SHIFTY BEHAVIOR: USING PUPILLOMETRY TO DETECT COVERT SHIFTS OF ATTENTION IN INFANTS

A Thesis Presented for the

Master of Arts

Degree

The University of Tennessee, Knoxville

Victoria “Tori” Jones

August 2025

Copyright © 2025 by Victoria “Tori” Jones

All rights reserved.

ACKNOWLEDGEMENTS

I would like to first thank my advisor, Dr. Shannon Ross-Sheehy, for supporting my interests and mentoring me as I undertook both this project and all that comes with grad school. Thank you to my committee members, Dr. Greg Reynolds, Dr. Jessica Hay, and Dr. Caglar Tas, for your interests in my projects and development. Your feedback has challenged me to question every choice I made with this project and deepen my understanding as a researcher. Thank you to my lab mates, Micalee Segers and Kenzie Sheets, for being sounding boards for both my research passions and struggles. I would like to thank all the families that came out to participate in this study. Without your enthusiasm for research, this would not be possible.

Finally, I am deeply thankful to my family and friends for being unending wells of encouragement. They answered every phone call and never failed to ground me throughout this time. My last and most heartfelt thank you to my dog, Phoebe, who was dragged to weekends in lab, heard the first draft of every talk I gave, and reminded me to take breaks to touch grass.

ABSTRACT

Environments have an overwhelming amount of visual input, therefore requiring a system that works diligently to select and filter the most relevant, or salient, information. Posner and colleagues posited a spatial "attentional spotlight" that is shifted by the viewer to new locations either accompanied by an eye movement, *overtly*, or while eyes are fixated elsewhere, *covertly*. These covert attentional shifts typically precede an eye movement facilitating efficient visual scanning. This critical component of pre-verbal learning develops around 4-months in infants. Adult research pairs behavioral responses with verbal or button box responses to determine the speed and capabilities of covert orienting. The purpose of this study was to pair traditional reaction time and accuracy measures with pupillometry to further inspect developmental and conditional differences of covert orienting across infancy. A linear mixed effect (LME) model revealed that pupil dynamics were reflective of developmental differences, with older infants showing significantly greater dilation than younger infants across multiple conditions. Further, conditions that required inhibition and re-orienting showed significantly greater dilations when compared to both the baseline (no visual cue condition) and the valid cue conditions. Taken together, result from this study suggest pupillometry may bea sensitive marker of attentional orienting, though dilation may be more reflective of saccade inhibition and attention re-orienting.

TABLE OF CONTENTS

Chapter One Introduction 1

Chapter Two Literature Review 4

Attention 4

Spatial attention's development and importance 4

The deployment of overt and covert attention 6

Endogenous and exogenous engagement of attention 6

Neurophysiology of covert attention 8

Pupillometry 10

Influences of pupil changes 10

Measuring covert attention with pupil 12

Significance for infant studies 14

The Current Study 15

Research Questions and Hypotheses 16

Chapter Three Materials and Methods 17

Participants 17

Stimuli and Procedure 17

Stimuli 17

Task Conditions 18

Chapter Four Results and Discussion 20

Data Processing 20

Behavioral analysis: Spatial Cueing Effect 20

Latency to Orient (LTO) 21
Group Accuracy 21
Pupil Change over Time 22
Linear Mixed Effect Model Fitting 22
Pupil Change over Covert Attention 24
Discussion 26
Limitations and Future Directions 31
Chapter Five Conclusions 34
References 36
Vita 57

LIST OF TABLES

Table 1. Follow-up paired-comparisons examining proportion correct as a function of age and condition. 49

Table 2. Model fits and comparisons and for all models. Note, M_4 was the best-fitting model 50

Table 3. Bonferroni-adjust pairwise comparisons of each Condition within each Age. .. 51

LIST OF FIGURES

Figure 1. Layout of experimental conditions for the Infant Orienting with Attention (IOWA) task..... 52

Figure 2. Mean latencies to orient to the target in milliseconds (ms). Note, latency is measured as the duration from target onset to the beginning of a saccade to the target for correct trials only..... 53

Figure 3. Proportion correct for each Age and Condition. 54

Figure 4. Pupil diameter change over the course of the trial for each Age and Condition. 55

Figure 5. Raw observations and model fits for pupil dilation as a function of Age, Condition, and Time. Each line represents a best-fitting linear trend (±95% CI) and points represent raw observations..... 56

CHAPTER ONE

INTRODUCTION

As we navigate the world, we move from one environment to the next, each one comprised of an abundance of sensory information competing for attentional resources. Visual attention is one mechanism that aids in selecting the most relevant information for higher processing. Spatial attention, specifically, is the ability to filter distractions at an early stage of visual processing so that input from a specific location in space can be visually analyzed (Mangun, 1995). The term "attentional spotlight" metaphorically represents the shape and movement of directed attention (Norman, 1968; Posner et al., 1980). Typically, the locus of the spotlight is oriented where the eyes are; however, it is not always the case that this overlap occurs. Thus, we have the separation of overt and covert attention. Individuals are said to be *overtly* attending to a stimulus when they are directing their gaze to the object or location of their attentional focus (Johnson, 1994). On the other hand, individuals are said to be *covertly* attending to a stimulus when their attentional focus does not match their current gaze (Posner, 1980).

Overt and covert attention often work in tandem to help guide our attentional spotlight to relevant information in the environment for higher processing (MacInnes et al., 2020). As such, both are vital to the exploration of our environment. Covert attention may first be deployed to guide the eye to a spatial location or object, followed by the overt shift of the eye to process the finer details of the stimulus (Perkovic et al., 2023). Thus, in most naturalistic settings, the deployment and redeployment of covert and overt attention are happening in quick succession. Though this is the majority of their

interactions, viewers can actively separate the two, choosing to maintain a fixation while manipulating covert attention to explore the surroundings of their visual field (Hunt & Kingstone, 2003; Posner, 1980). Researchers use this ability to isolate and explore the distinctions of overt and covert attention's capacity to perceive features of selected stimuli (Stewart et al, 2020) and to activate neural networks (Blair & Ristic, 2019).

Early research on covert attention predominantly used adult populations, however, covert attention develops in the first year of infancy and demonstrates an increasingly efficient visual system needed for environmental exploration (Hood, 1995; Richards, 2005). The utilization of covert attention indicates the viewer gaining increasing control of their attentional spotlight as underlying neural networks develop that are involved in the engagement, disengagement, and shifting of attention (Colombo, 2001). Without covert attention to act as a preprocessor to peripheral stimuli, viewers would be forced to explore environments by overtly fixating on all locations – greatly hindering quick, efficient processing of a scene. Covert attention is a critical helpmate to overt attention as it increases both discriminability and speed of information processing (Carrasco & McElree, 2001). Both skills valuable to quick decision-making, without the loss of accuracy (Perkovic et al., 2023). Adults use this skill daily while remaining aware of other drivers in neighboring lanes while watching the road ahead or searching for their keys on a cluttered counter.

Unaccompanied by eye movements, covert attention has a concealed nature that makes it difficult to detect. This is especially difficult in an infant population in which they are unable to report either verbally or with a button response. Although, researchers

have found successful modifications in which to interpret the presence of covert attention through looking behavior (Ross-Sheehy et al., 2015), additional markers of these shifts would aid in informing of its development that ties in so closely with neural pathways development.

Therefore, we look to the emerging behavioral measure of pupillometry. This method of monitoring changes of pupil diameter has an extensive history of cross-disciplinary applications relative to both nervous system and cognitive functions (Bertinotti et al., 2002; Jonas et al., 1990; Steinhauer & Hakerem, 1992; Winston et al., 2020). Specific to the field of psychology, there has been a recent surge in applying this measure to cognitive operations. Studies have been successful in finding pupils are reactive to varying levels of both stimulus-driven (i.e., varying luminance; Ellis, 1981) and goal-driven changes (i.e, meeting task demands; Mathôt et al., 2015; Unsworth & Robison, 2018). Therefore, this study seeks to test pupillometry as an effective indicator of covert shifts of attention in an infant population. The task used in this study is reliable for inducing covert shifts of attention through spatial cueing effects in an infant population (Ross-Sheehy et al., 2015). Thus, we expect that if pupillometry is a reliable measure of covert shifts of attention, then, when applied to this task, there will be an obvious pattern of pupil diameter change.

CHAPTER TWO

LITERATURE REVIEW

Attention

Visual attention is the ability to focus on relevant visual stimuli in an environment. While this definition seems simplistic, decades of research have been dedicated to uncovering the cognitive processes and neural activation involved in the allocation, maintenance, and shifting of attention (Posner & Petersen, 1990). In fact, Evans and colleagues (2011) explain visual attention, not as a single entity, but a conglomeration of cognitive mechanisms for multi-level visual processing. Though intimidating in its extensiveness, each component is important to understanding how viewers attend the environment, a skill crucial for learning, development, and decision making (Hunnius, 2007; Orquin et al., 2021).

Spatial attention's development and importance

This paper focuses on spatial attention as it develops rapidly during infancy (Johnson & Tucker, 1996), is a marker of developing attentional pathways (Posner & Peterson, 1980), and is foundational to spatial processing (i.e., understanding object location and movement; Lauer & Lourenco, 2016) and to visual working memory (Reynolds & Romano, 2016). Spatial attention specifically is the processing of locations in a visual environment, while surrounding areas are suppressed (Mangun, 1995). Posner et al (1980) depict this area of processing as a spotlight that the viewer shifts around the environment. As the region center of the spotlight beam is brightest, the locus of attention

is attended greatest. The further a stimulus is from the center of attention, the less resources are used to encode its details.

Early in infancy, attention is mainly driven by reflexive mechanisms (Johnson, 1990; Richards, 2001). Newborns tend to have an extremely limited capacity for attentiveness and respond automatically to salient features in the environment (Sigman et al., 1973) or seem to be stuck fixated on a centrally presented stimulus, known as *sticky fixation* (Hood, 1995). Around 3- to 4-months, maturation of attentional pathways and increased ocular-motor control allows for a more voluntary selective attention and disengagement from stimuli (Richards & Holley, 1999). Evidence of this development is seen in the increasing ability to track objects with smooth pursuit saccades (Aslin, 1981) and to make anticipatory eye movements to locations with predictable stimulus appearances (Haith et al., 1988).

These changes in looking behavior over the first year are indicative of the development of spatial attention and an increased voluntary selection of spatial orienting. Cueing tasks direct attention to certain spatial locations to measure the speed and accuracy of attentional shifts. While first used for adults, these tasks have been modified to capture shifting spatial attention in those as young as 3-months-old (Lunghi et al., 2020). While the cue influences directionality of the shifts, attentional control and inhibition are needed for accurate saccades to targets when the cue is misleading. Evidence of cueing effects is indicative of an attentional system that is responsive to both stimuli within the attentional spotlight and on the periphery.

