adults with a visual cue containing information relevant to the modality and spatial location of an upcoming auditory or visual target stimulus. Using MEG, the authors identified topographically segregated patterns of alpha-range modulation conforming to the cued modality: in anticipation of an auditory stimulus, source localization determined the auditory cortex as the generator of frontotemporal desynchronization observed, while in anticipation of a visual stimulus, source

localization determined the occipital cortex as the generator of the posterior desynchronization observed.

Gomez-Ramirez and colleagues (2011) investigated how sensory-specific alpha oscillations responded to multi-sensory stimuli when cued to attend to one stimulus modality (auditory or visual) and inhibit attention the other. Alpha ERD was observed at electrode sites over the cued sensory cortex, accompanied by alpha synchronization at electrode sites over the unattended distractor stimuli. A study of audio-visual anticipatory alpha-range modulation in children (8-12 years), adolescents (13-17 years) and adults found across the entire sample, the ability to task-switch was related to modulation of occipital alpha, such participants with the higher accuracy in detection of visual stimulus (following presentation of an auditory stimulus) exhibited greater suppression of anticipatory alpha power. Age-related differences in anticipatory modulation during task switching distinguished adolescents and adults from children, such that adolescents and adults exhibited significant alpha ERD when an visual target was expected following a trial with a auditory targets (compared to 'repeat' trials that no required no switch from the previously-cued modality), while this modulation was not significant in children. Consequently, children exhibited less accuracy in detecting visual targets following visual cues than adolescents and adults; adolescents detected visual targets less accurately than adults, but only when an auditory distractor was presented simultaneously (Gomez-Ramirez et al., 2011).

Gomez-Ramirez and colleagues (2011) suggest that by age 8, anticipation as defined by alpha-range ERSP modulation operates as a supra-modal entity as seen in adults. However, switching attention between modalities is cognitively demanding for children, and inhibition of attention to irrelevant distractors remains under development during adolescence. It is further speculated that anticipation may not develop at a consistent rate across all modalities. To further

bolster this assertion, it would be helpful to characterize alpha-range modulation in anticipation of stimuli across sensory modalities. Prior developmental studies of anticipatory EEG using auditory cues have been restricted to auditory and visual stimuli, both of which occur in extrapersonal space (Gomez-Ramirez et al., 2011); there is growing interest (particularly in infancy) in how stimuli in direct contact with the body, in peripersonal space, differentially engage attention (Bremner, Holmes, & Spence, 2008; Macaluso & Maravita, 2010).

Sensorimotor Mu Rhythm: Anticipation in the Somatosensory Modality

Although much of the work on alpha power fluctuations has focused on the visual alpha rhythm at posterior sites, another prominent alpha-range rhythm is the mu rhythm that occurs at central electrodes. Mu rhythm responses exhibit dissociable properties from occipital alpha visual responses (Ritter et al., 2009; Ying et al., 2016). The sensorimotor mu oscillations are maximal over central electrodes above the postcentral gyrus and are identified as an 8-13 Hz oscillation in adults and 5-9 Hz oscillation in infants (Marshall et al. 2002; Thorpe et al., 2012). The mean frequency of infant mu rhythm was found to increase from 6 Hz at 6 months to just above 7 Hz at 12 months (Marshall et al., 2002; Berchicci et al., 2011). The gradual increase in mean mu frequency observed in early childhood is suggested to be a function of increasing sensorimotor experience (Cannon, Thorpe & Fox, 2016; Van Elk et al., 2016). Mu rhythm modulation in infants has been implicated in linking action observation and execution (Filippi et al., 2016; Southgate & Verneti, 2014; Southgate et al., 2009; Marshall et al., 2011), though there remain lingering questions regarding the dynamics of mu oscillations as an index of spatial, self and/or bodily awareness (Filippetti et al., 2014; Coll et al., 2016; Marshall & Meltzoff, 2011). Lepage and Théoret (2006) reported alpha-range desynchronization at central sites during action observation and execution in a group of 7 – 10 year old children, though relatively few other

studies of the mu rhythm have focused on neurotypical older children (Fox et al., 2016). As adults execute actions with a specific body part, a somatotopic pattern of mu rhythm modulation occurs, localized in the corresponding homuncular region of the sensorimotor cortex (Penfield & Boldrey, 1937).

There is a growing literature studying adult mu rhythm activity in anticipation of touch. Haegens, Luther and Jensen (2012) presented an arrow as a spatial cue to direct adult participant's attention to the location of upcoming tactile stimuli to the right or left hand. As has been found in other studies eliciting expectation of touch (Jones et al., 2010; van Ede, Szabenyi, & Maris, 2014; Shen et al., 2017), the authors reported ERD of the mu rhythm in central electrodes contralateral to the direction of the spatial cue during anticipation of tactile stimuli (Haegens et al., 2012). This view is supported by findings that the detection of weak tactile stimuli is predicted by the extent of contralateral power of mu desynchronization (Anderson & Ding, 2011; Zhang & Ding, 2010; Jones et al., 2010) during anticipation of stimulation. In adults, we have identified individual differences in pre-stimulus mu desynchronization, which relate to the self-reported effortful deployment of attention, which was in turn associated with the ability to mindfully monitor bodily sensations (Drew et al., in prep).

Prior Investigation: Executive Function and Anticipatory Mu ERSP in Children

This section of the document describes and discusses a recent study (Weiss et al., 2018) in which we characterized sensorimotor mu rhythm activity in the EEG signal at central electrode sites during anticipation of tactile stimulation in children aged 6-8 years. Our endeavor was to create a protocol that facilitated children to map a visual cue to an anticipated bodily sensation, in order to elicit mu modulation during anticipatory attention (Kouider et al., 2015; Murphy, Foxe, & Molholm, 2016). To focus children's attention on simple bodily sensations,

participants completed a tactile discrimination task in which a spatial cue (an arrow) directed them to monitor their right or left hand in expectation of tactile stimulation (Haegens et al., 2011; Shen et al., 2017). Tactile stimuli were delivered to a membrane fixed to children's left and right middle fingers that was inflated by a short burst of compressed air 1500 ms after the onset of the spatial cue. Following the tactile discrimination task, children completed a task battery from the NIH Cognition Toolbox.

Consistent with adult findings (Haegens et al., 2011; Shen et al., 2017), a clear desynchronization of the sensorimotor mu rhythm was apparent at central electrode sites contralateral to the cue direction, primarily in the 1000 ms prior to onset of the tactile stimulus (Figure 1). The extent of this regionally-specific, anticipatory modulation of the mu rhythm was related to children's executive function skills, specifically accounting for 20% of the variance in Flanker scores and 15% of the variance in Card Sort scores. Importantly, anticipatory mu desynchronization was not associated with accuracy of children's behavioral responses to tactile stimulation or to their scores on tasks measuring Receptive Language and Processing Speed. The magnitude of mu desynchronization was also related to family SES, such that greater reductions in mu power were found in children from higher-income families (defined at the median for our sample, as families with incomes greater than \$35,000/year). Further analyses revealed an interaction such that the significant relations between executive function and mu modulation were only apparent for children from higher-income families.

The findings of Weiss et al. (2018) provide a novel extension of prior work in developmental cognitive neuroscience linking electrophysiological indices of selective attention to cognitive skills in children (Isbell et al., 2016; Shimi et al., 2015). Prior work similarly demonstrated SES differences in both executive function (Raver, Blair, & Willoughby, 2013;

Hackman, Gallop, Evans, & Farah, 2015) and EEG indices of selective attention (Coch, Sanders & Neville, 2005; D'Angiulli, Herdman, Stapells, & Hertzman, 2008). To our knowledge, the study of Weiss et al. (2018) was the first investigation of children's oscillatory brain responses during the monitoring of bodily sensations. Findings from the adult literature support the use of anticipatory mu desynchronization as an index of focused attention to one's own body (Jones et al., 2010; Kerr et al., 2013) and suggest further avenues for developmental investigation that are discussed later in this document.

The association we previously found between executive function scores and mu rhythm desynchronization during anticipation of tactile stimulation serves as a complement to studies linking children's cognitive abilities with aspects of event-related potential (ERP) responses to stimuli presented during auditory (Isbell et al., 2016; Stevens et al., 2009) and visual (Shimi et al., 2015) selective attention tasks. In summary, this literature review and our prior findings support theories of selective attention as an early indicator and promoter of executive function skills (Garon et al., 2008), but there remain questions regarding the modal specificity of these effects and their generalizability across development.

CHAPTER 2

CURRENT STUDY

The current study was motivated by bridging developmental cognitive neuroscientific evidence with computational accounts of cognition, which place prediction as foundational to fluctuations of oscillatory brain activity, the regulation of action and the organization of behavior (Howdy, 2013; Clark, 2017). However, there is limited empirical operationalization of prediction or available neural data to complement these theories. Anticipation is suggested as a source of common variability across domains of cognitive functioning, rather than the observed association serving as a function of processing speed or reaction time (Klenberg, Korkman & Lahti-Nuutila, 2002).

This developmental investigation was undertaken to address a gap in the literature around the characterization of neural indices of anticipation in childhood, and their relation to intra- and inter-individual variability in control of action and goal-directed behavior. Patterns of anticipatory EEG lateralization are compared across three modalities (visual/tactile/auditory) and two age ranges (6-8 and 18-25 year olds). This approach allowed us to determine the modality-specific or supramodal role of anticipatory EEG alpha-range responses in relation to higher-order cognitive functions.

This study endeavored to examine whether the magnitude of anticipatory changes in the EEG alpha band was associated with indicators of goal-directed action immediately relevant to the task paradigm: specifically, participant's reaction time in response to stimuli. Next, we employed multi-level analyses investigated whether alpha-range activity during anticipation of auditory, visual and tactile stimuli accounted for significant variance in executive function abilities, measured using standardized scores on the Dimensional Change Card Sort and the

Flanker tasks obtained from the NIH Cognitive Toolbox. Lateralized ERSP (LI), the difference between contralateral and ipsilateral alpha power, was used following the establishment of no significant differences in power by spatial cue, to capitalize on the variability in spatial attention across development and modality.

A series of hierarchical nested models parsed intraindividual and interindividual variability in neural responses, testing 1) at the trial level, the association of reaction time and within-subject lateralized ERSP (LI), as moderated by modality and participant age group; 2) at the subject level, the association of executive function and between-subject LI, as moderated by modality and participant age group; 3) at the trial and subject level, the association of executive function and between-subject LI, as moderated by modality and participant age group. This analytic approach draws upon recent advances in statistical segregation of variability in single-trial ('trial-level') from participant-specific ('subject-level') variability in brain-behavior relations, used successfully with ERP and ERSP measures, reaction time and individual behavioral differences (McKinney & Euler, 2019; Craddock et al., 2019; Smith & Kutas, 2017; Matthewson et al., 2020).

Participants

In order to take part in the study, participants were required to have no medical or psychological diagnoses, be right-handed, and be free of long-term medication. Forty-nine adult undergraduate participants were recruited using Temple University's SONA system, which awards course credit to students. Following participant loss due to excessive artifact ($n=2$), technical issues with recording ($n = 2$), and ineligible participants ($n = 5$, due to ESL comprehension issues, over age for inclusion or undisclosed history of seizure), our final sample included 40 adult participants aged 18-25 ($M = 20.91$, $SD = 4.22$, 10 male). There were no differences in behavioral, neural or demographic measures in the included and excluded samples.

Based on prior experience with a similar paradigm, we recruited 53 children in order to achieve a final sample of 40 6 – 8 year old children ($M=6.91$, $SD=0.84$, 23 male), with participant loss due to various reasons including excessive artifact ($n = 5$), intolerance of EEG cap ($n = 3$), technical issues with recording ($n = 4$) and ineligible participants ($n = 1$). Child participants aged between 6 and 8 years were recruited using mass mailings of a postcard to parents, flyers posted at businesses frequented by parents and members of the public, and advertisements placed at parent groups, online platforms and social media sites targeting local parents. The recruitment documents explained the study, compensation and solicited families to contact the lab if they would like to participate. The mailings were sent to families' homes, with the addresses and child ages received from the Bureau of Health Statistics & Registries of the Pennsylvania Department of Health through their "Vital Statistics" records (Approval 98241). Families who responded were screened to ensure their children met the age and health criteria; participating families were then emailed a copy of the consent form and provided with a thorough description (via e-mail or over the phone) of the study purpose, protocol, and EEG

collection process. The participating families then scheduled a time to visit the laboratory on the main campus of Temple University for a 2-3 hour visit. Participating families were compensated with a \$50 Visa gift card for their participation, and children received a small toy and a comic book certificate of participation.

Caregivers (on behalf of their participating children) and adult participants completed the MacArthur Sociodemographic Questionnaire, reporting total annual household income within a prescribed set of 10 categories, ranging from under \$5,000 to greater than \$125,000 (for exact increments, see Kishiyama et al., 2009). Across the entire sample, participants consisted of families from a wide range of income levels, with 16% of participants coming from families with an annual income of under \$20,000, and 18% of participating coming from families earning an annual income greater than \$125,000. In our child sample, the median income range reported was \$50,000 to \$74,999; in our adult sample, the median income range reported was \$75,000 to \$99,999. Highest maternal education attainment was also varied – in the child sample, 6 mothers reported having not attained a high school diploma or equivalent, 12 mothers attained a high school diploma or equivalent, 13 mothers attained an associate or bachelor's degree, and 9 attained masters, professional or doctoral degrees. In the adult sample, 4 participants reported that their mothers did not attain a high school diploma or equivalent, 14 participants had mothers who had attained a high school diploma or equivalent, 12 participants had mothers with an associate or bachelor's degree, and 10 had mothers with a masters, professional or doctoral degrees. Participants could report multiple racial identities; if they elected to, they were requested to indicate their primary identity. The ethnic and racial composition of the child sample (ten identified as Hispanic) reflected the demographics of the diverse, multi-cultural

metropolitan area that they were recruited from: participating families reported their primary racial identity as White (n = 22), African American (n = 17), Asian (n=3), Native American (n = 1), and Other (n = 4). Adult participants (seven identified as Hispanic) largely reflected the diversity of the undergraduate research participant pool: students reported their as primary racial identity White (n = 21), African American (n = 12), Asian (n = 6) and Other (n = 1).

Methods

Prior to data collection, adult participants consented and child participants were read an assent form in the presence of their caregiver. Participants were then fitted with an EEG cap, earphones and tactile stimulators (see below) and were seated at a table facing a computer screen, with instructions to rest their hands on their lap, under the table and out of sight. During the capping procedure, children were read the following cover story: “You will be a supersensor today! We are going to put these sensors on your eyes, ears and hands. The cap on your head does not do anything special to change your brain responses or put anything into your head, but it lets us scientists collect information or data in the form of numbers. We do math to these numbers to make a map of your brain, and use that guess what your eyes, ears and hands experienced. We’re trying to test how adults and kids differ in their sensory brain responses, and by studying you, we hope to learn more about how kids think!”

The multisensory selective attention paradigm (Figure 1) consisted of three blocks: auditory, tactile and visual cues. The block type was indicated by a visual icon (an ear, a hand or an eye) displayed at the start of each block. Experimenters instructed participants that an arrow cue would prepare them for stimulation delivered in the specified sensory modality. The order of blocks (i.e., modality) presented was counterbalanced to the six possible protocol sequences, which were randomly assigned across participants. At the start of each block, there were 6

practice trials in the attended modality, such that participants experienced completed a trial of each spatial manipulation and successfully discriminated between single and double stimuli (explained below) before the test trials began. Participants were then told to minimize movement, keep their hands on their lap (out of sight) and eyes on the screen.

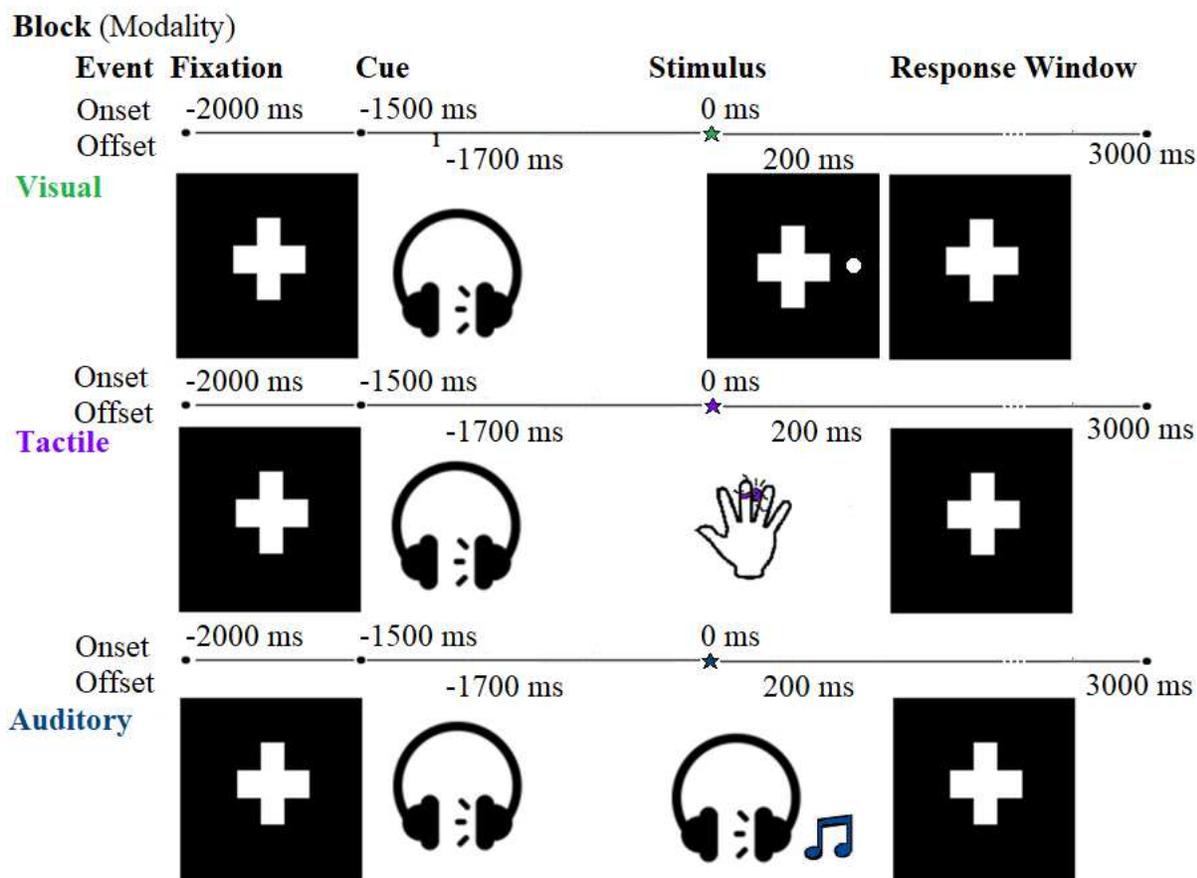


Figure 1. *Schematic of the selective attention protocol.* The multi-modal selective spatial attention protocol was designed to elicit anticipation of visual, auditory and tactile stimuli in three separate blocks, with the order of blocks counterbalanced across participants. A fixation point was displayed continuously for 2250 ms, with the onset of the low-pitch auditory spatial cue (200 ms in duration) occurring 500 ms following the fixation onset. The onset of the target stimulus occurred 1500 ms later (at 0 ms, as indicated by the star). Participants were instructed to respond immediately after each stimulus.