The ability of a viewer to process and plan an eye movement outside the center focus of the attentional spotlight, voluntarily or reflexively, is due to the viewer's capability to deploy attention in two different ways.

The deployment of overt and covert attention

The planning and executing of an eye movement outside the center focus of the attentional spotlight is due to the viewer's capability to deploy attention in two ways, overtly and covertly. The location and movement of the attentional spotlight is not always tied to where the viewer's eyes are directed (Posner et al., 1980). For instance, the viewer may look at an object and process the details of it (overt attention) or their eyes may be fixated while attending a location in their periphery (covert attention). Both are critical components of visual processing that can operate cooperatively and independently (Foster et al., 2021; Van der Stigchel & Theeuwes, 2007). Studying their development separately is crucial, as they respond differently to attentional drivers (Fernández et al., 2022) and engage overlapping but distinct neural networks (Kulke et al., 2016; Zhao et al., 2022).

Endogenous and exogenous engagement of attention

The selection of a particular stimulus for processing can be endogenous (i.e., goal-driven) or exogenous (i.e., stimulus-driven). Exogenous cues capture attention reflexively through very salient stimuli – an object or location that stands out for having an "eye-grabbing" feature (Theeuwes, 1991). An example of an exogenously driven shift of attention would be the rapid blinking of a fire alarm drawing the viewer's gaze. However, endogenously driven attention is voluntary and more strategic (Egeth & Yantis,

1997). An example of an endogenous, or goal-driven, shift of attention would be turning and looking over your shoulder to check for cars when backing out. Once attention is engaged, either endogenously or exogenously, attention is deployed either overtly or covertly.

A popular approach to measuring covert attention is a spatial cueing paradigm in which endogenous or exogenous cues illicit attention to a specific location (Posner, 1980). Posner's (1980) paradigm focused on demonstrating how attentional neural networks may be primed by visual cues to facilitate or interfere with programmed eye movements. Participants viewed a monitor in which a briefly presented visual cue(s) (an arrow) directs attention to varying locations. The cues were either in the same location as the subsequent target (i.e., valid cues) or directed attention to the opposite location of the target (i.e., invalid cues). Once the target appeared, participants responded via button press of which side the target was seen. While cues and targets were being presented, participants were instructed to maintain fixation on a central cross, therefore, the viewer relied on covert orienting to react to the cue(s) and target presentation. Valid cues elicited faster reaction times, while invalid cues resulted in slower reaction times and decreased accuracy. These *spatial cueing effects* highlight the influence of covert attention to either facilitate faster reaction times or hinder quick, accurate responses to environmental stimuli.

In adult studies of covert attention, it is common methodology to use both endogenous and exogenous cueing (Mulckhusye & Theeuwes, 2010; Soret et al., 2019). Endogenous cues are typically symbols such as arrows or verbal instructions that require

top-down processing and voluntary control to interpret. Exogenous cues automatically grab attention by being highly salient, such as a flashing light or a loud noise. Infant researchers rely much more heavily on exogenous cueing as it is difficult to elicit goal-driven attention without instructions (Martinez-Alvarez et al., 2017). Also, evidence of top-down processing needed for endogenous attentional control begins to be seen later in infancy while reflexive, exogenous attention seems to be the main driver for at least the first six months (Hunter et al., 2024). Presumably the increase in attentional control stems from the development of critical neural pathways (Oakes et al., 2002). Understanding the neurophysiology of covert attention in adults may provide insight into the emergence of these networks in infants.

Neurophysiology of covert attention

In adult literature, two major neural networks are involved with the capture and shifting of attention: the dorsal attention network (DAN) and the ventral attention network (VAN) (Suo et al., 2021). These networks interact dynamically to facilitate shifting attention as attentional demands change between goal-directed (VAN) and stimulus-driven orienting (DAN). Discerning how these networks work together in adults provides insights into the emergence of attentional control in infancy.

The DAN includes the posterior parietal cortex and frontal eye fields (Corbetta & Shulman, 2002; Manohar et al., 2014). The regions within the network are responsible for top-down, endogenous attention – requiring the maintenance of the mental representations of where objects are in the environment, detection of salient stimuli while suppressing irrelevant stimuli, and voluntary shifts to task-relevant stimuli (Chica et al.,

2013; Lanssens et al., 2020; Vossel et al., 2014). In contrast, the VAN facilitates more bottom-up processing as it is more reactive to sudden changes in the environment that capture attention (exogenously driven). The VAN includes the temporoparietal junction and the ventral frontal cortex, and these regions work in tandem to respond to relevant stimuli occurring outside of the spotlighted region of attention (Zhao et al., 2022).

While the dorsal and ventral networks have distinct functions, they do not operate fully independent of each other. Together, the ventral and dorsal systems work concurrently to allow the attentional spotlight to flow around the environment, guided both internally and externally. However, in infancy attention is initially predominantly reflexive, stimulus-driven looking in the first 6 months – governed mostly by the VAN. Over this first year, attentional control increases, and goal-driven looking indicates the maturation of the DAN rapidly occurring over the first year of life beginning as early as 3 months of age (Homae et al., 2013; Reynolds & Romano, 2016).

While these brain regions and connections between neural networks are fully developed in adults, infants are undergoing rapid neurocognitive development in the first year of life. Traditional methods of analyzing looking behavior may not fully capture the subtle shifts in the development of attention in nonverbal infants, therefore we look to pupillometry as a promising alternative. Changes in pupil diameter offer a non-invasive index of neural activity underlying attentional engagement. Since pupil is modulated by both endogenous and exogenous influences, this method provides a window into the functioning and maturation of the neural networks that support covert attention.

Pupillometry

Despite work existing prior to the 1960s using pupil measures, it is Hess and Polt's (1960) work that is generally credited with popularizing pupil diameter reactions as a response to psychological changes and neural processing (Sirois & Brisson, 2014). Simply defined, pupillometry is the observation of systematic pupil changes in response to various events (Fried, 1980). Methods of collecting and analyzing this data have rapidly progressed over the decades to modern eye-tracking systems that are capable of rapidly tracking track pupil changes (e.g., > 300 Hz), allowing for inferences about cognitive activity (Laeng et al., 2012). However, pupil changes can be influenced by individual differences, age, arousal level, light conditions, and mental effort (Aminihajibashi et al., 2019; Ellis, 1981; Unsworth & Robison, 2018). Researchers strive to account for these factors to isolate the effects of their manipulated variable from confounds as best as possible for reliable findings (Janisse, 1974).

Influences of pupil changes

Age, individual differences, and pupillometry. Prior to analyzing experimental data, it is important to understand how demographic variations impact expected pupil ranges. Specifically, resting-state pupil size – pupil diameter in a state of relaxation when not engaged in a task – increases across ages (Winn et al., 1994). Pupil diameter in infants under one year of age averages around 5.0 mm (Silbert et al., 2013), which is 1.16 mm smaller than a typical adult (19 years or older; Schnitzler et al., 2000). Furthermore, the variability of pupil constriction/dilation increases linearly into adulthood (Winston et al., 2020), until becoming more restricted in elderly adults as autonomic regulation and

function of the eye changes (Lazar et al., 2023). As infants are still developing these pathways, their range is more limited than older children and healthy adults. Though smaller in size and more limited in range, these changes of pupil diameter remain informative of internal changes.

To account for individual differences and changing internal states across the experiment, baseline correcting is done trial-by-trial (Mathôt & Vilotijević, 2022). This standardization allows researchers to isolate changes of pupils due to experimental manipulations rather than natural variability. While important in adult research, it is especially needed when working with a young population that is undergoing rapid development of neural systems that may cause large variation both between- and within-subjects.

Effects of the pupillary light response (PLR). By far, the most well-known and earliest studied influence on pupil dilation is light. Light elicits pupillary response more quickly and robustly than any other source – this is known as the pupillary light response (PLR). Luminance, the light energy emitted from an object or surface, is one of the first noted influences of patterned pupil reaction recognized in literature, going as far back as the second century to diagnose the severity of cataracts (Thompson, 2003). The PLR causes pupil change in response to stimulation around 200 ms after light onset with maximal difference around 750 ms after onset (Mathôt & Vilotijević, 2022).

The pupillary light reflex was once thought to simply be a reflexive change to external stimulus changes, specifically changes of luminance. However, recent work manipulating luminosity revealed constrictions and dilations occurring in response to

endogenously-driven covert shifts of attention. While maintaining a central fixation, adult participants' pupils dilated when covert attention was directed towards a dark peripheral target and constricted when attention was directed to a lighter target (Binda & Murray, 2015; Mathôt et al., 2013). These early works provide evidence that pupils respond to more than external changes of light but also can be tools to measure internal shifts of attention – making pupillometry a valuable tool for assessing covert attention.

The connection of the pupillometry to shifts of attention is further supported by the connection of the superior colliculus (SC) to both the dorsal and ventral attention networks (Alves et al., 2022). The SC is fundamental to both the selection of spatial targets, especially when cued (Krauzlis et al., 2004), and the motor movement in response to the shift of attention (Zubricky & Das, 2024). However, even in the absence of orienting movements, the SC is crucial to covert orienting (Krauzlis et al., 2013). Wang and Munoz (2021) investigated the relationship of the superior colliculus to saccade and pupil responses during an orienting task in monkeys. Their results suggest the SC coordinates attention, saccade movement, and pupil response. Therefore, the SC acts as a major bridge between the attentional networks involved in the orienting of attention and the systems involved in eye movements and pupil response. Further, it supports that pupils respond to more than luminance-driven changes – they also reflect neural dynamics of covert attention.

Measuring covert attention with pupil

Brocher and colleagues (2018) conducted three experiments that incorporated pupil responses to covert shifts of attention without utilizing luminance manipulation to

illicit a response. Inspired by the findings of Gabay et al (2011), these experiments included manipulations of both distance of peripheral stimuli and complexity of cognitive demands.

In Brocher and colleague's (2018) first experiment, adult participants maintained a central fixation while counting stimuli in the periphery that varied in distance from center fixation. As hypothesized, pupil followed an expected pattern of larger dilation in response to more effortful attentional shifts to more distal stimuli.

Next, they explored if the detection of peripheral stimuli was enough to elicit a dilation or if higher task demand such as counting was necessary. To evaluate this, participants completed trials in which they had to count peripheral stimuli while maintaining central fixation, similar to experiment 1, and detection trials where they simply noted the presence of a peripheral stimulus. While the counting condition produced a more robust effect of dilation, the detection condition also elicited a dilation from baseline. The findings from this experiment are particularly relevant to infant studies as infants have neither the language nor cognitive skills to complete complex cognitive processes, such as counting. The dilation that occurred in the detection condition lends to a possible predictive pattern of the same in an infant population.

For the third and final experiment, they sought to isolate pupil changes in response to difficulty of task demand from the covert attentional shift by varying the contrast of stimuli making it more difficult to discriminate. Again, the findings support the idea that pupils are sensitive to both distance of attentional shift and task difficulty.