The selective attention protocol for each trial involved a baseline fixation cross (+) displayed on a 17" CRT monitor for 500 ms. In trials across all blocks, the fixation was followed by a spatial cue, a low-pitched (200 Hz) tone presented for 200 ms at 90 dB that was delivered to the left or right ear via insert earphones and that directed participants to attend to the left or right, with the goal of eliciting anticipation of the upcoming target stimulus. Following a 1500 ms cue-stimulus interval, the target stimulus was presented for 200 ms at the cued spatial location, with the sensory modality of the stimulation varying by block. The target stimulus consisted of visual probes in the cued field of vision, pulses of tactile stimuli to the cued hand, or high-pitched target tones (600 Hz) to the cued ear (Figure 1). Participants were instructed to respond as quickly as possible to the target by pressing a foot pedal within 2 seconds of receiving the target stimulus. Irrespective of spatial cue, participants were instructed to report how many stimuli they perceived by the number of pedal presses. An inter-trial interval of 500 ms separated each trial, for a total trial duration of 4 seconds.

There were 360 trials in total: 120 trials of each modality (presented in separate blocks, with opportunity for rest in between) with 60 trials to each spatial location (right/left) within each modality (auditory, tactile or visual). Among these, 20 randomly interwoven trials consisted of 'double' stimuli, in which an additional target stimulus in the attended modality was presented to the cued spatial location; participants were instructed to respond to these trials with two rapid foot pedal presses. Behavioral indicators of task performance were assessed as variability in reaction time, which was measured as the time between target stimulus onset to the first foot pedal response. Whether the foot pedal was assigned to the right or left foot was counterbalanced across participants. Across all blocks, open-field white noise was played in the testing room to

facilitate focused attention and prevent responses to subtle noises from the hardware used to deliver tactile simulation.

Target Stimulus Parameters

Previous studies have established in children and adults that strength of ERSP modulation around a target stimulus is related to cue validity (Votbregt et al., 2015). Since our goal was to examine individual differences in sensory anticipation, rather than its manipulation under conditions of uncertainty or probabilistic titration, the location of the spatial cue was fully consistent with the subsequent spatial location of target stimuli.

The auditory target stimulus consisted of a high-pitch chime of 200 ms duration, with a 600 Hz initial tone (lasting 100 ms) followed by a 450 Hz offset tone (lasting 100 ms), calibrated to 90 dB SPL at the ear. Visual target stimuli consisted of a white square (2cm x 2cm on the monitor), displayed for 200 ms at a location 4 cm to the right or left of the fixation cross. Tactile stimuli consisted of a light tap, delivered to the distal tip of the left and right middle fingers using an inflatable membrane (10 mm diameter; MEG Services International, British Columbia, CA) mounted in a plastic casing and secured with a finger clip. The membrane was inflated by a short burst of compressed air delivered via flexible polyurethane tubing (3 m length, 3.2 mm outer diameter). The compressed air delivery was controlled by STIM stimulus presentation software in combination with a pneumatic stimulator unit (both from James Long Company, Caroga Lake, NY) and an adjustable regulator that restricted the airflow to 60 psi. To generate each tactile stimulus, the STIM software delivered a 10 ms trigger that opened and closed a solenoid in the pneumatic stimulator. Expansion of the membrane began 15 ms after trigger onset and peaked 35 ms later, with a total duration of membrane movement of around 200 ms. Previous studies in our lab have employed the same method of tactile stimulation on infants (Shen, Weiss, Metzloff &

Marshall, 2018), children (Weiss, Marshall, & Meltzoff, 2018) and adults (Smyk, Weiss & Marshall, 2018).

EEG Acquisition and Processing

EEG signals were collected from 32 scalp sites using a Lycra stretch cap (Electro-Cap, Eaton, OH) with Electro-Gel conducting gel. The sites used were Fp1, Fp2, F3, F4, Fz, FC1, FC2, FCz, FC5, FC6, F7, F8, C3, C4, CP1, CP2, CPz, CP5, CP6, T7, T8, P3, P4, Pz, P7, P8, O1, O2 and the left and right mastoids. The EEG signals were amplified by optically isolated, high input impedance ($>1\text{ G}\Omega$) bioamplifiers from SA Instrumentation (San Diego, CA) and were digitized using a 16-bit A/D converter ($\pm 2.5\text{ V}$ input range). Scalp electrode impedances were kept under $25\text{ k}\Omega$. Bioamplifier gain was 4000 for the EEG channels, and the hardware filter settings were .1 Hz (high-pass) and 100 Hz (low-pass), with a 12 dB/octave rolloff. The EEG signal were collected referenced to Cz with an AFz ground, and were re-referenced offline to the average of left and right mastoids. To keep a consistent number of trials across participants and groups, the 10 trials with the highest amplitude range were deleted for all participants (no remaining trials exceeded our threshold of $500\text{ }\mu\text{V}$). If visual inspection of the raw EEG signal identified of up to three non-neighboring electrodes with excess noise, these were interpolated using EEGLAB's spherical interpolation function. Movement and eye blink artifacts were detected and interpolated using independent component analysis (Hoffmann & Falkenstein, 2008). The EEG signals were spectrally analyzed with Gaussian tapered complex Morlet wavelets. Event-related spectral perturbation (ERSP) was computed for frequencies ranging from 4-30 Hz, with analyses focused on the alpha (8-12 Hz) range of oscillatory activity (Delorme, 2004). ERSP was calculated by means of the equation $ERSP = 10 * \log_{10}(pft/pbasef)$, where pft is the mean wavelet estimate for frequency bin f and time point t averaged over trials, and $pbasef$ is

the wavelet estimate in frequency bin f averaged over trials and sample points from the 500 ms pre-cue baseline period, during the display of the fixation cross (Jantzen et al., 2012).

EEG Analyses

The frequency range of the alpha rhythm moves from around 6-9 Hz in infancy to a higher frequency range in early childhood (Berchicci et al., 2011; Marshall et al., 2002). By the age of the current sample (6-8 years) the mu frequency band is close to the adult range of 8-12 Hz (Berchicci et al., 2011) so this frequency range was used for analyses. For each single-target trial with a correct behavioral response, an epoch of 2750 ms was extracted beginning 2000 ms prior to onset of the target stimulus and extending 750 ms after target stimulus onset, including the behavioral response window. Each participant had 40/trials per condition.

The envelope of the amplitude-modulated signal was computed via the Hilbert transform (“hilbert” function in Matlab), which discards phase information and reveals oscillatory power fluctuations over time. In addition, corrections were applied to the raw ERSP that controlled for fluctuations in $1/f$ aperiodic signal. To identify electrodes of interest, a mass univariate approach extracted the mean ERSP across the entire 32 sites, using Bonferroni-corrected permuted ranking to nominate the electrode sites with peak contrast in cue direction (left/right) by target stimulus modality (visual/tactile/auditory). The resulting analyses identified peak contrast at O1 and O2 for the visual stimuli, C3 and C4 for the tactile stimuli, and P7 and P8 for the auditory stimuli. These sites were confirmed by investigating the alpha distribution displayed via scalp maps (Figure 2). Mean ERSP at each of these electrode sites was extracted accordingly for further analyses and is displayed by modality, laterality and group (Figure 3

Using the results of the mass univariate scalp maps as a guide, a key variable submitted to ANOVAs and regressions was the mean alpha-range ERSP (per trial or per subject) for the

period from -500 ms to 0 ms. This time window, consistent with prior literature, was selected to prevent contamination of anticipatory responses by changes evoked by the auditory cue that occurred at -1500 ms. Once it was established that there were no significant differences by directional cue, mean alpha-range ERSP was collapsed into a lateralization index (LI), subtracting contralateral ERSP and ipsilateral ERSP. This plan for analyses is based on prior work on child and adult anticipatory mu modulation and is similar to the parameters (duration of anticipatory period and alpha-range criteria) used by a prior study of cross-modal visual-auditory attention in children (8-12 years) and adults (Murphy, Molholm, & Foxe, 2016). The following factors were entered to predict individual differences in ERSP values: direction of cue (left/right), sensory modality (visual/tactile/auditory) and participant age (child/adult).

Cognitive Skills Battery

Participants were detached from the EEG cap and had their executive function abilities assessed using the standardized measures provided in the NIH Cognitive Assessment toolbox. This computerized assessment includes a battery of tasks designed to parse the components of executive function, including cognitive flexibility (Dimensional Change Card Sort) and inhibitory control (Flanker). The dimensional change Card Sort task indexes task-switching and working memory abilities in childhood (Beck et al., 2011; Zelazo, 2006). Participants were directed to select one of two test stimuli that matched the shape (truck or ball) or color (red or blue) of the target stimuli, as instructed by a verbal prompt that varied randomly between trials. The Flanker task requires participants to indicate the direction of a central arrow that was presented between distractor or 'flanker' arrows (Eriksen & Eriksen, 1974; Fan et al., 2002; Rueda et al., 2004). The direction of arrows was randomized by trial, such that the flanking arrows were alternatively congruent or incongruent with the target central arrow. The Flanker

task indexes response inhibition and conflict monitoring (Fan et al., 2002; Diamond, 2013). Participants also completed a receptive Language task, resembling the widely used Picture Vocabulary Test, which also produced age-adjusted standardized scores.

For all measures on the Cognitive battery, age-adjusted t-standardized test scores were used (on a scale from 0 to 100, with a mean of 50) as derived by the NIH Toolbox. Participant's scores on the Card Sort and Flanker tasks were calculated to reflect both accuracy and reaction time for participants who correctly identified targets on 80% of trials; accuracy alone is considered for participants who did not meet this threshold. The age-standardized scores from the Card Sort and Flanker tasks for adults and children were averaged and group-centered to form composite executive function (EF) score. Descriptive statistics are reported for the behavioral variables used as dependent variables (Table 1).

Statistical Analyses

Descriptive statistics for demographic and behavioral variables are reported in Table 1. For all ANOVAs, within-subject effects were adjusted using Greenhouse-Geisser correction factors; pairwise t-test comparisons and multiple linear regressions were reported with p-values adjusted for multiple comparisons using the FDR correction. Three 3-way ANOVAs were conducted separately for each sensory modality, to investigate individual subject-level differences in behavioral responses (reaction time) and participant-mean ERSP amplitude during the anticipatory period. The following factors were entered to predict these outcomes: direction of cue (left/right), hemisphere (right/cue) and participant age (child/adult).

To account for variability in single trial alpha power (within-subject) and individual differences in alpha power (between-subject), executive function and reaction time were modelled using generalized linear mixed-effects models (GLMMs). GLMMs allow for the

inclusion of both random and fixed effects. Standard linear regression assumes independence of observations and is thus unsuitable for the analysis of a repeated-measures design. GLMMs can incorporate the dependence structure of the observations into the model using random effects.

Multi-level models involved regressing EF (averaging the standardized age-adjusted scores) over anticipatory alpha LI (calculated as contralateral – ipsilateral) at the pre-specified, regionally specific electrode sites and its moderation by sensory modality within-subjects and age group between-subjects, controlling for within-subjects variability in ERSP and reaction time. Post-hoc regressions probed the association of EF with anticipatory ERSP moderated sensory modality (auditory, visual or tactile), separately for ipsilateral or contralateral alpha power and participant age (child or adult). Post-hoc tests are reported with p-values adjusted for multiple comparisons using the FDR correction.

Prior studies have successfully employed multi-level GLMMs to examine similar outcomes using EEG data at both the trial and individual level (Euler & McKinney, 2018; Craddock, 2019), but no study has examined developmental differences in these mixed effects. Inter-individual variation in adult intelligence was found to be accounted for by the contribution of single-trial ERP amplitude, ERSP and reaction time (Euler & McKinney, 2018). Intra-individual variation in reaction time elicited by tactile and visual stimuli has been previously associated with anticipatory sensorimotor mu and visual alpha (Kline & Katus, 2019;).

The model was specified in R (R Core Team, 2015) using the lme4 package for model fitting (Bates et al., 2016). The model was specified by the following syntax in R:

```
RT ~ group + (1 + LI * modality | subject)
EF ~ LI * group * modality + (1 | subject)
EF ~ LI * group * modality + (1 | LI * RT | subject)
```

This specification indicates that the response variable on the left side of the ~ operator should be modelled as a function of the terms on the right side of the ~ operator. RT is group and subject-centered reaction time; EF is group-centered executive function composite, averaging standardized NIH Toolbox scores on the Flanker and Card Sort task. Terms outside of the brackets specify fixed effects, while terms inside the brackets specify random effects and slopes. The * operator indicates that main effects and interactions should be included in the model. Thus, the fixed effects were the single-trial estimates of anticipatory alpha ERSP, the modality of stimulus (visual/tactile/auditory), the group (adult/child), and all interactions between these factors. Participant was specified as a random effect, random slopes were estimated for all main effects and interactions. Likelihood ratio tests compared the goodness-of-fit of compatible models, which were performed by systematically removing each fixed effect term from the full model and comparing the log-likelihood of the model with the term to the log-likelihood of the model without the term. This provides a chi-square statistic and a p-value that indicate whether the term significantly improves the model. Where individual coefficients were significant, we follow-up with further FDR-corrected regressions, probing sub-groups to assess the source and direction of significant differences in relating outcomes to interaction terms.

CHAPTER 3 STUDY RESULTS

Behavioral Analyses

Participants' mean reaction time, consisting of time from stimulus onset to foot pedal press (calculated per participant within each sensory modality) was correlated with mean anticipatory alpha-range EEG modulation, $r = .451$, $p < 0.05$. Participant's stimulus detection accuracy, consisting of the percent of correct responses (defined as no false alarms or missed hits) over the total number of potential trials (calculated per participant within each sensory modality) was calculated. Participants overall correctly responded to 97.21% of the stimuli. This did not differ between adults (97.213%) and children (97.210%), nor did it correlate with other study measures; thus, we proceeded to focus on reaction time as the primary indicator of stimulus detection.

Repeated-measures analyses of variance (ANOVAs) were carried out on RT (from correct trials only) with following factors: spatial cue (right/left), modality (visual/tactile/auditory), and age group (child/adult) as a between-subjects factor. There were no main effects of spatial cue direction. Significant main effects of age group were observed on RT, $F(1,76) = 0.562$, $p < 0.001$, $\eta^2 = 0.609$, with adults responding more rapidly than children. Significant main effects of modality was observed on RT, such visual stimuli elicited slower reaction times relative to tactile, $F(1,76) = 5.902$, $p < 0.001$, $\eta^2 = 0.547$, or auditory stimuli, $F(1,76) = 4.913$, $p < 0.05$, $\eta^2 = 0.206$, which did not significantly differ from one another. No significant interactions were found predicting reaction time by cue, modality and group, $F(1,76) = 1.296$, $p = 0.269$.

Outlier detection, defined as values with a Mahalanobi's distance of greater than 2.5, was performed on single-trial and mean mu ERSP separately within child and adult samples, but no data points reached this threshold (Hadi, 1992). Assumption checks determined that the dependent variables in the analyses, mean mu ERSP and executive function, were normally distributed. As expected, reaction time was positively skewed. Rather than transform the variable, when reaction is the dependent variable, the models utilize a Gamma distribution rather than Gaussian distribution. This approach considers the unimodal skewed distribution of reaction time, appropriate for variables with continuous values greater than 0 and the variance of values increasing proportionally to the mean (Whelan, 2010; Lo & Andrews, 2015).

Table 1. *Descriptive Statistics for Behavioral Measures*

	Children				Adults			
	Mean	SD	Skew	Kurtosis	Mean	SD	Skew	Kurtosis
Reaction Time (ms)	357.33	0.48	-0.81	0.01	365.10	0.90	-0.69	0.05
Flanker	44.85	10.13	-0.42	0.57	49.52	9.30	-0.53	0.56
Card Sort	51.46	13.10	-0.15	0.74	47.48	10.16	0.12	0.61
Language	50.85	1.22	-0.17	0.59	52.04	11.67	-0.29	0.70

Anticipatory Alpha ERSP Analyses

Visual Alpha

A repeated-measures ANOVA was conducted to compare anticipatory visual alpha ERSP in the 500 ms window prior to the visual target stimulus. ERSP at occipital sites was entered as a function of electrode (O1/O2) and cue direction (left/right), submitted as within-subject variables, as well as age group (adult/child), which was submitted as a dichotic between-subjects variable. There was a significant main effect of group, $F(1, 79) = 4.03$, $SS = 9.318$, $p = 0.046$, $\eta^2_p = 0.094$, with adults overall exhibiting higher mean ERSP than children. A significant two-way interaction was observed between cue direction and electrode, $F(1, 79) = 6.37$, $SS = 10.167$, $p = 0.007$, $\eta^2_p = 0.204$. As expected from prior studies and supported by the ERSP scalp maps (Figure 3), this interaction was driven by more negative ERSP (i.e., greater mu desynchronization) at the contralateral site than at the ipsilateral site. There were no further significant main effects or interactions observed.

Sensorimotor Mu

A repeated-measures ANOVA was conducted to compare anticipatory mu ERSP in the 500 ms window prior to the tactile target stimulus. ERSP at central sites was entered as a function of electrode (C3/C4) and cue direction (left/right), submitted as within-subject variables, as well as age group (adult/child), which was submitted as a dichotic between-subjects variable. No main effects were observed. A significant two-way interaction was observed between cue direction and electrode, $F(1, 79) = 5.397$, $SS = 13.176$, $p = 0.009$, $\eta^2_p = 0.489$. As expected from prior studies and supported by the ERSP scalp maps (Figure 3), this interaction was driven by more negative ERSP (i.e., greater mu desynchronization) at the contralateral site than at the ipsilateral site. A three-way interaction was observed among electrode site, cue direction, and age group, F

(2, 76) = 6.247, SS = 17.934, $p = 0.026$, $\eta^2_p = 0.264$. The interaction appeared to be driven by the greater differences in lateralization of mu ERSP observed in adults: using FDR-corrected pairwise comparisons, it was determined that the mean ERS observed in adults at ipsilateral central sites ($M = 0.241$) was significantly greater relative to that of children, who exhibited minimal difference in ERSP from baseline ($M = -0.031$).

Auditory Tau

A repeated-measures ANOVA was conducted to examine variability in anticipatory tau ERSP in the 500 ms window prior to the target auditory stimulus. ERSP at parietal sites was entered as a function of electrode (P7/P8) and cue direction (left/right), submitted as within-subject variables, as well as age group (adult/child), which was submitted as a dichotic between-subjects variable. No significant main effects or two-way interactions were observed. A marginally significant, three-way interaction was observed among electrode site, cue direction, and age group, $F(2, 76) = 3.859$, $SS = 1.892$, $p = 0.055$, $\eta^2_p = 0.129$. The interaction appeared to be driven by the greater differences in lateralization of tau ERSP observed in adults: using FDR-corrected pairwise comparisons, it was determined that the mean ERSP observed in adults at ipsilateral parietal sites ($M = 0.474$) was significantly greater relative to that observed at contralateral parietal sites ($M = 0.023$), while children did not exhibit differences in ERSP at ipsilateral parietal sites ($M = 0.297$) and contralateral parietal sites ($M = 0.245$).

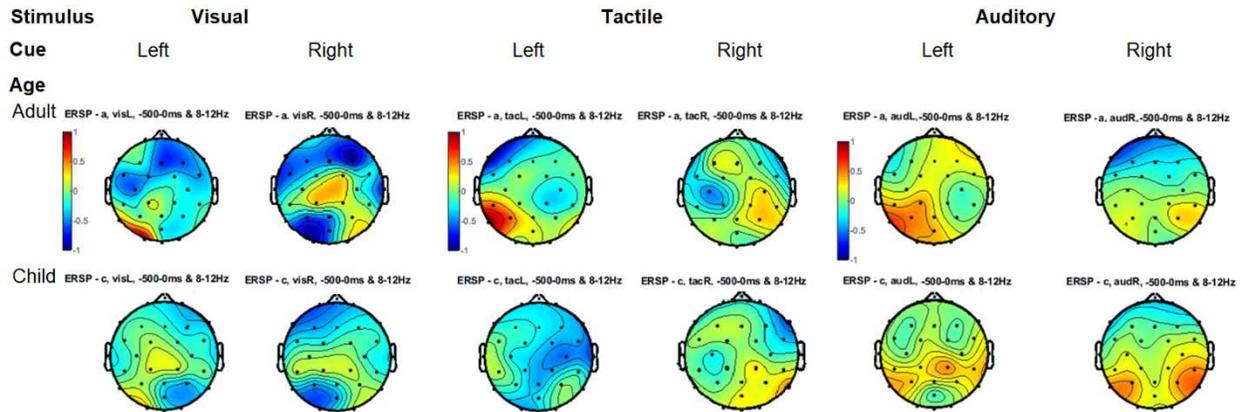


Figure 2. *Scalp maps of mean ERSP.* Baseline-corrected ERSP (in dB) is displayed at 32 electrode sites for the anticipatory period (from 500 ms prior to target stimulus onset at 0 ms), set to a consistent alpha power scale across cue direction, modality and group (-1 to 1 dB).

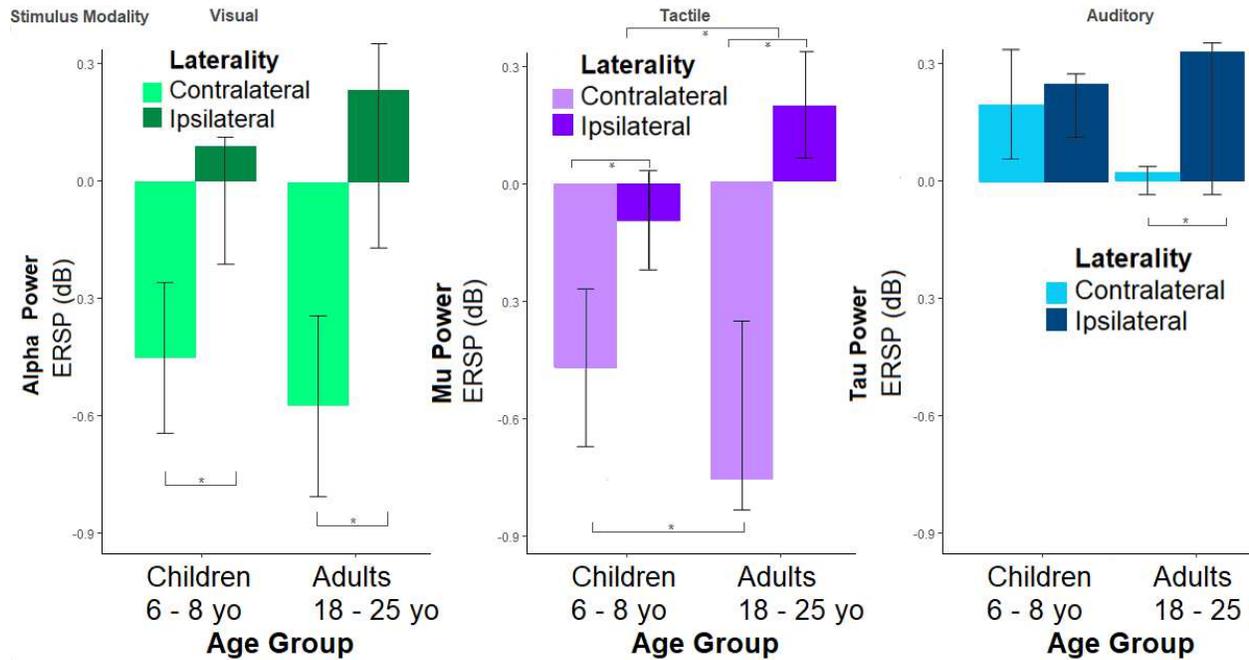


Figure 3. Bar graphs of Alpha ERSP by modality, age group and hemisphere. Mean alpha-range (8 – 12 Hz) ERSP and confidence interval of significance are displayed for electrodes of maximal contrast for each sensory stimulus, collapsed by laterality (as shown in ANOVA table, no asymmetries in response by cue direction were detected).

Table 2. *Repeated measures ANOVA of anticipatory Alpha ERSP by cue, hemisphere & age group*

Anticipatory Mu ERSP Predictors	Visual Alpha ERSP			Sensorimotor Mu ERSP			Auditory Tau ERSP		
	SS	F-value	P	SS	F-value	P	SS	F-value	P
Cue	0.107	0.046	0.830	0.779	0.099	0.830	0.032	0.020	0.887
Hemisphere	4.887	2.113	0.148	5.783	2.113	0.148	0.397	0.367	0.547
Group	9.318	4.030	0.046	3.981	2.891	0.126	0.576	0.105	0.748
Cue * Group	4.475	1.935	0.166	4.475	2.444	0.236	0.630	0.582	0.449
Cue * Hemisphere	10.167	6.397	0.007	13.167	5.397	0.009	0.029	0.060	0.808
Hemisphere * Group	0.764	0.330	0.566	1.840	1.636	0.721	0.059	0.037	0.848
Cue * Hemisphere * Group	0.825	0.357	0.551	17.934	6.247	0.026	1.892	3.859	0.055

Multi-level Analyses: Behavioral Outcomes by Anticipatory Alpha ERSP, Modality and Group

To examine differences in how behavioral outcomes were related to anticipatory ERSP by age group and modality, a series of multi-level mixed models were conducted, with variability in outcomes (reaction time, executive function and language) as a function of Lateralization Index (LI) ERSP value (calculated as contralateral alpha-range ERSP at sensory-specific sites) and its interactions with modality as a within-subjects factors and age group as a binary between-subjects factor. Fixed effects examined this main effect and its moderation by modality and age group. As reported in Table 3, significant variability in language was not accounted for by ERSP nor its interaction with modality and age group.

The first model estimated within-subject variability in reaction time (across trials) using within-subject ERSP as a predictor, testing how this varied as function of its interaction with modality and age group. LI was centered by participant to account for inter-individual differences, allowing analyses to highlight the association between intra-individual variability in LI and trial-specific reaction time. There was a main effect of LI, such that an increase by one standard deviation (SD) of LI for a given trial conferred a 0.14 point decrease in reaction time. There was also a main effect of group, such that children exhibited more variable (and slower) reaction time than adults. There was an interaction between group and LI, such that children exhibited a non-significant association between reaction time and LI, while adults ERSP lateralization was significantly associated with reaction time. There was a trending three-way interaction of this effect moderated by modality, such that the significant association between reaction time and adult LI was evident for in anticipation of visual and tactile stimuli, but not auditory stimuli.

The second model estimated between-subject variability in executive function using between-subject LI as a predictor, examining how this relation varied as function of LI's interaction with modality and age group. There was an inverse association of LI with EF, such that participants with lower LI exhibited greater executive function. There was an interaction between modality and LI in predicting EF variability, such that mu ERSP in anticipation of tactile stimuli was associated with EF, while there was no significant association for alpha LI in anticipation of visual stimuli and tau LI in anticipation of auditory stimuli. This relation was further moderated by age group, yielding a significant three-way interaction, $t(78) = -2.12$, $p = 0.034$, $\eta^2p = 0.092$. The regression results are displayed in Figure 4.

To detect the source of significance difference in the three-way interaction, a set of post-hoc regressions were conducted. Executive function was defined as a function of anticipatory ERSP values and their interaction with modality, examined separately by age group and ERSP laterality (contralateral/ipsilateral). Contralateral alpha ERSP at occipital sites was not associated with executive function abilities in children, $t(39) = -0.05$, $\beta = -0.01$, $p = 0.96$, or adults, $t(39) = -0.63$, $\beta = -0.12$, $p = 0.53$. Ipsilateral alpha ERSP was not associated with executive function abilities in children, $t(39) = 0.47$, $\beta = 0.08$, $p = 0.64$, or adults, $t(39) = 1.69$, $\beta = 0.26$, $p = 0.33$. Contralateral tau ERSP at parietal sites was not associated with executive function abilities in children, $t(39) = -0.09$, $\beta = -0.45$, $p = 0.65$, or adults, $t(39) = -0.61$, $\beta = -0.14$, $p = 0.55$. Ipsilateral tau ERSP was not associated with executive function abilities in children, $t(39) = 0.12$, $\beta = 0.03$, $p = 0.90$, or adults, $t(39) = 0.82$, $\beta = 0.17$, $p = 0.41$. Contralateral mu ERSP at central sites was inversely associated with executive function abilities in children, $t(39) = -2.18$, $\beta = -0.48$, $p = 0.03$, and adults, $t(39) = -2.70$, $\beta = -0.46$, $p = 0.02$. Ipsilateral mu ERSP was *not*

associated with executive function abilities in children, $t(39) = 0.82$, $\beta = 0.151$, $p = 0.42$, but it was associated with executive function in adults, $t(39) = 2.07$, $\beta = 0.44$, $p = 0.04$.

The multi-level model combined the first model's intra-individual, single-trial analyses approach with the inter-individual differences approach of the second model, to capture greater variability in EF relative to the second model ($\Delta R^2=0.096$). The multi-level model predicting EF includes a random intercept as well as a random slope. We found deviance is smaller in the random slope model ($D_1=2555.1$), indicating less model-data deviance when the effect of within-subject ERSP varies randomly compared to when only between-subject ERSP varies ($D_0=2556.9$). The chi-square value indicates that the random intercept initial model and random slope models are not equal in accounting for variation in EF, $\chi^2(2) = 0.706$, $p > 0.05$. The deviance test can be interpreted as indicating that there is significant explanatory power gained by allowing the effect of within-subject ERSP to vary randomly. By specifying a random slope, heteroscedasticity between participants can be partially accounted for by intra-individual variability in ERSP.

There was a marginal main effect of within-subject LI on EF, such that an increase by one standard deviation (SD) of LI for a given participant conferred a 0.23 point decrease in standardized EF score. There was a significant main effect of between-subject LI on EF, such that an increase by one standard deviation (SD) of LI for a given participant conferred a 0.66 point decrease in standardized EF score. There was an effect of reaction time by within-subject LI on EF, such that an increase by one standard deviation (SD) by the correspondence between reaction and within-subject LI, for a given participant conferred a 0.17 point decrease in standardized EF score. There were no other significant main effects. Importantly, despite accounting for significant within-subject variance in neural and behavioral responses, the three-

way interaction between between-subject LI, modality and age group remained significant, suggesting this effect is independent of intra-individual differences.

Table 3. *Multi-level mixed effects model of behavioral measures by neural measures*

Model	(1) Within-Subject (WS)			(2) Between-Subject (BS)			(3) Multi-level Model		
Outcomes	Reaction Time (RT)			Executive Function (EF)			EF ~ WS + BS + RT		
	R ² =.303			R ² =.123			R ² =.219		
				AIC=638.8			AIC=641.2		
Predictors	Beta (SE)	t-value	P	Beta (SE)	t-value	P	Beta (SE)	t-value	P
(1) WS LI ⁺	-0.14 (.05)	-2.52	.031				-0.23 (.12)	1.94	.052
WS ERSP * Trial RT							-0.17 (.08)	2.13	.001
Intercept	0.55 (.12)	4.44	.001	0.33 (.14)	2.42	.001	0.36 (.13)	2.59	.001
(2) BS LI ⁺⁺				-0.67 (.20)	-3.40	.001	-0.66 (.20)	-3.28	.017
Group	-1.12 (.18)	-6.34	.001	-0.09 (.10)	-0.93	.351	-0.08 (.11)	-0.94	.353
Modality	-0.20 (.17)	-0.12	.907	0.01 (.19)	0.01	.985	.003 (.19)	0.18	.985
LI * Group	0.14 (.11)	1.24	.217	0.12 (.13)	0.98	.329	0.26 (.13)	-2.01	.046
LI * Modality	0.27 (.13)	1.97	.047	0.36 (.16)	2.13	.032	0.33 (.15)	2.07	.039
Group * Modality	0.04 (.25)	0.158	.874	-0.01 (.28)	-0.02	.979	-0.03 (.28)	0.11	.914
LI * Group * Modality	-0.30 (.16)	-1.88	.061	-0.39 (.18)	-2.12	.034	-0.38 (.18)	2.09	.036

Significance: p >.05

⁺ In the trial-level (1) and multi-level model (3), trial-level WS (within-subject) LI and reaction time are centered by subject, which ensures its value represents intraindividual variation only. Thus, trial-level WS LI is not correlated ($r = .19$, $p < 0.10$) with subject-level BS LI.

⁺⁺ In the subject-level (2) and multi-level model (3), subject-level BS (between-subject) LI is centered by group, which ensures its value represents interindividual variation, controlling for trial-level LI and reaction time.