Collectively, all three experiments identify two critical components of pupillometry. First, it is a reliable measure of covert attention independent of the pupillary light response. Second, it is a reliable measure of covert attention in simple detection tasks absent of complex cognitive demands.

Significance for infant studies

The aforementioned studies were conducted with adult participants as few studies have applied the same methodologies to infant populations. However, we reason that this measure is sensitive to neural processes and pupil dynamics may reveal capture difference of underlying neural development that traditional behavioral methods may not fully capture. Traditional measures such as reaction time can reveal the presence of covert attention, however they are unable to capture the nuances of attention as pupillometry can (Hershman, et al., 2023). Pupillometry has high temporal resolution and is a continuous measure which is crucial for capturing the rapid covert attentional shifts occurring prior to the eye movement in a way reaction time cannot (Zhang & Emberson, 2020).

Also, covert orienting is a discreet neural process, therefore it stands to reason that a measure not reliant on an overt behavioral response would be a greater tool of measure to investigate the finer changes of attention. Importantly, this measure can be applied across all ages and in tasks with and without instructions – making it a great tool for comparing covert attention throughout development and beyond. Additionally, pupil data is accessible through most eye-tracking systems, allowing for widespread use. For

these reasons, we selected pupillometry as a tool for assessing covert shifts of attention in infants undergoing a modified spatial cueing task.

The Current Study

The current project sought to address a gap in understanding of the link between development of endogenous and exogenous attention networks (e.g., DAN, VAN) and covert attention. This was accomplished by combining both traditional behavioral measures (i.e., latency to orient and accuracy) and pupillometry. To accomplish this, infants were tested using the Infant Orienting with Attention (IOWA) task, a spatial cueing task designed to assess infant attention across multiple cue conditions (Ross-Sheehy et al., 2015). This task relies on reflexive orienting and overt eye movements and has been used to explore the presence of spatial cueing effects in infants as young as 4 months-old (Ross-Sheehy et al., 2015; Ross-Sheehy et al., 2020). Previous work focuses on reaction time as the dependent measure for analyzing responses to the cue, however, the current study isolates latency to orient (LTO) instead. This is defined as the time from target onset until the first saccade from center. This change was made to capture age and condition differences of orienting responses absent of developmental saccade speed differences.

In addition to previous work, measures will also include pupil change from baseline, after target presentation, and prior to the eye movement. In this way, this project was the first to separate infant covert orienting responses to the target from overt fixation or saccades to the target. In line with other contemporary work in the field, (Mathôt et al., 2016; Olmos-Solis et al., 2018), our study sought to answer the question of

whether changes in pupil diameter manifest as a physiological marker of covert attentional shifts prior to making eye movements in an infant population.

Research Questions and Hypotheses

The primary aim of the study was to investigate pupil dilations as a function of age and condition prior to the onset of an eye movement as a possible marker of covert attention in infants. This was accomplished using LME models on pupil timeseries data. However, before this assessment, it must first be established that spatial cueing (i.e., covert attention) effects are present, and how these effects vary with age. To achieve this, spatial cueing effects were assessed using latency to orient to a peripheral target (LTO) and percent correct. If spatial precues elicit an attention shift, then infants should be fast and accurate in the *valid* condition, and slow and inaccurate in the invalid condition, as has been previously demonstrated (e.g., Ross-Sheehy, Schneegans & Spencer, 2015).

Based on previous research, I expect that pupillometry will be sensitive to both condition and developmental effects. Specifically, conditions with a spatial precue (*valid, invalid,* and *double*) will elicit a covert shift of attention and subsequently greater pupil dilation than conditions that do not include a spatial precue (*none, tone*). Further, I expect that conditions that require inhibition and re-orienting (*invalid, double*) will result in a greater dilation than conditions that do not (*valid, tone, none*). Along with condition effects, I expect developmental differences in pupillary response, with older infants having significantly different responses as a result of increased attentional network development.

CHAPTER THREE

MATERIALS AND METHODS

Participants

Participants were selected from a previously reported cohort (Ross-Sheehy et al., 2020). Of the 102 infants who participated in the task, the final sample included the first 34 subjects at ages 5 months, 8 months, and 11 months with complete trial data for at least four of the five conditions. This resulted in a final sample of 102 infants (43% females, 57% males), with 34 at 5 months (M= 22.30 weeks, SD = 1.34), 34 at 8-month-olds (M= 35.20 weeks, SD = 1.20), and 34 at 11-month-olds (M= 47.78 weeks, SD = 1.19). All infants were healthy, full-term babies with no history of birth complications, hearing, or vision problems. 2.08% of mothers has some high school, 11.458% of mothers graduated high school and 86.46% had completed at least a bachelor's degree. Of the infants that participated, 89.58% of the sample's babies were parent-reported race and ethnicity as follows: as White 12.50% (half Hispanic and half non-Hispanic), as Black or African American, 2.08% as Asian, 1.04% as Middle Eastern, 1.04% as Indian, and 1.04% preferred not to say. Infant participants were recruited from Tennessee birth records. Families were not paid for their participation, but infants received a toy, book, or t-shirt for attending their appointment.

Stimuli and Procedure

Stimuli

Participants were seated in a dimly lit room 65 cm in front of a 23" monitor with a viewable surface of 45.5° (w) by 26.76° (h) and Tobii TX-300 eye tracker. Black curtains

were hung behind the display to limit the view of the observer. The infant remained seated on the caregiver's lap throughout the task with the caregiver keeping their eyes closed to reduce bias while infants gaze was tracked continuously. Each infant was calibrated using a 5-point calibration scheme, followed by qualitative validation. If any point deviated substantially past a 1° boundary, the researcher resampled and revalidated until all five points reflected precision and accuracy. Continuous gaze and pupil diameter were captured from both eyes during the task presentation. The task began with a smiley face attention getter in the center of the screen against a solid gray background (RGB: 136, 136, 136). Once the infant was judged to be fixating, the researcher began the trial events. Following the attention getter, a 60 ms pre-cue gap preceded the presentation of the 100 ms visual cue that was 11° to the left or right of fixation (1° black dot accompanied by 500 Hz tone). The cue was immediately followed by a 100 ms post-cue gap interval, and finally a randomly selected target presented 11° either to the left or right of fixation. The target remained on screen for 1000 ms before disappearing and the next trial beginning. Targets consisted of 182 5° (w) by 5° (h) photographs of everyday items (e.g., a car, an orange, a ball, etc.) that were randomly presented without replacement. Interest areas used for analyses were created for the attention getter, and locations of the cues and targets (11° left and right of screen) by adding 80 pixels to each of the three stimuli dimensions (see **Table 1**).

Task Conditions

There were five possible cue conditions consisting of different combinations of visual and auditory stimuli. Visual cues were presented to the left or right of fixation (or

both) across three experimental conditions: For the *valid* condition, the target appeared in the same location as the spatial cue. For the *invalid* condition, the target appeared on the opposite side of the screen as the spatial cue. For the *double* condition, the cue appeared simultaneously on both the left and right side of the screen, followed by a target either on the left or the right. In this way, the cues provided *timing* information, but not specific *spatial* information regarding the probable target location. The remaining two conditions were baseline conditions, designed to assess general orienting speed: The *tone* condition had only a tone cue (no spatial cue), and the *none* condition contained neither a spatial nor a tone cue (see **Figure 1**).

Conditions were randomized by block, such that each block contained 2 trials of each of the 5 conditions, one with the target on the left and one with the target on the right (e.g., 10 trials per block). Infants continued to be presented trials for as long as they maintained interest, up to a maximum of 12 blocks (120 trials).

CHAPTER FOUR

RESULTS AND DISCUSSION

Data Processing

Final data included all subjects with valid data in at least 4 of the 5 condition cells. For the behavioral analysis, any missing condition data were filled with the series mean prior to analysis to preserve power. The pupil analysis was based on pupil diameter (mm) data collected from target onset until the last sample prior to an eye movement away from central fixation. These pupil timeseries values were then processed using previously published guidelines (Sirois et al., 2023) including removing any samples during eye movements or blinks, filling small gaps, and smoothing using a cubic spline method. These raw values were then baseline corrected by setting the first sample to zero and subtracting that value from all remaining values for a given trial. Note this approach is well-validated, and considered robust and conservative (Mathôt et l., 2017).

Behavioral analysis: Spatial Cueing Effect

Spatial cueing effects were examined using a 3 x 5 repeated measures ANOVAs with Age (5, 8, 11mo) as the between-subjects variable, and Condition (valid, invalid, double, none, tone) as the within-subjects variable. Dependent variables included both latency to orient (LTO; the latency in ms to begin an eye movement toward the target after target presentation) and percent correct (PC; i.e., percentage of trials in which the first look was toward the target). Note, using LTO rather than reaction time was critical for at least two reasons: First, it ensured accurate pupil by eliminating any samples collected while the eyes were in flight (a major source of noise). Second, it helped to

increase the likelihood that pupil responses were driven by cognitive processes involved in prepping an orienting response. Repeated measures ANOVAS were selected to facilitate interpretation, and to be consistent with previous work (e.g., Ross-Sheehy et al., 2020). All ANOVAs were calculated using the SPSS.

Latency to Orient (LTO)

An ANOVA conducted on mean LTO revealed a significant main effect of Condition, $F(4, 396) = 54.35$, $p < 0.001$, suggesting a large portion of the variance in orienting speed is due to condition effects (see **Figure 2**). However, neither the Age, $F(2, 99) = 0.33$, $p = 0.718$, nor Age x Condition interactions were significant, $F(8, 396) = 1.55$, $p = 0.138$, suggesting the effect of Condition on LTO did not vary significantly across age groups. The significant condition effect was followed up using a univariate simple effects test with a Bonferroni correction for multiple comparisons. Results revealed that LTO was significantly *faster* for valid than for all other conditions (all *p*s < .001). In addition, LTO was significantly *slower* for invalid than all other conditions (all *p*s <.01). No other comparisons were significant.

Group Accuracy

An ANOVA conducted on mean proportion correct revealed a significant main effect of Condition, $F(4, 396) = 148.38$, $p < 0.001$, as well as a significant Condition by Age interaction, $F(8, 386) = 1.99$, $p = .046$. The Age main effect was not significant, $F(2, 99) = 1.57$, $p = .214$. Significant interaction effects were followed up using paired comparisons with a Bonferroni correction for multiple comparisons. Results revealed that although all ages showed significant condition effects, between-condition differences

varied slightly by age, with 8 and 11-month-olds showing slightly lower accuracy for the invalid condition than the 5-month-old infants (see **Table 1** and **Figure 3**). These accuracy measures confirm that the task elicits covert spatial shifts prior to the eye movement that impact both the speed of response and accuracy of saccades with highest accuracy in the valid, no cue and tone cue conditions, and lowest accuracy in the invalid and double cue conditions. Next, I examined changes in pupil dilation to see if these behavioral effects were preceded by differences in pupil dilation.