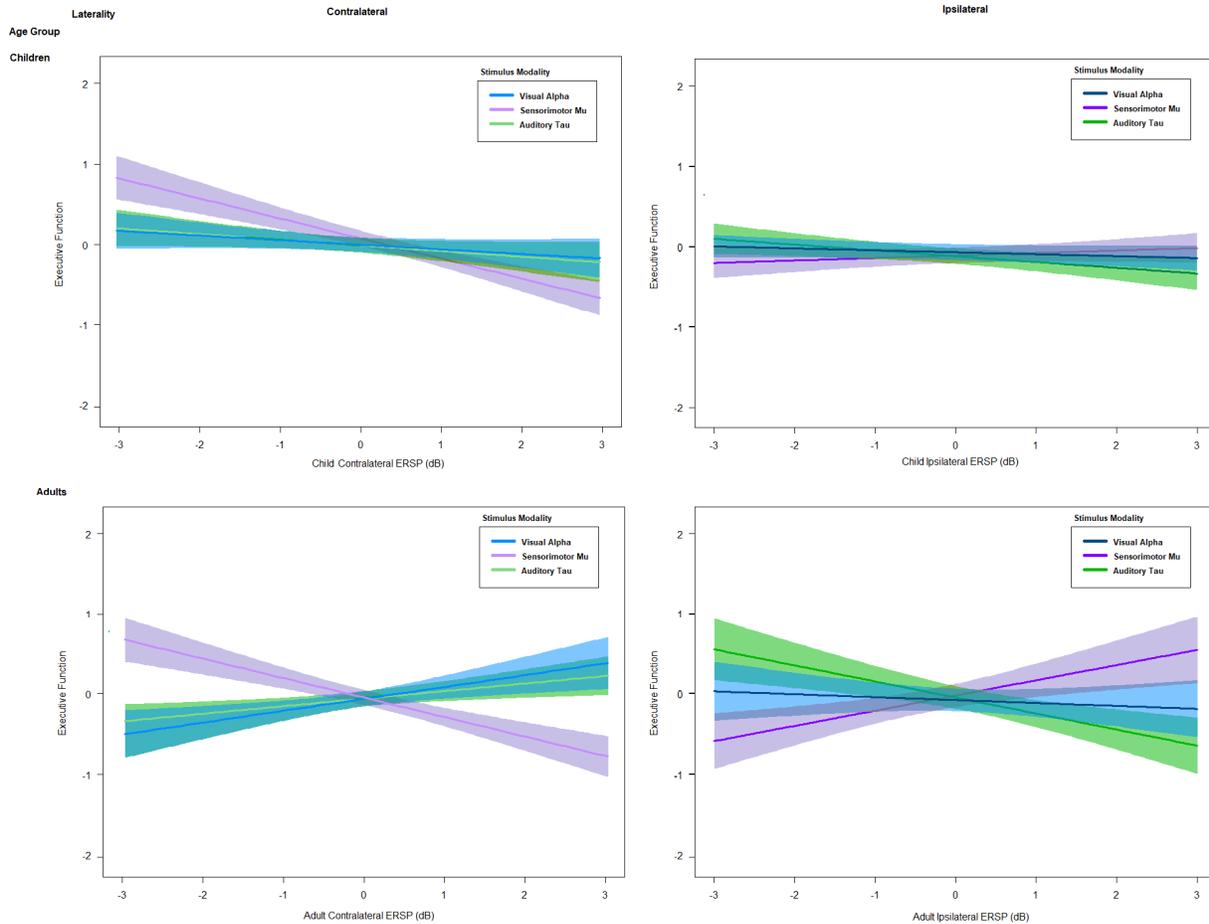


Figure 4. *Anticipatory alpha ERSP by sensory modality, presented by age group and lateralization.* The interaction of modality and alpha ERSP is displayed, separately (‘conditional’) for each age group (child/adult) and lateralization, controlling for within-subject variability in ERSP and its relations to reaction time at the single-trial level. Contralateral and ipsilateral between-subject mean ERSP are displayed on the X-axis, with standardized, group-centered executive function scores displayed on the Y-axis.

CHAPTER 4 DISCUSSION

The purpose of the current study was to assess linkages between neural measures of anticipation and variation in the ability to control action, capturing trial-level intra-individual dynamics and subject-level inter-individual variability. To further this aim, a cross-sectional developmental investigation explored variability in alpha-range EEG oscillatory activity during anticipation of visual, auditory and tactile stimuli in 40 6-8 year old children and 40 adults (undergraduate students aged 18 - 25). The primary findings concern age-related and modality-specific effects on the lateralization (contralateral – ipsilateral) of changes in EEG alpha power at electrode sites, indexing the stimulus-relevant sensory cortices. Further analyses examined how neural measures of sensory anticipation correspond with behavioral measures of action and cognitive control. Here, findings are summarized for readers, interpreted in the context of the wider literature and design limitations, and considered with regard to their implications for theories of cognitive development and attention malleability.

A blocked design was employed to elicit anticipation of visual, tactile and auditory target stimuli, with all targets preceded by an auditory cue that directed participant's attention to the spatial location (right or left) of the upcoming stimulus. Reaction time was recorded as the duration of time between target stimulus onset and participant's engagement with a foot pedal, which they used to report the number of target stimuli perceived (one vs. two). The ability to control action was operationalized via the speed of target stimulus detection (reaction time) and broader cognitive control abilities were operationalized via standardized scores on the NIH Toolbox measures of executive function. Child participants represented the diversity of the metropolitan area from which they were recruited, with even our sample of college-enrolled

adult participants representing a wide range of ethnic, cultural and socio-demographic backgrounds (Nielsen, Huan, Kartner & Legare, 2017).

A series of progressive, hierarchical nested models parsed intraindividual and interindividual variability in EEG responses. At the trial level, the first model estimated the association of reaction time and within-subject lateralized ERSP index (LI), as moderated by modality and participant age group. At the subject level, the second model estimated the association of executive function and between-subject LI, as moderated by modality and participant age group. A multi-level model combined variance at the trial and subject level to assess the association of executive function and between-subject LI, as moderated by modality and participant age group. The multi-level model revealed that individual differences observed in the second, subject-level model remained significant predictors of executive function scores when accounting for within-subject variability in LI and its association with single-trial reaction time.

Interpreting Study Findings

Consistent with the literature, reaction time was slower in children than in adults, and was fastest for tactile and auditory stimuli relative to visual stimuli. A noteworthy association was found between single-trial anticipatory visual alpha LI and reaction time to visual stimuli. Greater LI was associated with more rapid detection of the stimulus. This association was apparently driven by adult participants, but was also observed across most participants (including 24/40 children). A trending three-way interaction was observed, which was partially driven by children exhibiting reaction times that are more variable across trials than adults, even though mean reaction time was centered by age group and subject (thus group differences were

necessarily due to variability, not magnitude). Similar but slightly weaker associations between single-trial reaction time to tactile stimuli with anticipatory sensorimotor mu LI were observed, evident in children and adults.

A relation between EEG activity and reaction time was not found for auditory stimuli, which is consistent with the mixed literature on anticipatory tau rhythm responses to auditory stimuli. It is speculated that the unimodal nature of the auditory condition (an auditory target following an auditory cue) may have resulted in less salient stimulus anticipation, since participants were not required to shift across modalities (or indeed across spatial locations) between the cue and the target. In addition, although efforts were taken to remove time-locked ERPs from the ERSP signal, it is possible (though unlikely and not apparent in the sample-averaged frequency plots) that an orienting response elicited by the auditory cue contaminated a potential anticipatory tau rhythm response.

Consistent with previous investigations, desynchronization of the sensorimotor mu rhythm was observed in the hemisphere contralateral to the expected location of a tactile stimulus, suggesting that participants directed their attention to the relevant hand during the anticipatory epoch (Haegens et al., 2011; Anderson & Ding, 2011; Van Ede et al., 2014; Weiss, Meltzoff, & Marshall, 2018). Changes in mu power during anticipation of a tactile stimulus were associated with executive function abilities. Measures of executive function included the scores on a flanker task, which required participants to report the direction of a target central visual stimulus in a series, and a card sort task, which required participants to match test stimuli by a changing feature (shape or color) of the target stimulus.

Executive function score, the average of these age-standardized, group-centered scores on the flanker and card sort tasks, was significantly associated with *lateralized* individual differences in alpha power (the differences between contralateral and ipsilateral mu power). This effect was moderated by an interaction between the alpha power, sensory modality and group. The three-way interaction was driven by the negative association of executive function with children's contralateral desynchronization, while for adults there was a positive association of executive function and the lateralization index. As a result, executive function ability was explained by an interaction in the opposite direction for children and adults: for children, greater lateralization was indicated by a more negative LI value, while for adults, greater lateralization was indicated by a more positive LI value. The subject-level model accounted for 12% of variability in executive function score; a further 9% of variability in executive function was accounted for by a multi-level model that incorporated single-trial variability in alpha power, and its interaction with single-trial reaction time.

The use of the multi-level model and multiple NIH toolbox measures permitted us to identify the specificity of the findings. Importantly, anticipatory LI was not associated with accuracy of behavioral responses to target stimuli (presumably, because there was minimal sample and single-subject variation). Further, no such association was evident for within or between-subjects anticipatory LI with Receptive Language standardized score, as measured by the NIH Cognitive Toolbox.

The current findings contribute to the developmental cognitive neuroscience literature linking electrophysiological indices of selective attention to cognitive skills in children (Isbell et al., 2016; Shimi et al., 2015). The findings suggest that attention in the tactile modality is of

special neuropsychological significance, particularly given the status of touch as “the first sense” (Fulkerson, 2013), its relations with other modalities in early development (Bremner and Spence, 2017; Meltzoff et al., 2018; Saby et al., 2015), and the potential of work on attention to one’s own body to inform interventions targeted at improving attentional and executive abilities in young children (Diamond and Ling, 2016; Isbell et al., 2017). Our investigation informs models of action-oriented representation, in which anticipatory shifts in neural activity reflect biases in sensory processing in the context of impending action (Engel et al., 2013). The study of anticipatory attention, particularly in cross-modal, multi-level contexts, has the potential to further inform theories in developmental science (Meltzoff, 1990).

Specificity of Effects and Study Limitations

The results of this study are a novel advance in relating childhood EEG to executive function through studying the attention-related *change* in EEG responses specific to the deployment of attention. Further supporting the centrality of anticipatory attention in coordinating goal-directed regulation of behavior, only the executive function measures of behavioral inhibition (Flanker) and task-switching (Card Sort) were related to anticipatory changes in the mu rhythm. Receptive Language, which has been associated with alpha-range activity at rest in children (Kraybill & Bell, 2013), was not related to the extent of anticipatory alpha modulation.

In terms of limitations, the cross-sectional design of the study limits directional interpretations of the relations between anticipatory attention and executive function. Future studies would benefit from additional measures of executive function and could follow younger children over time, to test if the emergence of executive function skills may be predicted by earlier attention focusing abilities (Markant & Amso, 2016; Veer et al., 2017)., the Dimensional

Card Sort and Flanker tasks are widely used and well-studied in children. Future longitudinal EEG investigations of selective attention should consider including a battery of executive function measures (Kraybill & Bell, 2013), capturing children's increasing capacity to deal with complex, competing cognitive demands and flexibility of response (Zelazo et al., 2003), and that can be repeated from infancy to adolescence (Millar & Best, 2011).

One other important caveat is that in the studies of anticipation presented thus far, most tasks utilize spatial location as a distinguishing feature of targets, which can be leveraged in the study of lateralization and localization of EEG oscillations. The common role of spatial attention is implicit in both the executive function tasks and our anticipatory selective attention tasks (Ristic & Kingstone, 2009). Directional arrows cues have been found to facilitate children's reaction time on visual selective attention tasks (Ristic & Kingstone, 2006), more so than tasks which rely on feature-based characteristics as attentional cues to characteristics of upcoming stimuli. In contrast, this study utilized an auditory spatial cue to direct participant's attention, rather than a visuospatial cue; this provided two multi-modal conditions ideal for eliciting anticipation (tactile and visual), where effects were evident of anticipatory modulation and reaction time. This is not the ideal design to elicit and isolate stimulus-related anticipation in the auditory domain.

The ability to anticipate stimulation and to selectively attend to relevant spatial locations is often integral to executive function task demands (Banerjee et al., 2011; Garon et al., 2008; Veer et al., 2017). To circumvent consideration of spatial attention in paradigms concerning stimulus anticipation, future studies can modify our multi-modal selective attention paradigm by incorporating simultaneous distractors or pair a feature-based, non-spatial cue with a feature-based stimulus discrimination task. Our design utilized spatially-specific target stimuli to

explicitly examine the co-occurring process of spatial attention, to maintain consistency with the original Posner paradigm used to elicit stimulus anticipation and to capitalize on lateralized differences in ERSP across trials.

Relevant work in early childhood has typically focused on EEG or behavioral responses following presentation of the target stimulus, and often involves the presentation of simultaneous distracting stimuli in a spatial location and/or modality other than that indicated by the cue (Markant & Amso, 2016; Veer et al., 2017; Murphy et al., 2016). There is evidence that the ability to attend selectively to targets via attentional focusing (Heim & Keil, 2012; Veer et al., 2017) appears distinct from the slower-developing ability to inhibit attention to potential distractors (vigilance or inhibition; Plebanek, Sloutsky, Brodeurcowan, & Hulmezelazo, 2017).

One behavioral study found no significant differences in adult and 8-year old children's reaction time responses on the Posner cueing task, but when a visual distractor was also presented simultaneously in the uncued spatial location, children exhibited significant reductions in reaction time (Ristic & Kingstone, 2009). Thus, the presentation of distractors may interfere with attention deployment (Goldberg & Lewis 2001; Plebanek et al., 2017), our study of anticipatory attention required children to attend and respond to visual, tactile, and auditory stimulation. As such, the task demands differed from studies of selective attention in adults, which involve presentation of simultaneous distractors, leveraging distractors to study suppression of attention using synchronization of alpha-range EEG at ipsilateral sites (Haegens et al., 2011; Murphy et al., 2016; Zanto & Gazzaley, 2009). The differences between our protocol and other studies noted above is a plausible explanation for why children did not exhibit ipsilateral increases in sensorimotor mu ERSP, while although modest ipsilateral increases in visual alpha ERSP were evident.

The existing literature on EEG modulation elicited by distractor suppression may cloud the role of attentional focusing as a foundational construct of cognitive flexibility and executive functions. One strength of the current work is our focus on sensorimotor mu desynchronization preceding the onset of a target tactile stimulus as an index of anticipatory processing that is not clouded by neural responses to cue, target, or distractor stimuli – study of anticipatory neural activity across sensory modalities can further isolate the deployment of ‘endogenous’ attention, in preparation for action or while monitoring for changes in the environment (Arnal & Giraud, 2012).

Anticipatory Attention to the Body: Modality-Specific or Mu-Specific?

As shown by the findings of Model 1, the association of greater anticipatory alpha lateralization with faster reaction times suggests that across development (N=80), variability of within-subjects anticipatory alpha power indexes stimulus processing speed. Evident by Model 2, between-subjects mu ERSP in anticipation of a tactile stimulus is associated with the ability to control action, as measured by executive function. Model 3 demonstrated that although the trial-by-trial dynamics coupling alpha lateralization and action (level 1) partially cascade into individual differences in executive function, meaningful individual differences across development in alpha lateralization (in anticipation of tactile stimuli only) contribute to executive function variability (level 2).

Why might alpha fluctuations in anticipation of tactile stimuli, as opposed to auditory or visual stimuli, be a more viable index of variability in executive function abilities? The primacy of somatosensation to perception-action linkages may have evolutionary origins, with simple organisms using somatosensory information to direct their approach-avoid responses (Anishkin

et al., 2014; Fulkerson, 2013; Lumpkin, Marshall & Nelson, 2010). Across development, mu has been shown to change during spatial attention, tactile stimulus perception, action planning and motor execution (Bauer et al., 2012, Thorpe et al., 2012; Anderson & Ding, 2012; Cannon et al., 2016; Hobson & Bishop, 2017).

The current findings indicate developmental differences in how attention is allocated in expectation of a tactile stimulus: speculatively, younger children may deliberately focus on monitoring sensation at the cued location while adults deploy effort into inhibiting sensation at the uncued bodily location. Such task-specific strategies could explain the observed patterns of lateralized mu oscillations and the difference in which hemisphere accounted for a greater share of variance in executive function skills. It is possible that attention to bodily sensations and variability in perceived boundaries between the body, peripersonal space and extrapersonal space contributed to these developmental and individual differences (Bremner et al., 2017; Hunley et al., 2016; Serino, 2019), or that mu oscillations may have greater inter-individual variability than other alpha-range rhythms (Clayton et al., 2017).

In addition to the noted developmental differences in alpha modulation by sensory modality, the extent of lateralization differed in children and adults by sensory modality, such that adults exhibited greater lateralization due to heightened synchronization of alpha at ipsilateral sites than children. In adults compared to children, alpha modulation (across sensory modalities) exhibited wider variability in the ipsilateral cortices, while there was a more consistent response evident in the contralateral sensory cortices. However, children largely exhibited minimal changes in anticipatory alpha responses at sites indexing ipsilateral sensory cortices, while there

was greater variability in sites indexing contralateral sensory cortices. These results were apparent irrespective of cue direction.

Our results support the suggestion that the variability of anticipatory alpha-range responses may index individual differences in how adults approached the sensory anticipation task, relying on a subtle, strategic approach to selective attention deployment. Children might manifest less variability in task strategy than adults. One neural explanation for these differences in strategic attention allocation across development might be that global inhibition of neural activity (or ‘rest’ itself) is an effortful task for children (Camacho, Quiñones-Camacho, & Perlman, 2020). Thus, children may exhibit more variability in fluctuations of activity at baseline, altering the threshold for significant changes such that only contralateral reductions are consistently different across participants. Another possibility is that the prevalence of ipsilateral increases concomitant with contralateral reductions in ERSP may occur gradually over the course of development, and thus for children the association of anticipatory mu with executive function is primarily driven by the neural responses involved in the allocation (rather than inhibition) of attention.

In interpreting the significant association of *ipsilateral* mu activity with executive function, evident only in adults, we look to two current explanations for the function of sensory-specific alpha oscillations. In one account, alpha oscillations have been ascribed an inhibitory function (Klimesch et al., 1998; Mahzeri and Jensen, 2010), which underpins the notion of a ‘gating’ function of ipsilateral alpha increases. This suggestion is supported by associations between anticipatory ipsilateral alpha power increases and task-relevant stimulus detection rate as well as speed of behavioral responses, across various sensory modalities (Frey et al., 2015;

Jensen & Mazaheri, 2010; Van Diepen, Foxe, & Mazaheri, 2019). In the ‘active sensing’ account of alpha oscillations, increases in power (or power hovering at baseline) over ipsilateral sensory cortices serve to suppress the sampling of events at an unattended location (Shroeder and Latkos, 2009; van Ede et al., 2014; Thut et al., 2006). These complementary accounts provide insight into the functional significance of ipsilateral changes in sensory-specific alpha responses (Van Diepen, Foxe, & Mazaheri, 2019; Liley, & Muthukumarswamy, 2020).