Pupil Change over Time

Linear Mixed Effect Model Fitting

To determine if pupil changes reflect attentional orienting, baseline corrected pupil timeseries data were analyzed using a linear mixed effect model (Bates, et al., 2015) in R (R Core Team, 2025). This model was chosen as it robust in the face of missing data, allows for random subject effects (intercepts) and allows for the assessment of change over time. Pupil dilation in mm served as the dependent measure and additional dummy coded categorical factors included Age (5mo, 8mo, 11mo) and Condition (tone, none, valid, double, invalid), thus 5-month-olds in the tone cue condition served as intercept/baseline for all LMER models. Theoretically this baseline was sound for the following reasons: first, at 5-months previous research shows that covert attention has developed, though looking behavior may still be mostly reflexive making it a great ae baseline for the other two groups as we compare developmental differences. Second, the tone condition was the baseline condition as it both aligns with previous work published using this task and this condition contains the beep tone –

similar to visual cue conditions – but has no visual or directional input. Thus, ideally analyses are capturing the influence of the visual cue only. Time was numeric, beginning with target onset and continuing until the beginning of an eye movement away from central fixation. Gaze was sampled at 300Hz, thus each 3.33ms sample served as one time "bin".

Model fitting progressed in a step-wise fashion, starting with a baseline (M_0) model which included a fixed effect of Condition and random subject effects. The best-fitting model was then determined to be the simplest model that significantly improved previous model fits based on log likelihood, AIC and BIC criteria (**Table 2**). To the baseline model, I added a fixed effect of Age (M_1) which significantly improved model fits over the baseline model, $\chi^2 = 15.89$, $p < 0.001$, revealing significant a significant effect of age on pupil change. Next, I added an Age by Condition interaction (M_2) which again significantly improved fit, $\chi^2 = 217.88$, $p < 0.001$, demonstrating that pupil change varied more for some ages and conditions. Next, I added a fixed effect of time (M_3). This addition significantly improved model fit, $\chi^2 = 4672.81$, $p < 0.001$, suggesting that overall pupil dilation changed significantly throughout the trial. The final model, (M_4), included the three-way interaction of Condition, Age, and Time. This most complex model significantly improved fit, $\chi^2 = 1301.61$, $p < 0.001$, indicating that Age and Condition both contributed to changes in pupil dilation over the course of the trial. See **Table 2** for full model fits and M_4 parameter estimates.

Pupil change and covert shifts

To examine the influence of condition and age on pupil change, parameter estimates were examined from the best-fitting model (M_4, see **Figure 5** for raw observations and model fit). As can be seen in **Table 2**, there are several significant effects that speak to condition and developmental differences of dilation across the trials. Overall, the main effects for age (both *p*s > .1) and condition (*valid, invalid*, and *double*, all *p*s >.1) were not significant. This makes sense, as test intervals were short (generally less than 300ms) and many age/conditions effects didn't develop until the second half of the interval. However, there was nonetheless an important main effect of time ($p < .001$) suggesting that despite the short test interval, there was sufficient time for pupils to show significant change (see **Figure 4**). Importantly, this effect of time interacted in important ways with both age and condition. I will briefly summarize a few of the most theoretically important effects.

First, there were several significant two-way interactions of Age and Time as well as Condition and Time (all *p*s < 0.05). This suggests that overall, there are important differences in pupil dilation dynamically changing across the trial that vary by age and condition. However, these effects were subsumed under several significant age by condition by time effects for both 8- and 11-month-olds, again suggesting that differences emerged later in the test interval. Specifically, 8-month-old infants showed significant effects of condition over time for the *valid* ($p < .05$), *double* ($p < .001$) and *invalid* conditions ($p < .05$). 11-month-olds showed the same pattern for *valid, double* and *invalid* conditions (all *p*s < .001). These significant condition effects reveal clear

developmental differences in covert attention and saccade planning, with greater dilation when saccade planning had to be interrupted and attention re-deployed to the target location prior to a saccade. Interestingly, both 8- nor 11-month-olds showed a significant effect for the *none* condition (both *p*s < .001), evincing pupillometry was able to catch pupil changes in response to the beep tone on its own. In the *valid* condition, infants dilate at a slower rate compared to *tone* as infants get older. Meanwhile in the *double* and *invalid* conditions, infants dilate at a higher and faster rate than baseline. This is consistent with the possibility that pupil dilation in the invalid and double cue condition reflected the increased processing necessary for saccade interruption and attention re-orienting.

Follow-Ups

To further explore the independent effects of condition for each age, significant model results were followed up using pairwise comparisons with a Bonferroni correction (see **Table 3**). Within the 5-month-olds, the dilation in response to the *valid* cue did not differ significantly from both the *invalid* and *double* cues (both *p*s > .001). At 8-months, the *double* cue elicits a larger dilation than both *valid* and *invalid* (both *p*s > .001). Lastly, larger dilations are seen in the *invalid* and *double* conditions compared to the *valid* condition for the 11-month-olds (both *p*s <.001).

These direct comparisons suggest that within the visual cue conditions (i.e, *valid*, *invalid*, and *double*) there are differences of dilation in each age; however, the expected pattern of larger dilation due to reorienting does not begin to emerge until 8-months and becomes a stronger effect at 11-months.

Discussion

Covert orienting is a discreet shift of attention that is challenging to isolate and measure in infants due to developmental barriers (i.e., can't be instructed and limited voluntary attentional control). This study was the first to use pupillometry to attempt capture the development of covert attention over the first year. Specifically, the main aim of this study was to test if pupillometry is viable marker of covert attention and thus able to reveal conditional and developmental differences beyond the capacity of the current overt behavioral measures (reaction time and accuracy).

Prior to addressing pupillometry's role, first, analyses of latency to orient and proportion correct were used to establish the presence of spatial cueing effects. Both latency to orient and accuracy measures revealed an effect of Condition, indicating that the spatial placement of the visual cue(s) relative to the target influenced looking behavior. The deployment of covert attention to the cue specifically facilitated faster eye movements to the target when in the same location and slower saccades when located opposite the target, supporting the presence of cueing effects.

Contrary to prediction and previous work (Ross-Sheehy et al., 2015), Age did not significantly account for the variance of LTO, nor did the interaction between Age and Condition. One possible reason it did not replicate is that the present study utilized latency to orient (LTO) instead of reaction time (RT; Ross-Sheehy et al, 2015), the key difference being that RT is time until first fixation on the target. LTO removes age-related variability in saccade speed which may have contributed to greater variation of

response time in previous developmental effects with older infants making faster saccades.

Percent correct (PC) results supported the prediction that participants were less accurate for higher cue/target competition conditions compared to the baseline, *tone* condition. Further, the significant interaction of Age and Condition suggests that sensitivity to the cue is different across age groups. While infant research suggests older infants have increased inhibition and attentional control (Richards, 2005), the older infants in this study were less accurate in the *invalid* condition. Previous work suggests that this pattern is likely the result of increased processing speed with increasing age (Ross-Sheehy et al., 2015). In contrast, the 5-month-olds may have been slower to process and respond to the cue, therefore this group may have had less difficulty re-orienting when the target appeared. This faster, more sensitive response of the older groups resulted in quicker, accurate responses when the cue side was the same as target side but hindered them when the cues were misleading.

In addition to the spatial cueing effects noted above, pupil response during attentional orienting was also assessed. Results from a linear mixed effect (LME) model assessing Age, Condition and Time revealed multiple significant 2- and 3-way interactions suggesting pupillometry was able to capture meaningful developmental and condition differences within around 100 to 300 milliseconds.

First, I hypothesized that the presence of a visual cue prior to target presentation would cause a covert shift of attention resulting in a larger dilation, compared to no shift of attention to a visual cue. The three-way interaction of Age, Condition, and Time did

find a difference in pupil response for the *valid* condition compared to *tone* for 8- or 11-month-olds. However, this difference of dilation over the trial was not larger, it was in fact smaller than the dilation in response to *tone*. Contrastingly, *invalid* and *double* were significantly different in both overall dilation and the timing in which those dilations manifested across the trial at each age. These findings – while not hypothesized – highlight the ability of this measure to capture developmentally different response to visual cues.

One possible reason that the *valid* condition did not elicit a larger dilation than *baseline* is that in the valid cue condition, pupils began dilating prior to the time the target was presented, the dilation in response to the cue had already happened. Meaning, the time from target onset to saccade from center was capturing the tail end of the covert shift and saccade planning. This would set it apart from the *tone* condition as attention orienting does not begin until target onset, resulting in a larger dilation. Although the same could be said for the invalid condition, it is possible that dilation in both the *invalid* and *double* conditions may actually reflect saccade canceling, and/or attention re-orienting, and/or saccade preparation and execution. Should this be true, then it supports the idea that temporal resolution of pupillometry is much faster than previous researchers believed.

This pattern of visual cue condition findings may reflect the engagement of the DAN and VAN systems, which may be captured by pupil dynamics. The *valid* and *tone* cues, relying heavily on reflexive orienting, may have placed fewer demands on the DAN and interplay of the two systems, compared to the *invalid* and *double* conditions,

therefore less dilation was seen in comparison. This aligns with Corbetta & Shulman's (2002) work that looks at brain activation of the two systems in adults and monkeys. When targets appear in unlikely locations (i.e., *invalid* and *double*) the VAN system responds first, however the IPS and FEFs – core regions of the DAN – show increased activation in response to the orienting needed to attend the new location. Meaning, conditions in which there is competition of cue and target locations, may elicit larger dilations in response to the interplay of the two systems, specifically the activation of the DAN. While this work was done with monkeys and adults, it is applicable to the developing infant attention system as evidenced by the model and follow pairwise comparison results.

In addition to model results, planned comparisons explored condition effects (*valid, invalid, double*) by age. Overall, these findings support the hypothesis that pupillometry would be sensitive to attention beyond that of indicating the presence of a cue, but also differences of cue-induced looking behavior. Specifically, comparisons show that at five months the *valid* cue did not elicit a larger dilation than *invalid* and *double.* Although 5-month-olds were able to correctly fixate on targets in the *invalid* condition – potentially indicating some ability to reorient – their dilation patterns wer different than the older groups. One possible explanation may be that the increased task demands challenge a facet of the attentional systems that is in different stages of development across this first year. Specifically, 5-month-olds may have some inhibition, but it is not as strong as the 8- or 11-month-olds, therefore not picked up in pupil dynamics. Another possibility is that the 5-month-olds that are accurately making eye

movements to target when shown an *invalid* cue are not shifting attention to the cue fast enough to perceive and begin planning the eye movement on those trials. Thus, re-orienting is unnecessary, and the interplay of the two systems is not occurring or evinced in the pupil responses across the trial.