The current findings can inform existing computational and theoretical frameworks of sensory processing that show a relation between anticipatory neural activity and inter-individual variability in perceptual experience to target stimuli (Summerfield & de Lange, 2017). Neural responses associated with selective attention to the body and tactile stimulation provide an opportunity for further study of multisensory integration (Bremner & Spence, 2017) and the primacy of self-models and body-generated signals (Allen & Tsakiris, 2018; Yin et al., 2016). In adults, studying mu modulation evoked by tactile stimuli has demonstrated the centrality of somatosensory experience to sensory processing and goal-directed action. Coll et al. (2017) employed a multivariate classifier to examine whether variability in occipital alpha and central sensorimotor mu oscillations can parse action experience, action observation and tactile experience. During the study, adults watched an actor reach for an object, contact (touch) an object, or executed those actions themselves. The authors reported that changes in the mu rhythm distinguish between passive observation, action execution and the experience of tactile stimulation, finding that significant variance in mu activity (relative to co-occurring occipital alpha) was specific to observed and executed physical contact with an object, as well as the presence and anticipation of vibrotactile stimulation. Coll et al. (2017) suggest that the anticipated (imagined) and actual tactile experience which elicits similar activation, rather than

identifying the shared variance of alpha responses during observation and execution of an action as ‘sympathetic’ motor activation. Thus, it is suggested that responses specific to sensorimotor μ index the attention to the body boundary, relevant for the recognition of somatosensory expectancies and tactile events, rather than mirroring motor activity common to observation and execution of action kinds (Hobson & Bishop, 2017).

Further, anticipation presents a promising construct for investigating allostatic theories of neural self-regulation and prediction, given that variability in anticipatory neural activity may integrate both prior experience and ecologically driven expectancies (Allen & Friston, 2018; Bruinberg et al., 2018; Jones, 2019). Anticipation appears to elicit a goal-driven calibration of sensory input that may manifest in attention-related shifts in behavior as well as influencing perceptual experiences and responses to the appearance of the anticipated stimulus (Serino et al., 2019; de Lange, Heilbron & Kok, 2018; Ionta, Gassert, & Blanke, 2011).

Broader Implications: Applications for Malleability of Selective Attention

Once fully characterized, neural indices of cross-modal anticipation can be applied as a tool to investigate the efficacy of selective attention interventions, assessing theories of attention as a flexible, voluntary ability, influenced by instruction, motivation and environmental demands (Posner et al., 2012). Individual differences in selective attention and executive function abilities in early childhood have been shown to predict children’s later academic achievement (Raver et al., 2012; Stevens & Bavelier, 2012) and appear malleable to intervention (Bryck & Fisher, 2012; Diamond & Lee, 2011). Anticipatory changes in ERSP could prove a promising target for interventions if the goal is to train broad cognitive skills by brief, generalizable interventions. There is conflicting evidence on whether benefits of training one

aspect of executive function, such as working memory, generalizes to other cognitive domains or even to tangential executive function skills (for review, see Diamond & Ling, 2016; Morrison & Chein, 2011; Thorell et al., 2009). For example, though Blakey and Carroll (2015) found that executive function training improved 4-year-olds performance on similar working memory tasks, the benefits did not transfer to measures of other domains of executive function. In particular, children from lower income households appear to exhibit less robust responses to executive function interventions, even when the trained skill is tested (Traverso, Viterbori & Usai, 2015; Zelazo et al., 2018; Diamond & Ling, 2016). What remains evident is that executive function development and malleability are on-going across the lifespan, with great variability evident within individuals over time (Richmond, Morrison, Chein & Olsen, 2011).

In contrast to the mixed literature supporting the efficacy of executive function interventions, training selective attention appears to transfer to distal cognitive abilities (Tang & Posner, 2012). Significant changes have been observed in various task-relevant electrophysiological signals following selective attention interventions, whether implemented by directly targeting selective attention using computerized interventions (Rueda et al., 2005) and video games (Cardoso-Leite & Bavelier, 2014), or indirectly following parenting interventions (Neville et al., 2013) or mindfulness practice (Tang et al., 2014). A recent dissertation study comparing these strategies (Esposito, 2015) used neurocognitive assessments and ERP evoked by inhibition during the flanker, and reported improved efficiency of attentional networks after 12 classes of attention training (experimental group) compared with an equal exposure to mindfulness intervention and executive function training (control groups) in 4- to 6-year-old children (Esposito, 2015).

Our prior published study (Weiss, Meltzoff, & Marshall, 2018) included a finding of enhanced preparatory EEG activity in children from higher socio-economic status (SES) backgrounds, which supports the notion that the early environment shapes neural activation related to attentional focusing, expectation of sensation, and goal-directed action (Raver & Clancy, 2014; Hackman et al., 2015; Sheese et al., 2012). Further, the magnitude of mu suppression in higher-income children was comparable to the modulation observed in adults during a similar paradigm (Shen et al., 2017) while children from lower-income households exhibited less pronounced modulation of mu rhythm (Weiss, Meltzoff, & Marshall, 2018). The finding of enhanced preparatory EEG activity in children from higher-income families supports the notion that the early environment may shape neural activity related to attentional focusing, prediction, and goal-directed action (Hackman & Farah, 2009).

These findings are in line with prior ERP work finding higher-SES participants exhibited a more 'mature' pattern of activation (Markant & Amso, 2016), seen in a study of auditory selective attention in which only children with more educated caregivers exhibited ERP responses differentiating distracting stimuli from target stimuli (Stevens, Lauinger, & Neville, 2009). The results of Weiss et al. (2018) differed from the existing literature in that identifying SES differences in mu modulation elicited in anticipation of target stimuli rather than in response to the stimuli or distractors; previous studies of selective attention in children report ERP and theta modulation evoked by distracting, uncued auditory stimuli distinguished high and low-income children (Stevens et al., 2009). The extensive literature on SES disparities in development is largely focused on higher-order cognitive outcomes such as executive function (Raver, Blair, Willoughby, 2012; Noble, McCandliss, & Farah, 2007), language (Pace, Luo, Hirsh-Pasek, & Golinkoff, 2017), reading (Noble et al., 2006; Raizada, Richards, Meltzoff, &

Kuhl, 2008), and self-regulation (Sturge-Apple et al., 2016). The findings of Weiss et al. (2018) suggest some variability in these cognitive outcomes may be accounted for by SES differences in anticipation of, attention to and processing of stimuli in neurocognitive tasks (Raizada & Kishiyama, 2010), which can be furthered examined in these child and adult samples.

Our present findings are largely consistent with the related literature on proactive control of visual attention as a source of variation specific task-switching and working memory abilities (Elke & Wiebe, 2017; Schimi et al., 2015), with anticipatory alpha lateralization across modalities serving as a potential source of variation in self-regulation more broadly. Further, anticipatory mu desynchronization may have utility as a specific neural marker of attention to the body (Kerr et al., 2013). Additionally, reliable individual differences in anticipatory attention can be measured in infancy (Heim & Keil, 2012; Markant & Amso, 2016), so assessment of anticipatory capacities could be useful for identifying children with issues in regulating behavior and attention before school entry (Gutiérrez-Hernández et al., 2017; Felver et al., 2016). The presented findings informs our understanding of the contribution of development differences in attention to fluctuations of adult and child neural responses in multi-modal sensory paradigms. Training selective attention to stimuli in the visual and tactile modality have shown consistent and robust response to training that transfers across modalities (Posner et al., 2012; Thorrell et al., 2009), though it is unknown if interventions targeting selective attention deployment differs by the targeted sensory modalities (Zelazo et al., 2018). Our results suggest that stimulus anticipation may be a promising target for evaluating the efficacy of selective attention interventions, particularly those which focus on creating a more consistent response across trials may be an effective means of targeting selective attention and cognitive skills more broadly (Diamond & Ling, 2016).

Future Directions: Anticipation as a Framework for Theories of Cognitive Development

Situated at the interface of sensory processing and higher-order cognition, the ability to deploy anticipatory attention is a foundational skill that is present early in life (Johnson et al. 1991; Rueda et al., 2005; Tarantino et al., 2017; Xie et al., 2017). Our findings suggest important differences between children and adults in the balance of contralateral and ipsilateral anticipatory EEG responses across sensory modalities. These results invite work with children younger than those studied here: We suggest that alpha rhythm modulation during anticipatory attention tasks may potentially be a useful (and developmentally consistent) indicator of attention across a relatively wide age range.

Anticipation may be considered foundational to the development of autonomous control of action in infancy, shifting from largely reactive changes in an infant's immediate environment and bodily state, to the self-regulated attention evident in early childhood, in which children can act to exert deliberate, planned changes in their environment and to change or maintain their bodily state (Haith, 1998; Vernon, 2014; Aslin, 2014). Children's ability to anticipate caregiver responses to their own actions may be critical to facilitating quality parent-child interactions, engendering shared goals, joint attention (Hirsh-Pasek et al., 2015; Yu & Smith, 2016), and synchrony of action. Needham & Libertus (2011) suggest that infant cognition is 'more embodied' than adult cognition: although even fetuses learn to bias towards goals in steering their actions (Reissland et al., 2014; Zoia et al., 2007), goal-directed control of action is deemed an experience-dependent skill, which develops gradually across infancy (Needham & Libertus, 2011). The embodiment of cognition remains foundational to the ability to plan, direct and control action throughout the lifespan, such as an organism's physiological patterns and physical

composition enable (and constrain) the repertoire of imagined, anticipated, afforded and enacted behaviors (Marshall, 2016).

Future work can longitudinally follow the developmental trajectory of anticipatory neural responses, alongside behavioral measures tapping into cognitive development. Such studies can model cross-modal cueing as a tool that can be utilized to eavesdrop on anticipatory abilities in infancy, with a view to empirically testing prediction-based (i.e., Bayesian) theories of cognitive development (Koudier et al., 2015). Similar methods could be applied to the study of bodily attention, providing insights into the maturation of prospective capacities and developmental increases in organized, self-directed actions (Engel, 2013) and the emergence of executive functions in childhood. Studies of this kind can invite inquiries into and explanations of child development from diverse perspectives in cognitive science.

Inherent in most contemporary accounts of childhood behavior and neural activity are information processing models of cognition (Aslin, 2014; Woodward et al., 2012; Basirat, Dehaene, & Dehaene-Lambertz, 2015). Even infants' activities are thought to arise from procedural (associative or connectionist) or probabilistic reasoning based on a prior model, with this information processing encapsulated in the brain. A more integrative perspective sees anticipation as a function of the actions of the fully embodied organism (Clark, 1998). From this perspective, the organism as active agent both acts, which constitutes a prediction, and modifies its actions, which operates to reduce an error of prediction (Marshall, 2015). Elements of this framework are visible in some contemporary probabilistic accounts (Friston, Mattout, & Kilner, 2011; Huang & Rao, 2011) although a truly integrative perspective that acknowledges the embodied nature of development processes has yet to significantly inform work in this area (Marshall, 2015). Anticipatory modulation of the sensorimotor mu rhythm is well-suited to

related developmental investigations: Studies of tactile stimulation can uniquely inform the understanding of action-oriented representation (Bremner, 2016), with anticipatory shifts in neural activity understood as reflecting biases in sensory processing in the context of impending action (Engel et al., 2013).

Interpreting the findings of the current study and our prior investigation (Weiss et al., 2018) through an embodied predictive processing approach, adults and children can be viewed as constructing action-based models of possible events in the environment using prior sensory experience, thus the models have predictive value in terms of regularities in the environment. Specifically, the temporal and spatial information embedded in the spatial cue is associated with an upcoming event in another sensory modality, the tactile stimulation. Predictive coding would assume this model to be self-generated and dynamic, in that it can flexibly accommodate new experience and unexpected events (Clark, 2015). Such accommodation may be critical in facilitating the ongoing development of anticipatory abilities and their use in directing fluid action (Engel, 2013) across sensory modalities and domains of experience, such that predictions become more accurate and relevant to fluctuations in the immediate environment over the course of development. Ultimately, the continued development of prospective abilities in children allows them to select from a wider array of effective actions at any given time (Vernon, 2014). Integration of anticipatory alpha-range signals with behavioral indices of anticipation is needed to further cement the centrality of anticipation to action.

Conclusion: Anticipation as a Bridge across Perspectives in Developmental Science

The construct of anticipation provides a useful, quantifiable, specific means of tracking attention deployment across modalities and development, accounting for variance in measures of cognitive skills. The relations described here between modulation of the mu rhythm during bodily attention and executive function can be leveraged to study component processes of executive function and attention across a range of ages. Analysis of activity during stimulus anticipation can extend the understanding action control and self-regulation in young children. These results can be applied to understand infant attention fluctuations during interactions with objects and caregivers (Morse et al., 2014; Feldman, 2012), with anticipation in the somatosensory modality serving as one demonstration of how children's attentional state is guided dynamically by prior experience to facilitate perception and direct action.

REFERENCES

- Allen, M., Friston, K.J., 2018. From cognitivism to autopoiesis: towards a computational framework for the embodied mind. *Synthese* 195, 2459–2482. <https://doi.org/10.1007/s11229-016-1288-5>
- Amso, D., Scerif, G., 2015. The attentive brain: Insights from developmental cognitive neuroscience. *Nat. Rev. Neurosci.* <https://doi.org/10.1038/nrn4025>
- Arnal, L.H., Giraud, A.-L., 2012. Cortical oscillations and sensory predictions. *Trends Cogn. Sci.* 16, 390–398. <https://doi.org/10.1016/J.TICS.2012.05.003>
- Aslin, R.N., 2014. Infant Learning: Historical, Conceptual, and Methodological Challenges. *Infancy* 19, 2–27. <https://doi.org/10.1111/infa.12036>
- Baldwin, D.A., Baird, J.A., Saylor, M.M., Clark, M.A., 2001. Infants Parse Dynamic Action. *Child Dev.* 72, 708–717. <https://doi.org/10.1111/1467-8624.00310>
- Banerjee, S., Snyder, A.C., Molholm, S., Foxe, J.J., 2011. Oscillatory alpha-band mechanisms and the deployment of spatial attention to anticipated auditory and visual target locations: supramodal or sensory-specific control mechanisms? *J. Neurosci.* 31, 9923–9932. <https://doi.org/10.1523/JNEUROSCI.4660-10.2011>
- Basirat, A., Dehaene, S., Dehaene-Lambertz, G., 2014. A hierarchy of cortical responses to sequence violations in three-month-old infants. *Cognition* 132, 137–150. <https://doi.org/10.1016/J.COGNITION.2014.03.013>
- Beck, D.M., Schaefer, C., Pang, K., Carlson, S.M., 2011. Executive function in preschool children: Test–retest reliability. *J. Cogn. Dev.* 12, 169–193. <https://doi.org/10.1080/15248372.2011.563485>
- Bell, M.A., 2002. Power changes in infant EEG frequency bands during a spatial working memory task. *Psychophysiology* 39, 450–458. <https://doi.org/10.1017/S0048577201393174>
- Bengson, J.J., Mangun, G.R., Mazaheri, A., 2012. The neural markers of an imminent failure of response inhibition. *Neuroimage* 59, 1534–1539. <https://doi.org/10.1016/J.NEUROIMAGE.2011.08.034>
- Berchicci, M., Zhang, T., Romero, L., Peters, A., Annett, R., Teuscher, U., Bertollo, M., Okada, Y., Stephen, J., Comani, S., 2011. Development of mu rhythm in infants and preschool children. *Dev. Neurosci.* 33, 130–143. <https://doi.org/10.1159/000329095>
- Bergman Nutley, S., Söderqvist, S., Bryde, S., Thorell, L.B., Humphreys, K., Klingberg, T., 2011. Gains in fluid intelligence after training non-verbal reasoning in 4-year-old children: a controlled, randomized study. *Dev. Sci.* 14, 591–601. <https://doi.org/10.1111/j.1467-7687.2010.01022.x>

- Black, D.S., Fernando, R., 2014. Mindfulness Training and Classroom Behavior Among Lower-Income and Ethnic Minority Elementary School Children. *J. Child Fam. Stud.* 23, 1242–1246. <https://doi.org/10.1007/s10826-013-9784-4>
- Blair, C., Raver, C.C., 2015. School Readiness and Self-Regulation: A Developmental Psychobiological Approach. *Annu. Rev. Psychol.* 66, 711–731. <https://doi.org/10.1146/annurev-psych-010814-015221>
- Blair, C., Razza, R.P., 2007. Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Dev.* 78, 647–663. <https://doi.org/10.1111/j.1467-8624.2007.01019.x>
- Blakey, E., Carroll, D.J., 2015. A short executive function training Program improves Preschoolers' Working Memory. *Front. Psychol.* 6, 1827-1844. <https://doi.org/10.3389/fpsyg.2015.01827>
- Brandone, A.C., Horwitz, S.R., Aslin, R.N., Wellman, H.M., 2014. Infants' goal anticipation during failed and successful reaching actions. *Dev. Sci.* 17, 23–34. <https://doi.org/10.1111/desc.12095>
- Brandone, A.C., Wellman, H.M., 2009. You can't always get what you want. *Psychol. Sci.* 20, 85–91. <https://doi.org/10.1111/j.1467-9280.2008.02246.x>
- Bremner, A.J., 2016. Developing body representations in early life: combining somatosensation and vision to perceive the interface between the body and the world. *Dev. Med. Child Neurol.* 58, 12–16. <https://doi.org/10.1111/dmcn.13041>
- Bremner, A.J., Holmes, N.P., Spence, C., 2008. Infants lost in (peripersonal) space? *Trends Cogn. Sci.* 12, 298–305. <https://doi.org/10.1016/J.TICS.2008.05.003>
- Bressler, S.L., Tang, W., Sylvester, C.M., Shulman, G.L., Corbetta, M., 2008. Top-down control of human visual cortex by frontal and parietal cortex in anticipatory visual spatial attention. *J. Neurosci.* 28, 10056–10061. <https://doi.org/10.1523/JNEUROSCI.1776-08.2008>
- Brock, L.L., Rimm-Kaufman, S.E., Nathanson, L., Grimm, K.J., 2009. The contributions of 'hot' and 'cool' executive function to children's academic achievement, learning-related behaviors, and engagement in kindergarten. *Early Child. Res. Q.* 24, 337–349. <https://doi.org/10.1016/J.ECRESQ.2009.06.001>
- Bryck, R.L., Fisher, P.A., 2012. Training the brain: practical applications of neural plasticity from the intersection of cognitive neuroscience, developmental psychology, and prevention science. *Am. Psychol.* 67, 87–100. <https://doi.org/10.1037/a0024657>
- Bull, R., Lee, K., n.d. Title Executive functioning and mathematics achievement Executive Functioning and Mathematics Achievement. *Source Child Dev. Perspect.* 8, 36–41. <https://doi.org/10.1111/cdep.12059>
- Calipso Gutiérrez-Hernández, C., Harmony, T., Nélida, G., -Ramírez, A.-C., Barrón-Quiroz, I., Guillén-Gasca, V., Tre-Jo-Bautista, G., Bautista-Olvera, M.M., 2017. Infant Scale of Selective Attention: A proposal to assess cognitive abilities. *Rev. Evaluar* 17, 30–51.