In 8-month-olds, the *double* cue elicits a larger dilation than both the *invalid* and *valid* conditions. Past research suggests that inhibition and re-orienting develop around 6-months, so why would do we not see a larger dilation for *invalid* compared to *valid* as well at this age? One possible reason may be that the *double* cues are simultaneously spearing at both sides of the screen, potentially being both more arousing and more effortful to attend spatially even though *invalid* requires more re-orienting. Adult attention researchers continue to debate the merit of multiple spotlights versus a zoom lens that "zooms out" to capture multiple attended locations (McMains & Somers, 2005). Regardless which is happening, both cases require more attentional resources to attend than one location or possibly even re-orienting. Alnæs and colleagues (2014) specifically found pupil size to be correlated to activity in the DAN in response to multiple object tracking, or the divided attention needed to attend to multiple locations. Should this increased dilation for the *double* cue be a result of higher attentional effort, it would suggest divided attention presumably is more effortful and more developed than re-orienting in 8-month-olds. This would make sense as re-orienting across opposing spatial locations would need a developed attentional scope first.

By 11-months dilation is greater in both the *invalid* and *double* conditions compared to the *valid* condition. This aligns with the hypothesis that within the visual cue

conditions, the two with higher cue/target competition would be more effortful, therefore resulting in larger dilations than the *valid* cue. This change in pattern from 5- to 11-months may be due to the increasing development of inhibition, or the strengthening of the DAN's role in attention, needed for reorienting attention when the cue is competing with the target. Ellis and peers (2021) used fMRI to observe these regions in a cueing task using only visual cue conditions on a similar population (i.e., infants 5-11 months). Their findings support the idea that both systems may be active early in infancy, but the flexibility needed to reorient becomes stronger over the first year.

Limitations and Future Directions

A limitation of the current study is the difficulty of the *invalid* condition, for a few reasons. First, a trial is "correct" and used for analysis if the first saccade from center is to the target. As the invalid cue is meant to be misleading, it results in more incorrect trials than correct ones. For the infants that are fast processors or quick to begin a saccade, they are either not looking center when the target is presented or look to the wrong side for this condition, meaning this condition contributes way fewer correct trials for analyses than the other conditions. This could potentially skew the interpretation of the *invalid* trial findings as there are fewer data points and the trials that are correct may be contributed by slower processors or be trials in which the infant was less attentive, so they were not as sensitive to the cue. However, the difficulty of this condition is needed to highlight meaningful spatial cueing effects, especially in this nonverbal population.

A second limitation to address would be the reference group, specifically the baseline condition (i.e., *tone*). When analyzing a behavioral measure such as reaction

time, *tone* is a solid theoretical baseline. However, when analyzing pupil response there are some considerations. The absence of a visual cue creates two problems for consideration. First, the timing of the blank screen between the attention getter and target presentation is longer, therefore the sequence of visual stimulus is not temporally comparable between *tone* and other visual cue conditions. How pupils respond to a blank screen is going to be different from a screen with a similarly sized and colored baseline cue. This segues to the second problem; though the cue is small, even small dark changes of luminance can impact pupil reaction. These features of baseline may be the cause of why the model was unable to capture differences of dilation in response to the shift to the cue. Future studies looking to replicate these findings may attempt to devise a baseline including a visual cue. Despite these limitations, *tone* is still a good neutral baseline as it does not elicit a covert shift of attention away from center. It nevertheless lended to meaningful developmental insights of how covert shifts of attention in this population paired with a reaction time measure.

Past pupillometry studies have typically analyzed trends over much longer time points, some 10-30 seconds per trial (Markwell et al., 2010). More recent work has shortened this window to within a few seconds as methodology for preprocessing and analyzing pupil data has significantly changed. This project stands out as one of, if not the shortest, in terms of the window in which we are observing pupil changes. The findings of this study contribute to the growing body of evidence that suggests pupillometry is capable of capturing meaningful changes of pupil size within a short time frame. However, for the validity of these findings it is crucial to replicate these findings.

Future research would include a replication of these results in an infant population as well as tests on adult participants. This task would have adults view a similar spatial cueing task as an infant would, with no instructions, and then the same task maintaining a central fixation using a button response for target side. A task like this would seek to validate pupillometry's ability to capture covert attention in a short span of time and compare pupil dilations marking covert attention prior to an eye movement and in the absence of a saccade. Also, it would allow for comparisons between the basic attentional processing of an infant and adult levels.

Another avenue for exploration would be investigating the lateralization of pupil responses to covert attentional shifts. With previous work showing an asymmetry of pupil sizes in most adults, it would be interesting to explore differences of ipsilateral and contralateral dilations in response to covert attentional shifts. Adding neural imaging to this research would be informative to age-related difference of developing attentional networks and hemispheric differences of activation of these attentional networks.

CHAPTER FIVE

CONCLUSIONS

This study set out to explore the capability of pupillometry to be an informative measure of covert attention in infants in a way traditional measures could not. Results from the behavioral measures support the presence of spatial cueing effects from 5- to 11-months. Pupillometry findings highlighted differences of dilations that indicate an increasingly complex attentional system over the first year. Specifically, rates of dilation were increasingly different for the *valid, invalid* and *double* conditions as infants got older. These dilation patterns reflect the change from a largely reflexive orienting system to a two-network attentional system that interplays through the superior colliculus "hub" for a more flexible attentional system. Exogenous orienting mainly drives attention through the first six months of life, therefore the VAN network may be dominant at 5-months. By 8- and 11-months the DAN plays a much more active role in the inhibition and re-orienting of attention.

This study contributes to the increasing evidence that pupillometry is a continuous and sensitive measure capable of capturing early developmental changes of attention. Importantly, it suggests that pupil response has a high temporal resolution, making it a great tool for capturing quick processes such as attentional orienting. Covert attention is a critical skill for efficient scene exploration needed for more complex behaviors such as memory, decision-making, and learning. Having a measure that goes beyond capturing the presence of covert attention, but can potentially speak to differences of developing

attentional systems in a young population could be impactful to future research on both typical and atypical infant populations.

It still remains that covert attention is methodologically difficult to isolate in infancy, yet these findings seem promising that pupillometry is an accessible and non-invasive method of measuring developing attentional mechanisms in infants. In conjunction with ongoing research, this study offers one step more towards supporting pupillometry's ability to reveal covert shifts of attention and inform of the developing neural systems supporting it.

REFERENCES

Alnæs, D., Sneve, M. H., Espeseth, T., Endestad, T., van de Pavert, S. H. P., & Laeng, B. (2014). Pupil size signals mental effort deployed during multiple object tracking and predicts brain activity in the dorsal attention network and the locus coeruleus. *Journal of Vision*, *14*(4). https://doi.org/10.1167/14.4.1

Alves, P. N., Forkel, S. J., Corbetta, M., & Thiebaut de Schotten, M. (2022). The subcortical and neurochemical organization of the ventral and dorsal attention networks. *Communications Biology*, *5*(1), 1343.

Aminihajibashi, S., Hagen, T., Foldal, M. D., Laeng, B., & Espeseth, T. (2019). Individual differences in resting-state pupil size: Evidence for association between working memory capacity and pupil size variability. *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology*, *140*, 1–7.

Aslin, R. N. (1981). Development of smooth pursuit in human infants. In D. F. Fisher, R. A. Monty, & J. W. Senders (Eds.), Eye movements: Cognition and visual perception (pp. 31 – 51). Hillsdale, NJ: Erlbaum. Barbur, J. L. (1995). A study of pupil response components in human vision. In *Basic and Clinical Perspectives in Vision Research* (pp. 3–18). Springer US.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). *Fitting linear mixed-effects models using lme4. Journal of Statistical Software*, *67*(1), 1-48. https://doi.org/10.18637/jss.v067.i01

Bertinotti, L., Pietrini, U., Del Rosso, A., Casale, R., Colangelo, N., Zoppi, M., & Matucci-Cerinic, M. (2002). The use of pupillometry in joint and connective tissue diseases. *Annals of the New York Academy of Sciences*, *966*, 446–455.

Blair, C. D., & Ristic, J. (2019). Attention combines similarly in covert and overt conditions. *Vision (Basel, Switzerland)*, *3*(2), 16.

Binda, P., & Murray, S. O. (2015). Spatial attention increases the pupillary response to light changes. *Journal of Vision*, *15*(2), 1.

Brocher, A., Harbecke, R., Graf, T., Memmert, D., & Hüttermann, S. (2018). Using task effort and pupil size to track covert shifts of visual attention independently of a pupillary light reflex. *Behavior Research Methods*, *50*(6), 2551–2567.

Carrasco, M., & McElree, B. (2001). Covert attention accelerates the rate of visual information processing. *Proceedings of the National Academy of Sciences of the United States of America*, *98*(9), 5363–5367.

Chica, A. B., Bartolomeo, P., & Lupiáñez, J. (2013). Two cognitive and neural systems for endogenous and exogenous spatial attention. *Behavioural Brain Research*, *237*, 107–123.

Colombo, J. (2001). The development of visual attention in infancy. *Annual Review of Psychology*, *52*, 337–367.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews. Neuroscience*, *3*(3), 201–215.

Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology. General*, *113*(4), 501–517.

Egeth, H. E., & Yantis, S. (1997). Visual attention: control, representation, and time course. *Annual Review of Psychology*, *48*(1), 269–297.

Ellis, C. J. (1981). The pupillary light reflex in normal subjects. *The British Journal of Ophthalmology*, *65*(11), 754–759.

Ellis, C. T., Skalaban, L. J., Yates, T. S., & Turk-Browne, N. B. (2021). Attention recruits frontal cortex in human infants. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(12), e2021474118.

Esterman, M., & Rothlein, D. (2019). Models of sustained attention. *Current Opinion in Psychology*, *29*, 174–180.

Evans, K. K., Horowitz, T. S., Howe, P., Pedersini, R., Reijnen, E., Pinto, Y., Kuzmova, Y., & Wolfe, J. M. (2011). Visual attention. *Wiley Interdisciplinary Reviews. Cognitive Science*, *2*(5), 503–514.

Fernández, A., Okun, S., & Carrasco, M. (2022). Differential effects of endogenous and exogenous attention on sensory tuning. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *42*(7), 1316–1327.

Foster, J. J., Thyer, W., Wennberg, J. W., & Awh, E. (2021). Covert attention increases the gain of stimulus-evoked population codes. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *41*(8), 1802–1815.

Fried, R. (1980). Pupillometry: The Psychology of the Pupillary Response (Book). *Journal of Personality Assessment*, *44*(4), 441–444.

Grossmann, T., & Johnson, M. H. (2010). Selective prefrontal cortex responses to joint attention in early infancy. *Biology Letters*, *6*(4), 540–543.

Haith, M. M., Hazan, C., & Goodman, G. S. (1988). Expectation and anticipation of dynamic visual events by 3.5-month-old babies. *Child Development*, *59*(2), 467–479.

Hershman, R., Milshtein, D., & Henik, A. (2023). The contribution of temporal analysis of pupillometry measurements to cognitive research. *Psychological Research*, *87*(1), 28–42.

Hess, E. H., & Polt, J. M. (1960). Pupil size as related to interest value of visual stimuli. *Science, 132*(3423), 349–350.

Homae, F., Watanabe, H., Otobe, T., Nakano, T., Go, T., Konishi, Y., & Taga, G. (2010). Development of global cortical networks in early infancy. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *30*(14), 4877–4882.

Hood, B.M. (1995). Visual selective attention in the human infant: A neuroscientific approach. In: Rovee-Collier, C., Lipsett, L. (Eds.), Advances in Infancy Research. Ablex, New Jersey.

Hunnius, S. (2007). The early development of visual attention and its implications for social and cognitive development. *Progress in Brain Research, 164*, 187–209.

Hunt, A. R., & Kingstone, A. (2003). Covert and overt voluntary attention: linked or independent? *Brain Research. Cognitive Brain Research*, *18*(1), 102–105.

Hunter, B., Montgomery, B., Sridhar, A., & Markant, J. (2024). Endogenous control and reward-based mechanisms shape infants' attention biases to caregiver faces. *Developmental Psychobiology*, *66*(6), e22521.

James, W. (1890). Principles of Psychology. New York, NY: Henry Holt and Company.

Janisse, M. P. (1974). Pupillometry: Some Advances, Problems and Solutions. In M. P. Janisse (Ed.), *Pupillary Dynamics and Behavior* (pp. 1–8). Springer US.

Johnson, M. H. (1990). Cortical maturation and the development of visual attention in early infancy. *Journal of Cognitive Neuroscience*, *2*(2), 81–95.

Johnson, M. H. (1994). *Visual attention and the control of eye movements in early infancy*. wexler.free.fr. http://wexler.free.fr/library/files/johnson%20(1994)%20visual%20attention%20and%20the%20control%20of%20eye%20movements%20in%20early%20infancy.pdf

Jonas, J. B., Zäch, F. M., & Naumann, G. O. (1990). Quantitative pupillometry of relative afferent defects in glaucoma. *Archives of Ophthalmology*, *108*(4), 479–480.

Krauzlis, R. J., Liston, D., & Carello, C. D. (2004). Target selection and the superior colliculus: goals, choices and hypotheses. *Vision Research*, *44*(12), 1445–1451.

Kulke, L. V., Atkinson, J., & Braddick, O. (2016). Neural differences between covert and overt attention studied using EEG with simultaneous remote eye tracking. *Frontiers in Human Neuroscience*, *10*, 592.

Krauzlis, R. J., Lovejoy, L. P., & Zénon, A. (2013). Superior colliculus and visual spatial attention. *Annual Review of Neuroscience*, *36*, 165–182.

Laeng, B., Sirois, S., & Gredebäck, G. (2012). Pupillometry: A window to the preconscious? *Perspectives on Psychological Science: A Journal of the Association for Psychological Science*, *7*(1), 18–27.

Lanssens, A., Pizzamiglio, G., Mantini, D., & Gillebert, C. R. (2020). Role of the dorsal attention network in distracter suppression based on features. *Cognitive Neuroscience, 11*(1–2), 37–46.

Lazar, R., Degen, J., Fiechter, A.-S., Monticelli, A., & Spitschan, M. (2023). Regulation of pupil size in natural vision across the human lifespan. In *bioRxiv* (p. 2023.10.16.562484). https://doi.org/10.1101/2023.10.16.562484

Lawrence, M. A. (2016). Ez: Easy Analysis and Visualization of Factorial Experiments. https://CRAN.R-project.org/package=ez

Lenth, R. V. (2024). *Emmeans:Estimated Marginal Means, aka Least-Squares Means* (Version 1.10.1) [R package]. https://CRAN.R-project.org/package=emmeans

Lewkowicz, D. J., & Hansen-Tift, A. M. (2012). Infants deploy selective attention to the mouth of a talking face when learning speech. *Proceedings of the National Academy of Sciences of the United States of America, 109*(5), 1431–1436.

MacInnes, W. J., Jóhannesson, Ó. I., Chetverikov, A., & Kristjánsson, Á. (2020). No Advantage for Separating Overt and Covert Attention in Visual Search. *Vision (Basel, Switzerland), 4*(2). https://doi.org/10.3390/vision4020028

Mangun, G. R. (1995). Neural mechanisms of visual selective attention. *Psychophysiology, 32*(1), 4–18.

Manohar, S., Bonnelle, V., & Husain, M. (2014). Neurological disorders of attention. *The Oxford Handbook of Attention.*, *1242*(2014), 1028–1061.

Markwell, E. L., Feigl, B., & Zele, A. J. (2010). Intrinsically photosensitive melanopsin retinal ganglion cell contributions to the pupillary light reflex and circadian

rhythm. *Clinical & Experimental Optometry: Journal of the Australian Optometrical Association*, *93*(3), 137–149.

Martinez-Alvarez, A., Pons, F., & de Diego-Balaguer, R. (2017). Endogenous temporal attention in the absence of stimulus-driven cues emerges in the second year of life. *PloS One*, *12*(9), e0184698.

Mathôt, S., Fabius, J., Van Heusden, E., & Van der Stigchel, S. (2018). Safe and sensible preprocessing and baseline correction of pupil-size data. *Behavior Research Methods*, *50*(1), 94–106.

Mathôt, S., Melmi, J.-B., van der Linden, L., & Van der Stigchel, S. (2016). The Mind-Writing Pupil: A Human-Computer Interface Based on Decoding of Covert Attention through Pupillometry. *PloS One*, *11*(2), e0148805.

Mathôt, S., Siebold, A., Donk, M., & Vitu, F. (2015). Large pupils predict goal-driven eye movements. *Journal of Experimental Psychology. General*, *144*(3), 513–521.

Mathôt, S., van der Linden, L., Grainger, J., & Vitu, F. (2013). The pupillary light response reveals the focus of covert visual attention. *PloS One*, *8*(10), e78168.

Mathôt, S., & Vilotijević, A. (2022). Methods in cognitive pupillometry: Design, preprocessing, and statistical analysis. *Behavior Research Methods*. https://doi.org/10.3758/s13428-022-01957-7

McMains, S. A., & Somers, D. C. (2005). Processing efficiency of divided spatial attention mechanisms in human visual cortex. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *25*(41), 9444–9448.

Mukai, I., Bahadur, K., Kesavabhotla, K., & Ungerleider, L. G. (2011). Exogenous and endogenous attention during perceptual learning differentially affect post-training target thresholds. *Journal of Vision*, *11*(1). https://doi.org/10.1167/11.1.25

Mulckhuyse, M., & Theeuwes, J. (2010). Unconscious attentional orienting to exogenous cues: A review of the literature. *Acta Psychologica*, *134*(3), 299–309.

Norman, D. A. (1968). Toward a theory of memory and attention. *Psychological Review*, *75*(6), 522–536.

Oakes, L. M., Kannass, K. N., & Shaddy, D. J. (2002). Developmental changes in endogenous control of attention: the role of target familiarity on infants' distraction latency. *Child Development*, *73*(6), 1644–1655.

Olmos-Solis, K., van Loon, A. M., & Olivers, C. N. L. (2018). Pupil Dilation Reflects Task Relevance Prior to Search. *Journal of Cognition*, *1*(1), 11.

Orquin, J. L., Lahm, E. S., & Stojić, H. (2021). The visual environment and attention in decision making. *Psychological Bulletin*, *147*(6), 597–617.

Perkovic, S., Schoemann, M., Lagerkvist, C.-J., & Orquin, J. L. (2023). Covert attention leads to fast and accurate decision-making. *Journal of Experimental Psychology. Applied*, *29*(1), 78–94.

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, *32*(1), 3–25.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, *13*, 25–42.

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology*, *109*(2), 160–174.

R Core Team (2025). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. https://www.R-project.org/

Reynolds, G. D., & Romano, A. C. (2016). The Development of Attention Systems and Working Memory in Infancy. *Frontiers in Systems Neuroscience*, *10*, 15.

Richards, J. E. (2001). Cortical indexes of saccade planning in infants. *Infancy: The Official Journal of the International Society on Infant Studies*, *2*(2), 123–133.

Richards, J. E. (2005). Development of covert orienting in young infants. In *Neurobiology of Attention* (pp. 82–88). Elsevier.

Richards, J. E., & Holley, F. B. (1999). Infant attention and the development of smooth pursuit tracking. *Developmental Psychology*, *35*(3), 856–867.

Ross-Sheehy, S., Reynolds, E., & Eschman, B. (2020). Evidence for Attentional Phenotypes in Infancy and Their Role in Visual Cognitive Performance. *Brain Sciences*, *10*(9). https://doi.org/10.3390/brainsci10090605

Ross-Sheehy, S., Schneegans, S., & Spencer, J. P. (2015). The Infant Orienting With Attention task: Assessing the neural basis of spatial attention in infancy. *Infancy: The Official Journal of the International Society on Infant Studies*, *20*(5), 467–506.

Schnitzler, E. M., Baumeister, M., & Kohnen, T. (2000). Scotopic measurement of normal pupils: Colvard versus Video Vision Analyzer infrared pupillometer. *Journal of Cataract and Refractive Surgery*, *26*(6), 859–866.

Sigman, M., Kopp, C. B., Parmelee, A. H., & Jeffrey, W. E. (1973). Visual attention and neurological organization in neonates. *Child Development*, *44*(3), 461–466.

Silbert, J., Matta, N., Tian, J., Singman, E., & Silbert, D. I. (2013). Pupil size and anisocoria in children measured by the plusoptiX photoscreener. *Journal of AAPOS: The Official Publication of the American Association for Pediatric Ophthalmology and Strabismus / American Association for Pediatric Ophthalmology and Strabismus*, *17*(6), 609–611.

Sirois, S., & Brisson, J. (2014). Pupillometry. *Wiley Interdisciplinary Reviews. Cognitive Science*, *5*(6), 679–692.

Sirois, S., Brisson, J., Blaser, E., Calignano, G., Donenfeld, J., Hepach, R., Hochmann, J.-R., Kaldy, Z., Liszkowski, U., Mayer, M., Ross-Sheehy, S., Russo, S., & Valenza, E. (2023). The pupil collaboration: A multi-lab, multi-method analysis of goal attribution in infants. *Infant Behavior & Development*, *73*(101890), 101890.

Spelke, E., Hirst, W., & Neisser, U. (1976). Skills of divided attention. *Cognition*, *4*(3), 215–230.

Soret, R., Charras, P., Hurter, C., & Peysakhovich, V. (2019, June 25). Attentional orienting in virtual reality using endogenous and exogenous cues in auditory and visual modalities. *Proceedings of the 11th ACM Symposium on Eye Tracking*

Research & Applications. ETRA '19: 2019 Symposium on Eye Tracking Research and Applications, Denver Colorado. https://doi.org/10.1145/3317959.3321490

Steinhauer, S. R., & Hakerem, G. (1992). The pupillary response in cognitive psychophysiology and schizophrenia. *Annals of the New York Academy of Sciences*, *658*, 182–204.