- Cannon, E.N., Simpson, E.A., Fox, N.A., Vanderwert, R.E., Woodward, A.L., Ferrari, P.F., 2016. Relations between infants' emerging reach-grasp competence and event-related desynchronization in EEG. *Dev. Sci.* 19, 50–62. <https://doi.org/10.1111/desc.12295>
- Cannon, E.N., Woodward, A.L., 2012. Infants generate goal-based action predictions. *Dev. Sci.* 15, 292–298. <https://doi.org/10.1111/j.1467-7687.2011.01127.x>
- Capilla, A., Schoffelen, J.-M., Paterson, G., Thut, G., Gross, J., 2014. Dissociated α -Band Modulations in the Dorsal and Ventral Visual Pathways in Visuospatial Attention and Perception. *Cereb. Cortex* 24, 550–561. <https://doi.org/10.1093/cercor/bhs343>
- Cardoso, C. de O., Dias, N., Senger, J., Colling, A.P.C., Seabra, A.G., Fonseca, R.P., 2018. Neuropsychological stimulation of executive functions in children with typical development: A systematic review. *Appl. Neuropsychol. Child* 7, 61–81. <https://doi.org/10.1080/21622965.2016.1241950>
- Cardoso-Leite, P., Bavelier, D., 2014. Video game play, attention, and learning. *Curr. Opin. Neurol.* 27, 185–191. <https://doi.org/10.1097/WCO.0000000000000077>
- Carlson, S.M., 2005. Developmentally Sensitive Measures of Executive Function in Preschool Children. *Dev. Neuropsychol.* 28, 595–616. https://doi.org/10.1207/s15326942dn2802_3
- Chica, A.B., Bartolomeo, P., Lupiáñez, J., 2013. Two cognitive and neural systems for endogenous and exogenous spatial attention. *Behav. Brain Res.* 237, 107–123. <https://doi.org/10.1016/J.BBR.2012.09.027>
- Clark, A., 1998. *Being there: Putting brain, body, and world together again*, MIT press.
- Clark, A., 2017. *Surfing uncertainty : prediction, action, and the embodied mind*. Oxford University Press.
- Clark, A., Chalmers, D., 1998. *The Extended Mind. Analysis.* <https://doi.org/10.2307/3328150>
- Coch, D., Sanders, L.D., Neville, H.J., 2005. An Event-related Potential Study of Selective Auditory Attention in Children and Adults. *J. Cogn. Neurosci.* 17, 605–622.
- Crane, R.S., Brewer, J., Feldman, C., Kabat-Zinn, J., Santorelli, S., Williams, J.M.G., Kuyken, W., 2017. What defines mindfulness-based programs? The warp and the weft. *Psychol. Med.* 47, 990–999. <https://doi.org/10.1017/S0033291716003317>
- Duggan, M., & Tressoldi, P. 2018. Predictive physiological anticipatory activity preceding seemingly unpredictable stimuli: An update of Mossbridge et al's meta-analysis. *F1000Research*, 7, 407. <https://doi.org/10.12688/f1000research.14330.2>
- Davidson, R.J., Kabat-Zinn, J., Schumacher, J., Rosenkranz, M., Muller, D., Santorelli, S.F., Urbanowski, F., Harrington, A., Bonus, K., Sheridan, J.F., 2003. Alterations in Brain and Immune Function Produced by Mindfulness Meditation. *Psychosom. Med.* 65, 564–570. <https://doi.org/10.1097/01.PSY.0000077505.67574.E3>

- de Barbaro, K., Johnson, C.M., Forster, D., Deák, G.O., 2016. Sensorimotor Decoupling Contributes to Triadic Attention: A Longitudinal Investigation of Mother-Infant-Object Interactions. *Child Dev.* 87, 494–512. <https://doi.org/10.1111/cdev.12464>
- Denis, D., Rowe, R., Williams, A.M., Milne, E., 2017. The role of cortical sensorimotor oscillations in action anticipation. *Neuroimage* 146, 1102–1114. <https://doi.org/10.1016/J.NEUROIMAGE.2016.10.022>
- Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* 134, 9–21. <https://doi.org/10.1016/J.JNEUMETH.2003.10.009>
- Diamond, A., 2013. Executive Functions. *Annu. Rev. Psychol.* 64, 135–168. <https://doi.org/10.1146/annurev-psych-113011-143750>
- Diamond, A., Lee, K., 2011. Interventions shown to aid executive function development in children 4 to 12 years old. *Science* 333, 959–964. <https://doi.org/10.1126/science.1204529>
- Diamond, A., Ling, D.S., 2016. Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Dev. Cogn. Neurosci.* 18, 34–48. <https://doi.org/10.1016/J.DCN.2015.11.005>
- Dick, A., Overton, W., 2010. Executive function: Description and explanation. *Self Soc. Regul. Soc. Interact. Dev. Soc. Underst. Exec. Funct.* 7–34.
- Doricchi, F., Macci, E., Silvetti, M., Macaluso, E., 2010. Neural Correlates of the Spatial and Expectancy Components of Endogenous and Stimulus-Driven Orienting of Attention in the Posner Task. *Cereb. Cortex* 20, 1574–1585. <https://doi.org/10.1093/cercor/bhp215>
- Drew, A.R., Quandt, L.C., Marshall, P.J., 2015. Visual influences on sensorimotor EEG responses during observation of hand actions. *Brain Res.* 1597, 119–128. <https://doi.org/10.1016/J.BRAINRES.2014.11.048>
- Driver, J., Frackowiak, R.S.J., 2001. Neurobiological measures of human selective attention. *Neuropsychologia* 39, 1257–1262. [https://doi.org/10.1016/S0028-3932\(01\)00115-4](https://doi.org/10.1016/S0028-3932(01)00115-4)
- Duckworth, A., Steinberg, L., 2015. Unpacking Self-Control. *Child Dev. Perspect.* 9, 32–37. <https://doi.org/10.1111/cdep.12107>
- Emberson, L.L., Boldin, A.M., Riccio, J.E., Guillet, R., Aslin, R.N., 2017. Deficits in Top-Down Sensory Prediction in Infants At Risk due to Premature Birth. *Curr. Biol.* 27, 431–436. <https://doi.org/10.1016/J.CUB.2016.12.028>
- Engel, A.K., Fries, P., Singer, W., 2001. Dynamic predictions: Oscillations and synchrony in top-down processing. *Nat. Rev. Neurosci.* 2, 704–716. <https://doi.org/10.1038/35094565>
- Engel, A.K., Maye, A., Kurthen, M., KöNig, P., 2013. Where's the action? The pragmatic turn in cognitive science. *Trends Cogn. Sci.* 17, 202–209. <https://doi.org/10.1016/j.tics>

- Falck-Ytter, T., Gredebäck, G., von Hofsten, C., 2006. Infants predict other people's action goals. *Nat. Neurosci.* 9, 878–879. <https://doi.org/10.1038/nn1729>
- Fan, Y., Tang, Y.-Y., Tang, R., Posner, M.I., 2014. Short Term Integrative Meditation Improves Resting Alpha Activity and Stroop Performance. *Appl. Psychophysiol. Biofeedback* 39, 213–217. <https://doi.org/10.1007/s10484-014-9258-5>
- Fausey, C.M., Jayaraman, S., Smith, L.B., 2016. From faces to hands: Changing visual input in the first two years. *Cognition* 152, 101–107. <https://doi.org/10.1016/J.COGNITION.2016.03.005>
- Feldman, R., 2012. Bio-behavioral Synchrony: A Model for Integrating Biological and Microsocial Behavioral Processes in the Study of Parenting. *Parenting* 12, 154–164. <https://doi.org/10.1080/15295192.2012.683342>
- Felver, J.C., Celis-de Hoyos, C.E., Tezanos, K., Singh, N.N., 2016. A Systematic Review of Mindfulness-Based Interventions for Youth in School Settings. *Mindfulness (N. Y.)* 7, 34–45. <https://doi.org/10.1007/s12671-015-0389-4>
- Flook, L., Smalley, S.L., Kitil, M.J., Galla, B.M., Kaiser-Greenland, S., Locke, J., Ishijima, E., Kasari, C., 2010. Effects of Mindful Awareness Practices on Executive Functions in Elementary School Children. *J. Appl. Sch. Psychol.* 26, 70–95. <https://doi.org/10.1080/15377900903379125>
- Foxe, J.J., Snyder, A.C., 2011. The Role of Alpha-Band Brain Oscillations as a Sensory Suppression Mechanism during Selective Attention. *Front. Psychol.* 2, 154–170. <https://doi.org/10.3389/fpsyg.2011.00154>
- Frey, J.N., Mainy, N., Lachaux, J.-P., Müller, N., Bertrand, O., Weisz, N., 2014. Selective modulation of auditory cortical alpha activity in an audiovisual spatial attention task. *J. Neurosci.* 34, 6634–6649. <https://doi.org/10.1523/JNEUROSCI.4813-13.2014>
- Frey, J.N., Ruhnau, P., Weisz, N., 2015. Not so different after all: The same oscillatory processes support different types of attention. *Brain Res.* 1626, 183–197. <https://doi.org/10.1016/J.BRAINRES.2015.02.017>
- Friston, K., Kiebel, S., 2009. Predictive coding under the free-energy principle. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 364, 1211–1221. <https://doi.org/10.1098/rstb.2008.0300>
- Friston, K., Mattout, J., Kilner, J., 2011. Action understanding and active inference. *Biol. Cybern.* 104, 137–160. <https://doi.org/10.1007/s00422-011-0424-z>
- Fuhs, M.W., Nesbitt, K.T., Farran, D.C., Dong, N., 2014. Longitudinal associations between executive functioning and academic skills across content areas. *Dev. Psychol.* 50, 1698–1709. <https://doi.org/10.1037/a0036633>
- Fujioka, T., Mourad, N., Trainor, L.J., 2011. Development of auditory-specific brain rhythm in infants. *Eur. J. Neurosci.* 33, 521–529. <https://doi.org/10.1111/j.1460-9568.2010.07544.x>

Fujioka, T., Ross, B., 2008. Auditory processing indexed by stimulus-induced alpha desynchronization in children. *Int. J. Psychophysiol.* 68, 130–140.

<https://doi.org/10.1016/J.IJPSYCHO.2007.12.004>Fulkerson, M., 2014. *The First Sense. A Philosophical Study of Human Touch.* Cambridge,

MA: MIT Press; 10.7551/mitpress/9780262019965.001.0001

Gallant, S.N., 2016. Mindfulness meditation practice and executive functioning: Breaking down the benefit. *Conscious. Cogn.* 40, 116–130. <https://doi.org/10.1016/J.CONCOG.2016.01.005>

Garon, N., Smith, I.M., Bryson, S.E., 2014. A novel executive function battery for preschoolers: Sensitivity to age differences. *Child Neuropsychol.* 20, 713–736. <https://doi.org/10.1080/09297049.2013.857650>

Gazzaley, A., Nobre, A.C., 2012. Top-down modulation: bridging selective attention and working memory. *Trends Cogn. Sci.* 16, 129–135. <https://doi.org/10.1016/J.TICS.2011.11.014>

Gerstadt, C.L., Hong, Y.J., Diamond, A., 1994. The relationship between cognition and action: performance of children 312–7 years old on a stroop- like day-night test. *Cognition* 53, 129–153. [https://doi.org/10.1016/0010-0277\(94\)90068-X](https://doi.org/10.1016/0010-0277(94)90068-X)

Giuliano, R.J., Karns, C.M., Neville, H.J., Hillyard, S.A., 2014. Early Auditory Evoked Potential Is Modulated by Selective Attention and Related to Individual Differences in Visual Working Memory Capacity. *J. Cogn. Neurosci.* 26, 2682–2690. https://doi.org/10.1162/jocn_a_00684

Goldberg, M.C., Maurer, D., Lewis, T.L., 2001. Developmental changes in attention: the effects of endogenous cueing and of distractors. *Dev. Sci.* 4, 209–219. <https://doi.org/10.1111/1467-7687.00166>

Gomez-Ramirez, M., Hysaj, K., Niebur, E., 2016. Neural mechanisms of selective attention in the somatosensory system. *J. Neurophysiol.* 116, 1218–1231. <https://doi.org/10.1152/jn.00637.2015>

Gottwald, J.M., Achermann, S., Marciszko, C., Lindskog, M., Gredebäck, G., 2016. An Embodied Account of Early Executive-Function Development. *Psychol. Sci.* 27, 1600–1610. <https://doi.org/10.1177/0956797616667447>

Haegens, S., Handel, B.F., Jensen, O., 2011. Top-Down Controlled Alpha Band Activity in Somatosensory Areas Determines Behavioral Performance in a Discrimination Task. *J. Neurosci.* 31, 5197–5204. <https://doi.org/10.1523/JNEUROSCI.5199-10.2011>

Hamlin, J.K., Hallinan, E. V., Woodward, A.L., 2008. Do as I do: 7-month-old infants selectively reproduce others' goals. *Dev. Sci.* 11, 487–494. <https://doi.org/10.1111/j.1467-7687.2008.00694.x>

Hampton Wray, A., Stevens, C., Pakulak, E., Isbell, E., Bell, T., Neville, H., 2017. Development of selective attention in preschool-age children from lower socioeconomic status backgrounds. *Dev. Cogn. Neurosci.* 26, 101–111. <https://doi.org/10.1016/J.DCN.2017.06.006>

- Händel, B.F., Haarmeier, T., Jensen, O., 2011. Alpha Oscillations Correlate with the Successful Inhibition of Unattended Stimuli. *J. Cogn. Neurosci.* 23, 2494–2502. <https://doi.org/10.1162/jocn.2010.21557>
- Harris, J., George, N.R., Hirsh-Pasek, K., Newcombe, N.S., 2018. Where will it go? How children and adults reason about force and motion. *Cogn. Dev.* 45, 113–124. <https://doi.org/10.1016/J.COGDEV.2018.01.002>
- Hartmann, T., Schlee, W., Weisz, N., 2012. It's only in your head: Expectancy of aversive auditory stimulation modulates stimulus-induced auditory cortical alpha desynchronization. *Neuroimage* 60, 170–178. <https://doi.org/10.1016/J.NEUROIMAGE.2011.12.034>
- Heim, S., Keil, A., 2012. Developmental Trajectories of Regulating Attentional Selection Over Time. *Front. Psychol.* 3, 277–291. <https://doi.org/10.3389/fpsyg.2012.00277>
- Hendry, A., Jones, E.J.H., Charman, T., 2016. Executive function in the first three years of life: Precursors, predictors and patterns. *Dev. Rev.* 42, 1–33. <https://doi.org/10.1016/J.DR.2016.06.005>
- Hoffmann, S., Falkenstein, M., 2008. The Correction of Eye Blink Artefacts in the EEG: A Comparison of Two Prominent Methods. *PLoS One* 3, 3004–3030. <https://doi.org/10.1371/journal.pone.0003004>
- Holmboe, K., Bonneville-Roussy, A., Johnson, M.H., 2017. Longitudinal development of attention and inhibitory control during the first year of life. *Dev. Sci.* 1–45.
- Holmes, N.P., Spence, C., 2004. The body schema and multisensory representation(s) of peripersonal space. *Cogn. Process.* 5, 94–105. <https://doi.org/10.1007/s10339-004-0013-3>
- Hölzel, B.K., Lazar, S.W., Gard, T., Schuman-Olivier, Z., Vago, D.R., Ott, U., 2011. How Does Mindfulness Meditation Work? Proposing Mechanisms of Action From a Conceptual and Neural Perspective. *Perspect. Psychol. Sci.* 6, 537–559. <https://doi.org/10.1177/1745691611419671>
- Huang, Y., Rao, R.P.N., 2011. Predictive coding. *Wiley Interdiscip. Rev. Cogn. Sci.* 2, 580–593. <https://doi.org/10.1002/wcs.142>
- Hunnius, S., Bekkering, H., 2014. What are you doing? How active and observational experience shape infants' action understanding. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 369, 2013–2030. <https://doi.org/10.1098/rstb.2013.0490>
- Iguchi, Y., Hoshi, Y., Tanosaki, M., Taira, M., Hashimoto, I., 2005. Attention induces reciprocal activity in the human somatosensory cortex enhancing relevant- and suppressing irrelevant inputs from fingers. *Clin. Neurophysiol.* 116, 1077–1087. <https://doi.org/10.1016/j.clinph.2004.12.005>
- Isbell, E., Calkins, S.D., Swingler, M.M., Leerkes, E.M., 2015. Attentional fluctuations in preschoolers: Direct and indirect relations with task accuracy, academic readiness, and school performance. *J. Exp. Child Psychol.* 167, 388–403. <https://doi.org/10.1016/J.JECP.2017.11.013>