Stewart, E. E. M., Valsecchi, M., & Schütz, A. C. (2020). A review of interactions between peripheral and foveal vision. *Journal of Vision*, *20*(12), 2.

Suo, X., Ding, H., Li, X., Zhang, Y., Liang, M., Zhang, Y., Yu, C., & Qin, W. (2021). Anatomical and functional coupling between the dorsal and ventral attention networks. *NeuroImage*, *232*, 117868.

Theeuwes, J. (1991). Exogenous and endogenous control of attention: the effect of visual onsets and offsets. *Perception & Psychophysics*, *49*(1), 83–90.

Thompson, H. S. (2003). The Vitality of the Pupil: A History of the Clinical Use of the Pupil as an Indicator of Visual Potential. *Journal of Neuro-Opthalmology*, *23*(3), 213–224.

Tummeltshammer, K. S., Mareschal, D., & Kirkham, N. Z. (2014). Infants' selective attention to reliable visual cues in the presence of salient distractors. *Child Development*, *85*(5), 1981–1994.

Unsworth, N., & Robison, M. K. (2018). Tracking arousal state and mind wandering with pupillometry. *Cognitive, Affective & Behavioral Neuroscience*, *18*(4), 638–664.

Van der Stigchel, S., & Theeuwes, J. (2007). The relationship between covert and overt attention in endogenous cuing. *Perception & Psychophysics*, *69*(5), 719–731.

Vossel, S., Geng, J. J., & Fink, G. R. (2014). Dorsal and ventral attention systems: distinct neural circuits but collaborative roles. *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, *20*(2), 150–159.

Wang, C.-A., & Munoz, D. P. (2021). Coordination of pupil and saccade responses by the superior colliculus. *Journal of Cognitive Neuroscience*, 1–14.

Winn, B., Whitaker, D., Elliott, D. B., & Phillips, N. J. (1994). Factors affecting light-adapted pupil size in normal human subjects. *Investigative Ophthalmology & Visual Science*, *35*(3), 1132–1137.

Wickham, H. (2016). Ggplot2: Elegnat Graphics for Data Analysis. Springer-Verlag New York. https://ggplot2.tidyverse.org

Wickham, H., François, R., Henry, L., Müller, K., & Vaughan, D. (2023). Dplyr: A Grammar of Data Manipulation. https://CRAN.R-project.org/package=dplyr

Winston, M., Zhou, A., Rand, C. M., Dunne, E. C., Warner, J. J., Volpe, L. J., Pigneri, B. A., Simon, D., Bielawiec, T., Gordon, S. C., Vitez, S. F., Charnay, A., Joza, S., Kelly, K., Panicker, C., Rizvydeen, S., Niewijk, G., Coleman, C., Scher, B. J., … Weese-Mayer, D. E. (2020). Pupillometry measures of autonomic nervous system regulation with advancing age in a healthy pediatric cohort. *Clinical Autonomic Research: Official Journal of the Clinical Autonomic Research Society*, *30*(1), 43–51.

Zhao, J., Wang, J., Huang, C., & Liang, P. (2022). Involvement of the dorsal and ventral attention networks in visual attention span. *Human Brain Mapping*, *43*(6), 1941–1954.

Zhang, F., & Emberson, L. L. (2020). Using pupillometry to investigate predictive processes in infancy. *Infancy: The Official Journal of the International Society on Infant Studies*, *25*(6), 758–780.

Zubricky, R. D., & Das, J. M. (2025). Neuroanatomy, superior colliculus. In *StatPearls*. StatPearls Publishing.

TABLES AND FIGURES

Table 1. Follow-up paired-comparisons examining proportion correct as a function of age and condition.

		Condition				
Age	Condition	none	tone	double	invalid	valid
5mos	none		.010	.169***	.387***	.005
	tone			.159***	.377***	-.005
	double				.218**	-.164***
	invalid					-.382*
	valid					
8mos	none		-.001	.148***	.544***	-.012
	tone			.149***	.545***	-.011
	double				.396***	-.160***
	invalid					-.556***
	valid					
11mos	none		.002	.114**	.448***	.006
	tone			.112**	.446***	.003
	double				.335***	-.108*
	invalid					-.443***
	valid					

Note: Significance denoted as * for $p<.05$, ** for $p<.01$, and *** for $p<.001$.

Table 2. Model fits and comparisons and for all models. Note, M_4 was the best-fitting model.

	Note. Dependent variable is normalized pupil size.				
	Model 0	Model 1	Model 2	Model 3	Model 4
Intercept	0.01*** (0.002)	0.01* (0.003)	0.01*** (0.003)	-0.01*** (0.003)	-0.002 (0.003)
Condition: None	0.0002 (0.0004)	0.0002 (0.0004)	-0.01*** (0.001)	-0.005*** (0.001)	-0.001 (0.001)
Condition: Valid	-0.01*** (0.0005)	-0.01*** (0.0005)	-0.01*** (0.001)	-0.0002 (0.001)	0.0002 (0.001)
Condition: Double	-0.0000 (0.0004)	-0.0000 (0.0004)	-0.005*** (0.001)	-0.01*** (0.001)	-0.001 (0.001)
Condition: Invalid	0.001 (0.0005)	0.001 (0.0005)	-0.004*** (0.001)	-0.004*** (0.001)	-0.002 (0.001)
Age: 8 mos				0.0002*** (0.0000)	0.0001*** (0.0000)
Age: 11 mos			0.01*** (0.001)	0.01*** (0.001)	0.002 (0.002)
Time			0.01*** (0.001)	0.01*** (0.001)	-0.004** (0.002)
None × 8 mos			0.002 (0.001)	0.002 (0.001)	0.001 (0.002)
Valid × 8 mos			-0.01*** (0.001)	-0.01*** (0.001)	0.001 (0.002)
Double × 8 mos			0.01*** (0.001)	0.01*** (0.001)	-0.002 (0.002)
Invalid × 8 mos			0.003** (0.001)	0.004*** (0.001)	-0.003 (0.002)
None × 11 mos			0.01*** (0.001)	0.01*** (0.001)	0.003 (0.002)
Valid × 11 mos			0.01*** (0.001)	0.01*** (0.001)	-0.001 (0.002)
Double × 11 mos					0.0001*** (0.0000)
Invalid × 11 mos					0.0002*** (0.0000)
None × Time					-0.0000*** (0.0000)
Valid × Time					-0.0000** (0.0000)
Double × Time					-0.0000*** (0.0000)
Invalid × Time					-0.0000* (0.0000)
8 mos × Time					0.0001*** (0.0000)
11 mos × Time					0.0001*** (0.0000)
None × 8 mos × Time					0.0000* (0.0000)
Valid × 8 mos × Time					-0.0001*** (0.0000)
Double × 8 mos × Time					0.0001*** (0.0000)
Invalid × 8 mos × Time					0.0001*** (0.0000)
None × 11 mos × Time					0.0000* (0.0000)
Valid × 11 mos × Time					0.0001*** (0.0000)
Double × 11 mos × Time		0.01* (0.004)	0.003 (0.004)	0.004 (0.004)	-0.002 (0.004)
Invalid × 11 mos × Time		0.02*** (0.004)	0.01*** (0.004)	0.02*** (0.004)	0.001 (0.004)
Model Comparison	m0	m1	m2	m3	m4
Likelihood Ratio Test	--	p < .001	p < .001	p < .001	p < .001
Observations	24,912	24,912	24,912	24,912	24,912
Log Likelihood	58,474.72	58,483.60	58,651.27	62,118.24	63,109.47
Akaike Inf. Crit.	-116,935.40	-116,949.20	-117,268.50	-124,200.50	-126,154.90
Bayesian Inf. Crit.	-116,878.60	-116,876.10	-117,130.40	-124,054.30	-125,895.00
Note:					*p<0.05; **p<0.01; ***p<0.001

Table 3. Bonferroni-adjust pairwise comparisons of each Condition within each Age.

Age	Contrast	Estimate	SE	df	z	p
5mos	tone - none	0.01	0	Inf	8.05	< .001
5mos	tone - valid	0.00	0	Inf	4.94	< .001
5mos	tone - double	0.00	0	Inf	7.39	< .001
5mos	tone - invalid	0.00	0	Inf	6.73	< .001
5mos	none - valid	0.00	0	Inf	-1.67	0.947
5mos	none - double	0.00	0	Inf	-0.62	1.000
5mos	none - invalid	0.00	0	Inf	-1.07	1.000
5mos	valid - double	0.00	0	Inf	1.16	1.000
5mos	valid - invalid	0.00	0	Inf	0.75	1.000
5mos	double - invalid	0.00	0	Inf	-0.47	1.000
8mos	tone - none	0.00	0	Inf	-4.18	< .001
8mos	tone - valid	0.00	0	Inf	-1.26	1.000
8mos	tone - double	0.00	0	Inf	-7.25	< .001
8mos	tone - invalid	0.00	0	Inf	-1.99	0.468
8mos	none - valid	0.00	0	Inf	1.99	0.470
8mos	none - double	0.00	0	Inf	-3.14	0.017
8mos	none - invalid	0.00	0	Inf	1.71	0.881
8mos	valid - double	0.00	0	Inf	-4.40	< .001
8mos	valid - invalid	0.00	0	Inf	-0.46	1.000
8mos	double - invalid	0.00	0	Inf	4.43	< .001
11mos	tone - none	0.00	0	Inf	-1.08	1.000
11mos	tone - valid	0.01	0	Inf	12.67	< .001
11mos	tone - double	0.00	0	Inf	0.85	1.000
11mos	tone - invalid	0.00	0	Inf	-0.58	1.000
11mos	none - valid	0.01	0	Inf	13.65	< .001
11mos	none - double	0.00	0	Inf	1.90	0.569
11mos	none - invalid	0.00	0	Inf	0.40	1.000
11mos	valid - double	-0.01	0	Inf	-11.73	< .001
11mos	valid - invalid	-0.01	0	Inf	-12.59	< .001
11mos	double - invalid	0.00	0	Inf	-1.37	1.000

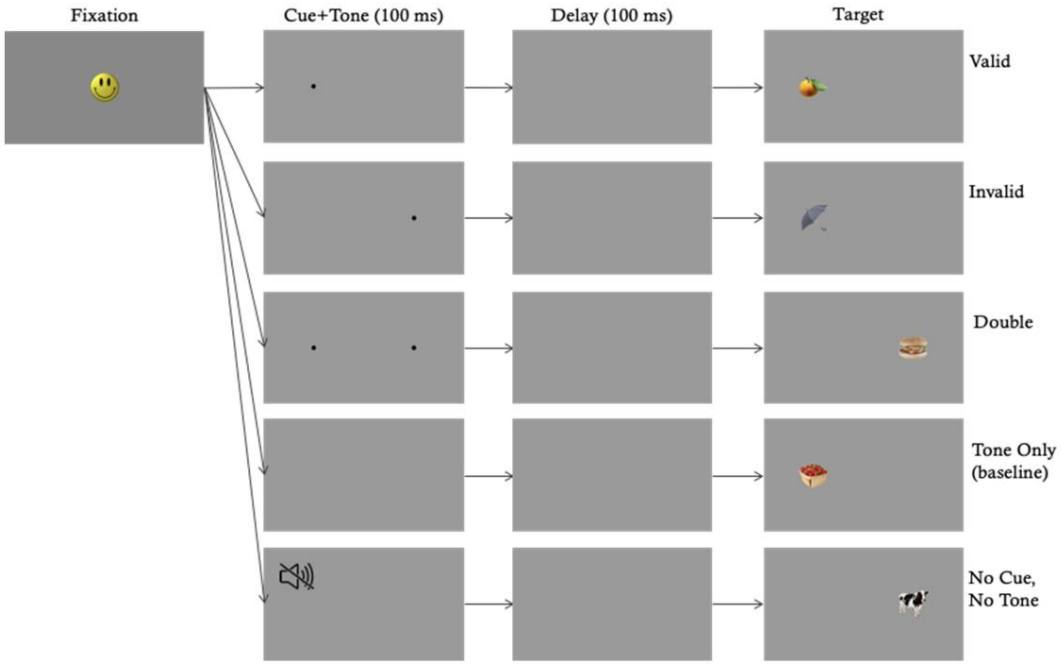


Figure 1. Layout of experimental conditions for the Infant Orienting with Attention (IOWA) task.