- Isbell, E., Stevens, C., Pakulak, E., Hampton Wray, A., Bell, T.A., Neville, H.J., 2017. Neuroplasticity of selective attention: Research foundations and preliminary evidence for a gene by intervention interaction. *Proc. Natl. Acad. Sci. U. S. A.* 114, 9247–9254. <https://doi.org/10.1073/pnas.1707241114>
- Itthipuripat, S., Cha, K., Byers, A., Serences, J.T., 2017. Two different mechanisms support selective attention at different phases of training. *PLOS Biol.* 15, 1724–2000. <https://doi.org/10.1371/journal.pbio.2001724>
- Jacobson, L.A., Williford, A.P., Pianta, R.C., 2011. The role of executive function in children's competent adjustment to middle school. *Child Neuropsychol.* 17, 255–280. <https://doi.org/10.1080/09297049.2010.535654>
- Jiang, H., Van Gerven, M.A.J., Jensen, O., Van Gerven, M.A.J., 2014. Modality-specific Alpha Modulations Facilitate Long-term Memory Encoding in the Presence of Distracters. *Artic. J. Cogn. Neurosci.* 28, 1–10. https://doi.org/10.1162/jocn_a_00726
- Johnson, M.H., Posner, M.I., Rothbart, M.K., 1991. Components of Visual Orienting in Early Infancy: Contingency Learning, Anticipatory Looking, and Disengaging. *J. Cogn. Neurosci.* 3, 335–344. <https://doi.org/10.1162/jocn.1991.3.4.335>
- Jones, L.B., Rothbart, M.K., Posner, M.I., 2003. Development of executive attention in preschool children. *Dev. Sci.* 6, 498–504. <https://doi.org/10.1111/1467-7687.00307>
- Jones, S.R., Kerr, C.E., Wan, Q., Pritchett, D.L., Hämäläinen, M., Moore, C.I., 2010. Cued spatial attention drives functionally relevant modulation of the mu rhythm in primary somatosensory cortex. *J. Neurosci.* 30, 13760–13775. <https://doi.org/10.1523/JNEUROSCI.2969-10.2010>
- Kanakogi, Y., Itakura, S., 2011. Developmental correspondence between action prediction and motor ability in early infancy. *Nat. Commun.* 2, 341. <https://doi.org/10.1038/ncomms1342>
- Karns, C.M., Knight, R.T., 2009. Intermodal Auditory, Visual, and Tactile Attention Modulates Early Stages of Neural Processing. *J. Cogn. Neurosci.* 21, 669–683. <https://doi.org/10.1162/jocn.2009.21037>
- Katus, T., Müller, M.M., Eimer, M., 2015. Sustained maintenance of somatotopic information in brain regions recruited by tactile working memory. *J. Neurosci.* 35, 1390–1405. <https://doi.org/10.1523/JNEUROSCI.3535-14.2015>
- Kennett, S., van Velzen, J., Eimer, M., Driver, J., 2007. Disentangling gaze shifts from preparatory ERP effects during spatial attention. *Psychophysiology* 44, 69–78. <https://doi.org/10.1111/j.1469-8986.2006.00470.x>
- Kerr, C.E., Sacchet, M.D., Lazar, S.W., Moore, C.I., Jones, S.R., 2013. Mindfulness starts with the body: somatosensory attention and top-down modulation of cortical alpha rhythms in mindfulness meditation. *Front. Hum. Neurosci.* 7, 12–30. <https://doi.org/10.3389/fnhum.2013.00012>

- Klenberg, L., Korkman, M., Lahti-Nuutila, P., 2001. Differential Development of Attention and Executive Functions in 3- to 12-Year-Old Finnish Children. *Dev. Neuropsychol.* 20, 407–428. https://doi.org/10.1207/S15326942DN2001_6
- Klimesch, W., Doppelmayr, M., Russegger, H., Pachinger, T., Schwaiger, J., 1998. Induced alpha band power changes in the human EEG and attention. *Neurosci. Lett.* 244, 73–76. [https://doi.org/10.1016/S0304-3940\(98\)00122-0](https://doi.org/10.1016/S0304-3940(98)00122-0)
- Klimesch, W., 2012. Alpha-band oscillations, attention, and controlled access to stored information. *Trends Cogn. Sci.* 16, 606–617. <https://doi.org/10.1016/J.TICS.2012.10.007>
- Klimesch, W., 1999. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Res. Rev.* 29, 169–195. [https://doi.org/10.1016/S0165-0173\(98\)00056-3](https://doi.org/10.1016/S0165-0173(98)00056-3)
- Klimesch, W., Sauseng, P., Hanslmayr, S., 2007. EEG alpha oscillations: The inhibition–timing hypothesis. *Brain Res. Rev.* 53, 63–88. <https://doi.org/10.1016/J.BRAINRESREV.2006.06.003>
- Knowland, V.C.P., Mercure, E., Karmiloff-Smith, A., Dick, F., Thomas, M.S.C., 2014. Audio-visual speech perception: a developmental ERP investigation. *Dev. Sci.* 17, 110–124. <https://doi.org/10.1111/desc.12098>
- Kok, P., Jehee, J.F.M., de Lange, F.P., 2012. Less Is More: Expectation Sharpens Representations in the Primary Visual Cortex. *Neuron* 75, 265–270. <https://doi.org/10.1016/J.NEURON.2012.04.034>
- Kouider, S., Long, B., Le Stanc, L., Charron, S., Fievet, A.-C., Barbosa, L.S., Gelskov, S. V, 2015. Neural dynamics of prediction and surprise in infants. *Nat. Commun.* 6, 1–8. <https://doi.org/10.1038/ncomms9537>
- Krause, C.M., Pesonen, M., Himilinen, H., 2006. Brain oscillatory responses during the different stages of an auditory memory search task in children. *Neuroreport* 18, 213–216.
- Kuhlman, W.N., 1978. Functional topography of the human mu rhythm. *Electroencephalogr. Clin. Neurophysiol.* 44, 83–93.
- Lepsien, J., Nobre, A.C., 2006. Cognitive control of attention in the human brain: Insights from orienting attention to mental representations. *Brain Res.* 1105, 20–31. <https://doi.org/10.1016/J.BRAINRES.2006.03.033>
- Lopes da Silva, F., 2013. EEG and MEG: Relevance to Neuroscience. *Neuron* 80, 1112–1128. <https://doi.org/10.1016/J.NEURON.2013.10.017>
- Macaluso, E., Eimer, M., Frith, C.D., Driver, J., 2003. Preparatory states in crossmodal spatial attention: spatial specificity and possible control mechanisms. *Exp. Brain Res.* 149, 62–74. <https://doi.org/10.1007/s00221-002-1335-y>

- Mackey, A.P., Park, A.T., Robinson, S.T., Gabrieli, J.D.E., 2017. A Pilot Study of Classroom-Based Cognitive Skill Instruction: Effects on Cognition and Academic Performance. *Mind, Brain, Educ.* 11, 85–95. <https://doi.org/10.1111/mbe.12138>
- Mazaheri, A., van Schouwenburg, M. R., Dimitrijevic, A., Denys, D., Cools, R., & Jensen, O. (2014). Region-specific modulations in oscillatory alpha activity serve to facilitate processing in the visual and auditory modalities. *Neuroimage*, 87, 356-362.
- Makeig, S., 1993. Auditory event-related dynamics of the EEG spectrum and effects of exposure to tones. *Electroencephalogr. Clin. Neurophysiol.* 86, 283–293. [https://doi.org/10.1016/0013-4694\(93\)90110-H](https://doi.org/10.1016/0013-4694(93)90110-H)
- Makeig, S., Debener, S., Onton, J., Delorme, A., 2004. Mining event-related brain dynamics. *Trends Cogn. Sci.* 8, 204–210. <https://doi.org/10.1016/j.tics.2004.03.008>
- Markant, J., Ackerman, L.K., Nussenbaum, K., 2016. Selective attention neutralizes the adverse effects of low socioeconomic status on memory in 9-month-old infants. *Dev. Cogn. Neurosci.* 18, 26–33. <https://doi.org/10.1016/J.DCN.2015.10.009>
- Markant, J., Amso, D., 2016. The Development of Selective Attention Orienting is an Agent of Change in Learning and Memory Efficacy. *Infancy* 21, 154–176.
- Marsh, H.L., Stavropoulos, J., Nienhuis, T., Legerstee, M., 2010. Six- and 9-Month-Old Infants Discriminate Between Goals Despite Similar Action Patterns. *Infancy* 15, 94–106. <https://doi.org/10.1111/j.1532-7078.2009.00002.x>
- Marshall, P.J., Bar-Haim, Y., Fox, N.A., 2002. Development of the EEG from 5 months to 4 years of age. *Clin. Neurophysiol.* 113, 1199–1208.
- Marshall, P.J., Meltzoff, A.N., 2015. Body maps in the infant brain. *Trends Cogn. Sci.* 19, 499–505. <https://doi.org/10.1016/j.tics.2015.06.012>
- Marshall, P.J., Meltzoff, A.N., 2014. Neural mirroring mechanisms and imitation in human infants. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 369, 2013–2020. <https://doi.org/10.1098/rstb.2013.0620>
- Mazaheri, A., Nieuwenhuis, I.L.C., van Dijk, H., Jensen, O., 2009. Prestimulus alpha and mu activity predicts failure to inhibit motor responses. *Hum. Brain Mapp.* 30, 1791–1800. <https://doi.org/10.1002/hbm.20763>
- Mazaheri, A., van Schouwenburg, M., Dimitrijevic, A., Denys, D., Cools, R., Jensen, O., 2013. Region specific modulations in oscillatory alpha activity serves to facilitate processing in the visual and auditory modalities. *Neuroimage* 356–362. <https://doi.org/10.1016/j.neuroimage.2013.10.052>
- Melby-Lervåg, M., Redick, T.S., Hulme, C., 2016. Working Memory Training Does Not Improve Performance on Measures of Intelligence or Other Measures of “Far Transfer.” *Perspect. Psychol. Sci.* 11, 512–534. <https://doi.org/10.1177/1745691616635612>

- Mento, G., Valenza, E., 2016. Spatiotemporal neurodynamics of automatic temporal expectancy in 9-month old infants. *Sci. Rep.* 6, 303–325. <https://doi.org/10.1038/srep36525>
- Mezzacappa, E., 2004. Alerting, Orienting, and Executive Attention: Developmental Properties and Sociodemographic Correlates in an Epidemiological Sample of Young, Urban Children. *Child Dev.* 75, 1373–1386. <https://doi.org/10.1111/j.1467-8624.2004.00746.x>
- Miyake, A., Friedman, N.P., 2012. No Title. *Curr. Dir. Psychol. Sci.* 21, 8–14. <https://doi.org/10.1177/0963721411429458>
- Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., Wager, T.D., 2000. The Unity and Diversity of Executive Functions and Their Contributions to Complex “Frontal Lobe” Tasks: A Latent Variable Analysis. *Cogn. Psychol.* 41, 49–100. <https://doi.org/10.1006/cogp.1999.0734>
- Moffitt, T.E., 1990. Juvenile Delinquency and Attention Deficit Disorder: Boys’ Developmental Trajectories from Age 3 to Age 15. *Child Dev.* 61, 893–910. <https://doi.org/10.1111/j.1467-8624.1990.tb02830.x>
- Moffitt, T.E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R.J., Harrington, H., Houts, R., Poulton, R., Roberts, B.W., Ross, S., Sears, M.R., Thomson, W.M., Caspi, A., 2011. A gradient of childhood self-control predicts health, wealth, and public safety. *Proc. Natl. Acad. Sci. U. S. A.* 108, 2693–2698. <https://doi.org/10.1073/pnas.1010076108>
- Morrison, A.B., Chein, J.M., 2011. Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychon. Bull. Rev.* 18, 46–60. <https://doi.org/10.3758/s13423-010-0034-0>
- Morse, A.F., Benitez, V.L., Belpaeme, T., Cangelosi, A., Smith, L.B., 2014. Posture Affects How Robots and Infants Map Words to Objects. *PLoS One* 10, 1–17. <https://doi.org/10.1371/journal.pone.0116012>
- Muller, U., Steven Dick, A., Gela, K., Overton, W.F., Zelazo, P.D., 2006. The Role of Negative Priming in Preschoolers’ Flexible Rule Use on the Dimensional Change Card Sort Task. *Child Dev.* 77, 395–412. <https://doi.org/10.1111/j.1467-8624.2006.00878.x>
- Murphy, J.W., Foxe, J.J., Molholm, S., 2016. Neuro-oscillatory mechanisms of intersensory selective attention and task switching in school-aged children, adolescents and young adults. *Dev. Sci.* 19, 469–487. <https://doi.org/10.1111/desc.12316>
- Neville, H.J., Stevens, C., Pakulak, E., Bell, T.A., Fanning, J., Klein, S., Isbell, E., 2013. Family-based training program improves brain function, cognition, and behavior in lower socioeconomic status preschoolers. *Proc. Natl. Acad. Sci. U. S. A.* 110, 12138–12143. <https://doi.org/10.1073/pnas.1304437110>
- Nyström, P., Ljunghammar, T., Rosander, K., Von Hofsten, C., 2014. Using mu rhythm desynchronization to measure mirror neuron activity in infants. *Dev. Sci.* 14, 327–335. <https://doi.org/10.1111/j.1467-7687.2010.00979.x>

- Ondobaka, S., Bekkering, H., 2013. Conceptual and perceptuo-motor action control and action recognition. *Cortex* 49, 2966–2967. <https://doi.org/10.1016/j.cortex.2013.06.005>
- Ondobaka, S., Bekkering, H., 2012. Hierarchy of Idea-Guided Action and Perception-Guided Movement. *Front. Psychol.* 3, 579. <https://doi.org/10.3389/fpsyg.2012.00579>
- Ondobaka, S., de Lange, F.P., Newman-Norlund, R.D., Wiemers, M., Bekkering, H., 2012. Interplay Between Action and Movement Intentions During Social Interaction. *Psychol. Sci.* 23, 30–35. <https://doi.org/10.1177/0956797611424163>
- O'Regan, J.K., Noë, A., 2001. A sensorimotor account of vision and visual consciousness. *Behav. Brain Sci.* 24, 939–973. <https://doi.org/10.1017/S0140525X01000115>
- Owen, A.M., Hampshire, A., Grahn, J.A., Stenton, R., Dajani, S., Burns, A.S., Howard, R.J., Ballard, C.G., 2010. Putting brain training to the test. *Nature* 465, 775–778. <https://doi.org/10.1038/nature09042>
- Pace, A., Luo, R., Hirsh-Pasek, K., Golinkoff, R.M., 2017. Identifying pathways between socioeconomic status and language development. *Annu. Rev. Linguist.* 3, 285–308. <https://doi.org/10.1146/annurev-linguistics-011516-034226>
- Papageorgiou, K.A., Farroni, T., Johnson, M.H., Smith, T.J., Ronald, A., 2015. Individual Differences in Newborn Visual Attention Associate with Temperament and Behavioral Difficulties in Later Childhood. *Sci. Rep.* 5, 11264–11280. <https://doi.org/10.1038/srep11264>
- Papageorgiou, K.A., Smith, T.J., Wu, R., Johnson, M.H., Kirkham, N.Z., Ronald, A., 2014. Individual differences in infant fixation duration relate to attention and behavioral control in childhood. *Psychol. Sci.* 25, 1371–1379. <https://doi.org/10.1177/0956797614531295>
- Payne, L., Sekuler, R., 2014. The Importance of Ignoring. *Curr. Dir. Psychol. Sci.* 23, 171–177. <https://doi.org/10.1177/0963721414529145>
- Perchet, C., Revol, O., Fournier, P., Mauguère, F., Garcia-Larrea, L., 2001. Attention shifts and anticipatory mechanisms in hyperactive children: An ERP study using the Posner paradigm. *Biol. Psychiatry* 50, 44–57. [https://doi.org/10.1016/S0006-3223\(00\)01119-7](https://doi.org/10.1016/S0006-3223(00)01119-7)
- Perry, N.B., Swingler, M.M., Calkins, S.D., Bell, M.A., 2016. Neurophysiological correlates of attention behavior in early infancy: Implications for emotion regulation during early childhood. *J. Exp. Child Psychol.* 142, 245–261. <https://doi.org/10.1016/J.JECP.2015.08.007>
- Petersen, S.E., Posner, M.I., 2012. The attention system of the human brain: 20 Years After. *Annu. Rev. Neurosci.* 35, 73–89. <https://doi.org/10.1146/annurev-neuro-062111-150525>
- Pezzulo, G., 2012. An Active Inference view of cognitive control. *Front. Psychol.* 3, 478–499. <https://doi.org/10.3389/fpsyg.2012.00478>

- Pezzulo, G., Barsalou, L.W., Cangelosi, A., Fischer, M.H., McRae, K., Spivey, M.J., 2011. The Mechanics of Embodiment: A dialog on embodiment and computational modeling. *Front. Psychol.* 2, 5–20. <https://doi.org/10.3389/fpsyg.2011.00005>
- Pfurtscheller, G., 1989. Functional topography during sensorimotor activation studied with event-related desynchronization mapping. *J. Clin. Neurophysiol.* 6, 75–84.
- Pfurtscheller, G., Lopes da Silva, F.H., 1999. Event-related EEG/MEG synchronization and desynchronization: basic principles. *Clin. Neurophysiol.* 110, 1842–1857. [https://doi.org/10.1016/S1388-2457\(99\)00141-8](https://doi.org/10.1016/S1388-2457(99)00141-8)
- Plebanek, D.J., Sloutsky, V.M., 2017. Costs of Selective Attention: When Children Notice What Adults Miss. *Psychol. Sci.* 28, 723–732. <https://doi.org/10.1177/0956797617693005>
- Posner, M.I., 1980. Orienting of attention. *Q. J. Exp. Psychol.* 32, 3–25. <https://doi.org/10.1080/00335558008248231>
- Posner, M.I., Rothbart, M.K., 2007. *Educating the human brain.*, American Psychological Association. American Psychological Association, Washington. <https://doi.org/10.1037/11519-000>
- Posner, M.I., Rothbart, M.K., n.d. Development of attention networks., in: *Cognition and Brain Development: Converging Evidence from Various Methodologies.* American Psychological Association, Washington, pp. 61–83. <https://doi.org/10.1037/14043-004>
- Posner, M.I., Rothbart, M.K., Tang, Y.-Y., 2015. Enhancing attention through training. *Curr. Opin. Behav. Sci.* 4, 1–5. <https://doi.org/10.1016/j.cobeha.2014.12.008>
- Quandt, L.C., Marshall, P.J., Bouquet, C.A., Shipley, T.F., 2013. Somatosensory experiences with action modulate alpha and beta power during subsequent action observation. *Brain Res.* 1534, 55–65. <https://doi.org/10.1016/J.BRAINRES.2013.08.043>
- Raizada, R.D.S., Richards, T.L., Meltzoff, A., Kuhl, P.K., 2008. Socioeconomic status predicts hemispheric specialisation of the left inferior frontal gyrus in young children. *Neuroimage* 40, 1392–1401. <https://doi.org/10.1016/J.NEUROIMAGE.2008.01.021>
- Raver, C.C., Blair, C., Willoughby, M., 2013. Poverty as a predictor of 4-year-olds' executive function: New perspectives on models of differential susceptibility. *Dev. Psychol.* 49, 292–304. <https://doi.org/10.1037/a0028343>
- Reddy, V., Markova, G., Wallot, S., 2013. Anticipatory Adjustments to Being Picked Up in Infancy. *PLoS One* 8, 65289–65298. <https://doi.org/10.1371/journal.pone.0065289>
- Repacholi, B.M., Meltzoff, A.N., Rowe, H., Toub, T.S., 2014. Infant, control thyself: Infants' integration of multiple social cues to regulate their imitative behavior. *Cogn. Dev.* 32, 46–57. <https://doi.org/10.1016/J.COGDEV.2014.04.004>

- Rochat, P., Hespos, S.J., 1996. Tracking and anticipation of invisible spatial transformations by 4- to 8-month-old infants. *Cogn. Dev.* 11, 3–17. [https://doi.org/10.1016/S0885-2014\(96\)90025-8](https://doi.org/10.1016/S0885-2014(96)90025-8)
- Romei, V., Gross, J., Thut, G., 2010. On the role of prestimulus alpha rhythms over occipito-parietal areas in visual input regulation: correlation or causation? *J. Neurosci.* 30, 8692–8697. <https://doi.org/10.1523/JNEUROSCI.0160-10.2010>
- Ruberry, E.J., Lengua, L.J., Crocker, L.H., Bruce, J., Upshaw, M.B., Sommerville, J.A., 2017. Income, neural executive processes, and preschool children’s executive control. *Dev. Psychopathol.* 29, 143–154. <https://doi.org/10.1017/S095457941600002X>
- Rueda, M.R., Posner, M.I., Rothbart, M.K., Davis-Stober, C.P., 2004. Development of the time course for processing conflict: an event-related potentials study with 4 year olds and adults. *BMC Neurosci.* 5, 39–48. <https://doi.org/10.1186/1471-2202-5-39>
- Rueda, M.R., Rothbart, M.K., McCandliss, B.D., Saccomanno, L., Posner, M.I., 2005. Training, maturation, and genetic influences on the development of executive attention. *Proc. Natl. Acad. Sci. U. S. A.* 102, 14931–14936. <https://doi.org/10.1073/pnas.0506897102>
- Rueda, M.R., Posner, M.I., Rothbart, M.K., 2005. The Development of Executive Attention: Contributions to the Emergence of Self-Regulation. *Dev. Neuropsychol.* 28, 573–594. https://doi.org/10.1207/s15326942dn2802_2
- Rueda, M.R., Fan, J., McCandliss, B.D., Halparin, J.D., Gruber, D.B., Lercari, L.P., Posner, M.I., 2004. Development of attentional networks in childhood. *Neuropsychologia* 42, 1029–1040. <https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2003.12.012>
- Ruff, C.C., 2013. Sensory processing: Who’s in (top-down) control? *Ann. N. Y. Acad. Sci.* 1296, 88–107. <https://doi.org/10.1111/nyas.12204>
- Saby, J.N., Meltzoff, A.N., Marshall, P.J., 2013. Infants’ Somatotopic Neural Responses to Seeing Human Actions: I’ve Got You under My Skin. *PLoS One* 8, 77905–77916. <https://doi.org/10.1371/journal.pone.0077905>
- Sadaghiani, S., Kleinschmidt, A., 2016. Brain Networks and α -Oscillations: Structural and Functional Foundations of Cognitive Control. *Trends Cogn. Sci.* 20, 805–817. <https://doi.org/10.1016/J.TICS.2016.09.004>
- Sanders, L.D., Stevens, C., Coch, D., Neville, H.J., 2006. Selective auditory attention in 3- to 5-year-old children: An event-related potential study. *Neuropsychologia* 44, 2126–2138. <https://doi.org/10.1016/j.neuropsychologia.2005.10.007>
- Sarter, M., Gehring, W.J., Kozak, R., 2006. More attention must be paid: The neurobiology of attentional effort. *Brain Res. Rev.* 51, 145–160. <https://doi.org/10.1016/J.BRAINRESREV.2005.11.002>
- Sauseng, P., Klimesch, W., Stadler, W., Schabus, M., Doppelmayr, M., Hanslmayr, S., Gruber, W.R., Birbaumer, N., 2005. A shift of visual spatial attention is selectively associated with human EEG

alpha activity. *Eur. J. Neurosci.* 22, 2917–2926. <https://doi.org/10.1111/j.1460-9568.2005.04482.x>

- Sauseng, P., Klimesch, W., Schabus, M., Doppelmayr, M., 2005. Fronto-parietal EEG coherence in theta and upper alpha reflect central executive functions of working memory. *Int. J. Psychophysiol.* 57, 97–103. <https://doi.org/10.1016/j.ijpsycho.2005.03.018>
- Sebanz, N., Bekkering, H., Knoblich, G., 2006. Joint action: bodies and minds moving together. *Trends Cogn. Sci.* 10, 70–76. <https://doi.org/10.1016/J.TICS.2005.12.009>
- Sheese, B.E., Rothbart, M.K., Posner, M.I., White, L.K., Fraundorf, S.H., 2008. Executive attention and self-regulation in infancy. *Infant Behav. Dev.* 31, 501–510. <https://doi.org/10.1016/j.infbeh.2008.02.001>
- Shimi, A., Nobre, A.C., Scerif, G., 2015. ERP markers of target selection discriminate children with high vs. low working memory capacity. *Front. Syst. Neurosci.* 9, 153–160. <https://doi.org/10.3389/fnsys.2015.00153>
- Shulman, E.P., Smith, A.R., Silva, K., Icenogle, G., Duell, N., Chein, J., Steinberg, L., 2016. The dual systems model: Review, reappraisal, and reaffirmation. *Dev. Cogn. Neurosci.* 17, 103–117. <https://doi.org/10.1016/J.DCN.2015.12.010>
- Simons, D.J., Boot, W.R., Charness, N., Gathercole, S.E., Chabris, C.F., Hambrick, D.Z., Stine-Morrow, E.A.L., 2016. Do “Brain-Training” Programs Work? *Psychol. Sci. Public Interes.* 17, 103–186. <https://doi.org/10.1177/1529100616661983>
- Simpson, G. V, Weber, D.L., Dale, C.L., Pantazis, D., Bressler, S.L., Leahy, R.M., Luks, T.L., 2011. Dynamic activation of frontal, parietal, and sensory regions underlying anticipatory visual spatial attention. *J. Neurosci.* 31, 13880–9. <https://doi.org/10.1523/JNEUROSCI.1519-10.2011>
- Slagter, H.A., Prinssen, S., Reteig, L.C., Mazaheri, A., 2016. Facilitation and inhibition in attention: Functional dissociation of pre-stimulus alpha activity, P1, and N1 components. *Neuroimage* 125, 25–35. <https://doi.org/10.1016/J.NEUROIMAGE.2015.09.058>
- Smith, L. B., & Thelen, E. 2003. Development as a dynamic system. *Trends in cognitive sciences*, 7(8), 343-348.
- Song, L., Pruden, S.M., Golinkoff, R.M., Hirsh-Pasek, K., 2016. Prelinguistic foundations of verb learning: Infants discriminate and categorize dynamic human actions. *J. Exp. Child Psychol.* 151, 77–95. <https://doi.org/10.1016/J.JECP.2016.01.004>
- Stapel, J.C., Hunnius, S., Bekkering, H., 2015. Fifteen-month-old infants use velocity information to predict others’ action targets. *Front. Psychol.* 6, 1092–2000. <https://doi.org/10.3389/fpsyg.2015.01092>
- Steinberg, L., 2010. A dual systems model of adolescent risk-taking. *Dev. Psychobiol.* 52, 216–224. <https://doi.org/10.1002/dev.20445>

- Stets, M., Reid, V.M., 2011. Infant ERP amplitudes change over the course of an experimental session: Implications for cognitive processes and methodology. *Brain Dev.* 33, 558–568. <https://doi.org/10.1016/J.BRAINDEV.2010.10.008>
- Stevens, C., Lauinger, B., Neville, H., 2009. Differences in the neural mechanisms of selective attention in children from different socioeconomic backgrounds: an event-related brain potential study. *Dev. Sci.* 12, 634–46. <https://doi.org/10.1111/j.1467-7687.2009.00807.x>
- Stroganova, T.A., Orekhova, E. V, Posikera, I.N., 1999. EEG alpha rhythm in infants. *Clin. Neurophysiol.* 110, 997–1012. [https://doi.org/10.1016/S1388-2457\(98\)00009-1](https://doi.org/10.1016/S1388-2457(98)00009-1)
- Stroganova, T.A., Orekhova, E. V, Posikera, I.N., 1999. EEG alpha rhythm in infants. *Clin. Neurophysiol.* 110, 997–1012. [https://doi.org/10.1016/S1388-2457\(98\)00009-1](https://doi.org/10.1016/S1388-2457(98)00009-1)
- Sturge-Apple, M.L., Suor, J.H., Davies, P.T., Cicchetti, D., Skibo, M.A., Rogosch, F.A., 2016. Vagal Tone and Children’s Delay of Gratification. *Psychol. Sci.* 27, 885–893. <https://doi.org/10.1177/0956797616640269>
- Tang, Y.-Y., Hölzel, B.K., Posner, M.I., 2015. The neuroscience of mindfulness meditation. *Nat. Rev. Neurosci.* 16, 213–225. <https://doi.org/10.1038/nrn3916>
- Tang, Y.-Y., Posner, M.I., 2014. Training brain networks and states. *Trends Cogn. Sci.* 18, 345–350. <https://doi.org/10.1016/J.TICS.2014.04.002>
- Tang, Y.-Y., Posner, M.I., 2009. Attention training and attention state training. *Trends Cogn. Sci.* 13, 222–227. <https://doi.org/10.1016/j.tics.2009.01.009>
- Tang, Y.-Y., Yang, L., Leve, L.D., Harold, G.T., 2012. Improving Executive Function and Its Neurobiological Mechanisms Through a Mindfulness-Based Intervention: Advances Within the Field of Developmental Neuroscience. *Child Dev. Perspect.* 6, 361–366. <https://doi.org/10.1111/j.1750-8606.2012.00250.x>
- Telkemeyer, S., Rossi, S., Nierhaus, T., Steinbrink, J., Obrig, H., Wartenburger, I., 2011. Acoustic processing of temporally modulated sounds in infants: Evidence from a combined near-infrared spectroscopy and EEG study. *Front. Psychol.* 2, 62–80. <https://doi.org/10.3389/fpsyg.2011.00062>
- Thorell, L.B., Lindqvist, S., Bergman, S., Bohlin, G., Klingberg, T., 2008. Training and transfer effects of executive functions in preschool children. *Dev. Sci.* 116, 969–976. <https://doi.org/10.1111/j.1467-7687.2008.00745.x>
- Thut, G., 2006. -Band Electroencephalographic Activity over Occipital Cortex Indexes Visuospatial Attention Bias and Predicts Visual Target Detection. *J. Neurosci.* 26, 9494–9502. <https://doi.org/10.1523/JNEUROSCI.0875-06.2006>
- Van Dijk, H., Schoffelen, J.-M., Oostenveld, R., Jensen, O., 2008. Prestimulus Oscillatory Activity in the Alpha Band Predicts Visual Discrimination Ability. *J. Neurosci.* 28, 1816–1823.

- Van Diepen, R. M., Foxe, J. J., & Mazaheri, A. (2019). The functional role of alpha-band activity in attentional processing: the current zeitgeist and future outlook. *Current opinion in psychology*, 29, 229-238.
- van Ede, F., Szebényi, S., Maris, E., 2014. Attentional modulations of somatosensory alpha, beta and gamma oscillations dissociate between anticipation and stimulus processing. *Neuroimage* 97, 134–141. <https://doi.org/10.1016/J.NEUROIMAGE.2014.04.047>
- Varela, F. J., Thompson, E., & Rosch, E. (2017). *The embodied mind: Cognitive science and human experience*. MIT press.
- Vernon, D., 2014. *Artificial Cognitive Systems*, MIT Press.
<https://doi.org/10.1017/CBO9781107415324.004>
- Vernon, D., Lowe, R., Thill, S., Ziemke, T., 2015. Embodied cognition and circular causality: on the role of constitutive autonomy in the reciprocal coupling of perception and action. *Front. Psychol.* 6, 1660. <https://doi.org/10.3389/fpsyg.2015.01660>
- Vibell, J., Klinge, C., Zampini, M., Nobre, A.C., Spence, C., 2017. Differences between endogenous attention to spatial locations and sensory modalities. *Exp. Brain Res.* 235, 2983–2996.
<https://doi.org/10.1007/s00221-017-5030-4>
- Vollebregt, M.A., Zumer, J.M., ter Huurne, N., Castricum, J., Buitelaar, J.K., Jensen, O., 2015. Lateralized modulation of posterior alpha oscillations in children. *Neuroimage* 123, 245–252.
<https://doi.org/10.1016/J.NEUROIMAGE.2015.06.054>
- Wagner, A. R., Brandon, S. E., Klein, S. B., & Mowrer, R. R., 1989. Evolution of a structured connectionist model of Pavlovian conditioning (AESOP). *Contemporary learning theories: Pavlovian conditioning and the status of traditional learning theory*, 149-189.
- Walz, J.M., Goldman, R.I., Carapezza, M., Muraskin, J., Brown, T.R., Sajda, P., 2015. Prestimulus EEG alpha oscillations modulate task-related fMRI BOLD responses to auditory stimuli. *Neuroimage* 113, 153–163. <https://doi.org/10.1016/J.NEUROIMAGE.2015.03.028>
- Willoughby, M.T., Blair, C.B., Kuhn, L.J., Magnus, B.E., 2018. The benefits of adding a brief measure of simple reaction time to the assessment of executive function skills in early childhood. *J. Exp. Child Psychol.* 170, 30–44. <https://doi.org/10.1016/j.jecp.2018.01.003>
- Wilsch, A., Henry, M.J., Herrmann, B., Maess, B., Obleser, J., 2015. Alpha Oscillatory Dynamics Index Temporal Expectation Benefits in Working Memory. *Cereb. Cortex* 25, 1938–1946.
<https://doi.org/10.1093/cercor/bhu004>
- Worden, M.S., Foxe, J.J., Wang, N., Simpson, G. V, 2000. Anticipatory Biasing of Visuospatial Attention Indexed by Retinotopically Specific α -Band Electroencephalography Increases over Occipital Cortex. *J. Neurosci.* 20, 1–6.
- Xu, Y., Regier, T., Newcombe, N.S., 2017. An adaptive cue combination model of human spatial reorientation. *Cognition* 163, 56–66.

- Yu, C., Smith, L.B., 2016. Multiple Sensory-Motor Pathways Lead to Coordinated Visual Attention. *Cogn. Sci.* 1–27. <https://doi.org/10.1111/cogs.12366>
- Yu, C., Smith, L.B., 2013. Joint Attention without Gaze Following: Human Infants and Their Parents Coordinate Visual Attention to Objects through Eye-Hand Coordination. *PLoS One* 8, 79659–79670. <https://doi.org/10.1371/journal.pone.0079659>
- Zanto, T.P., Gazzaley, A., 2009. Neural Suppression of Irrelevant Information Underlies Optimal Working Memory Performance. *J. Neurosci.* 29, 3059–3066. <https://doi.org/10.1523/JNEUROSCI.4621-08.2009>
- Zeidan, F., Johnson, S.K., Diamond, B.J., David, Z., Goolkasian, P., 2010. Mindfulness meditation improves cognition: Evidence of brief mental training. *Conscious. Cogn.* 19, 597–605. <https://doi.org/10.1016/j.concog.2010.03.014>
- Zelazo, P.D., 2006. The Dimensional Change Card Sort (DCCS): a method of assessing executive function in children. *Nat. Protoc.* 1, 297–301. <https://doi.org/10.1038/nprot.2006.46>
- Zelazo, P.D., Anderson, J.E., Richler, J., Wallner-Allen, K., Beaumont, J.L., Weintraub, S., 2013. NIH Toolbox Cognition Battery (CB): measuring executive function and attention. *Monogr. Soc. Res. Child Dev.* 78, 16–33. <https://doi.org/10.1111/mono.12032>
- Zhou, Q., Chen, S.H., Main, A., 2012. Commonalities and Differences in the Research on Children’s Effortful Control and Executive Function: A Call for an Integrated Model of Self-Regulation. *Child Dev. Perspect.* 6, 112–121. <https://doi.org/10.1111/j.1750-8606.2011.00176.x>
- Zoogman, S., Goldberg, S.B., Hoyt, W.T., Miller, L., 2015. Mindfulness Interventions with Youth: A Meta-Analysis. *Mindfulness (N. Y.)*. 6, 290–302. <https://doi.org/10.1007/s12671-013-0260-4>
- Zukow-Goldring, P., Arbib, M.A., 2007. Affordances, effectivities, and assisted imitation: Caregivers and the directing of attention. *Neurocomputing* 70, 2181–2193. <https://doi.org/10.1016/J.NEUCOM.2006.02.029>