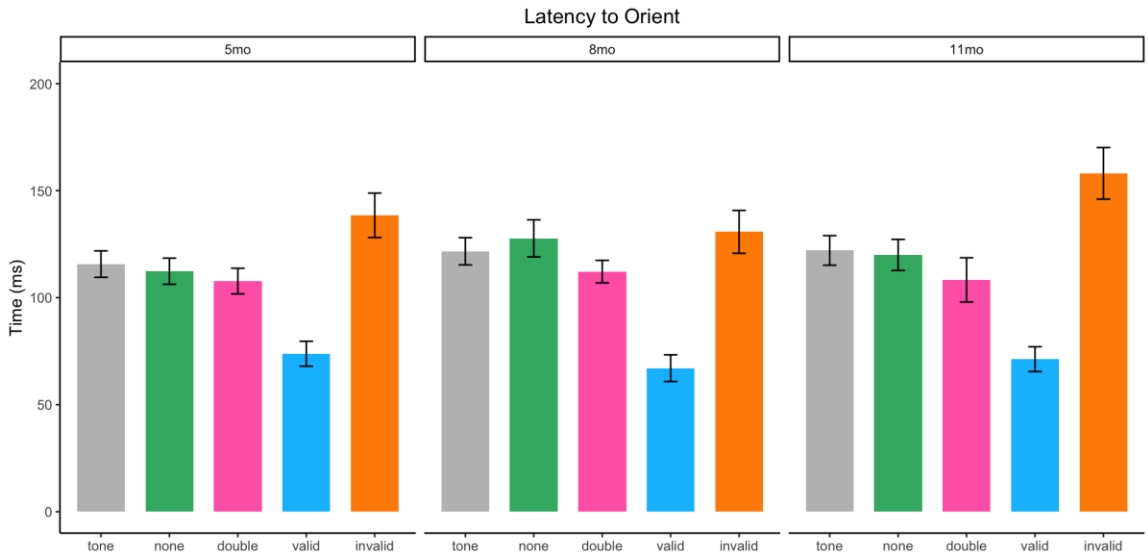


Figure 2. Mean latencies to orient to the target in milliseconds (ms). Note, latency is measured as the duration from target onset to the beginning of a saccade to the target for correct trials only.

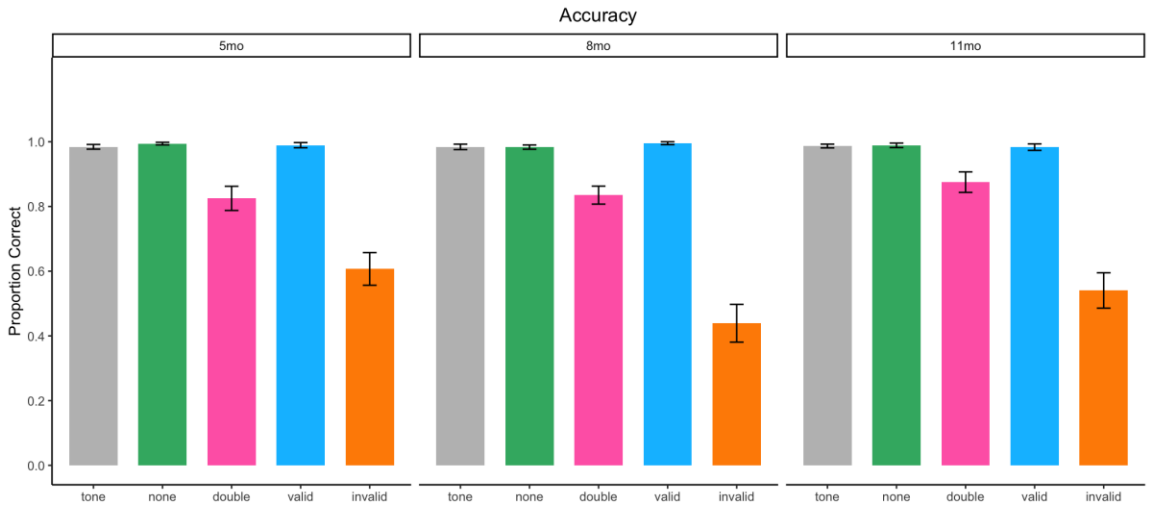


Figure 3. Proportion correct for each Age and Condition.

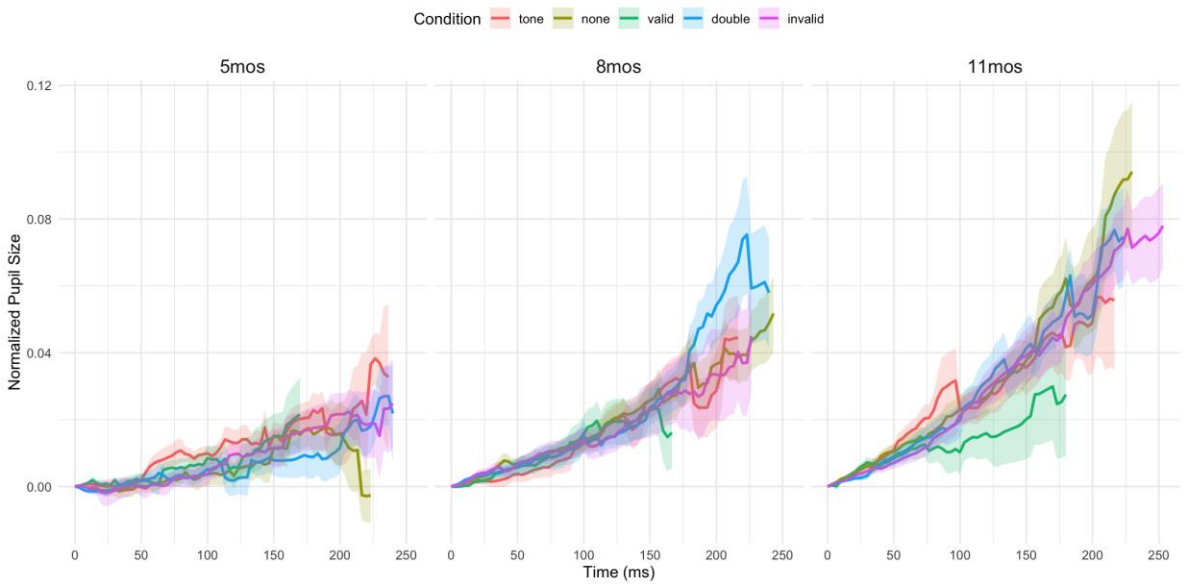


Figure 4. Pupil diameter change over the course of the trial for each Age and Condition.

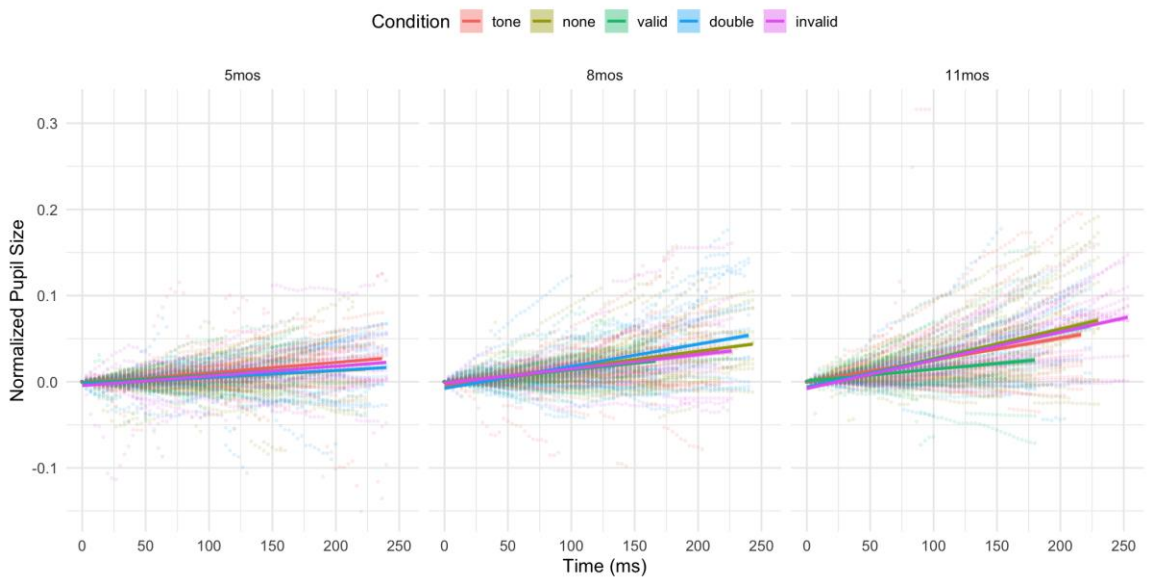


Figure 5. Raw observations and model fits for pupil dilation as a function of Age, Condition, and Time. Each line represents a best-fitting linear trend (±95% CI) and points represent raw observations.

VITA

Victoria “Tori” Jones was born in Conway, South Carolina, in 1998. She attended a dual enrollment high school, the Scholars Academy, and graduated in May 2016. She received her Bachelor of Science in Experimental Psychology from the University of South Carolina in 2019. Following graduation from U of SC, she worked at Carolina Behavior & Beyond where she was early interventionist for a year and half. In 2021, she was accepted to the University of Tennessee, where her research in the Infant Visual Cognition lab with Dr. Shannon Ross-Sheehy has focused on covert attention development and pupillometry in infancy.