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A multi-method approach to addressing the toddler data desert in attention research

Anastasia Kerr-German [a,*], A. Caglar Tas [b], Aaron T. Buss [b]

[a] Boys Town National Research Hospital, Center for Childhood Deafness, Language, and Learning, USA
[b] University of Tennessee, Department of Psychology, USA

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ABSTRACT

Visual attention skills undergo robust development change during infancy and continue to co-develop with other cognitive processes in early childhood. Despite this, this is a general disconnect between measures of the earliest foundations of attention during infancy and later development of attention in relation to executive functioning during the toddler years. To examine associations between these different measures of attention, the current study administered an oculomotor task (infant orienting with attention, IOWA) and a manual response (Flanker) task with a group of toddlers. We collected simultaneous neural recordings (using functional near-infrared spectroscopy), eye-tracking, and behavioral responses in 2.5- and 3.5-year-olds to examine the neural and behavioral associations between these skills. Results revealed that oculomotor facilitation in the IOWA task was negatively associated with accuracy on neutral trials in the Flanker task. Second, conflict scores between the two tasks were positively associated. At the neural level, however, the tasks showed distinct patterns of activation. Left frontal cortex was engaged during the Flanker task whereas right frontal and parietal cortex was engaged during the IOWA task. Activation during the IOWA task differed based on how well children could control oculomotor behavior during the task. Children with high levels of stimulus reactivity activated parietal cortex more strongly, but children with more controlled oculomotor behavior activated frontal cortex more strongly.

1. A multi-method approach to addressing the toddler data desert in attention research

Many important attentional skills emerge during infancy and early childhood that are linked to long-term cognitive, social-emotional, academic, and executive attention outcomes in childhood (Cuevas & Bell, 2013; Rothbart et al., 2011; Veer et al., 2017). Despite this, our measurement tools are limited in their scalability across early development with specific neglect seen in the toddler literature. Typically, attention in infancy is measured via tasks that use oculomotor behavior as an index of attentional efficiency. In contrast, manual responses are dominant indexes of attentional efficiency in the preschool years. Little data exists to determine whether these tasks tap the same cognitive and neural mechanisms during the toddler transition nor which methods would best capture attentional development in toddlers.

* Correspondence to: Boys Town National Research Hospital, 555 North 30th Street, Omaha, NE 68131, USA.
E-mail address: Anastasia.kerr-german@boystown.org (A. Kerr-German).

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1.1. Measures of attention in early development

Ross-Sheehy et al. (2015) developed the IOWA task to measure the development of attentional control in *infancy*. In this task, each trial begins with a central attention-getter (i.e., looming smiley face) until infants fixate on the center of the screen. A cue followed by a target object is then presented left or right of fixation. Attentional measures are calculated based on saccade latency and accuracy of the initial saccade after the presentation of the target. The visual cue briefly presented before the target object is intended to manipulate the covert orienting of attention. This visual cue can be at the same location as the target object (valid cue), at the opposite location of the target object (invalid cue), or on both sides of the screen (double cue). In addition to visual cues, the task also incorporates an auditory cue condition to manipulate attentional alertness and a no-cue condition as a baseline. Using this task, Ross-Sheehy et al. (2017) demonstrated that oculomotor behaviors reveal attentional change over the first year of life. That is, older infants execute saccades more quickly than younger infants. Relatedly, the youngest group of infants (5-month-olds) made fewer errors on invalid cue trials compared to the two older groups of infants (7- and 10-month-olds), suggesting that attentional processing becomes faster over development and more prone to distraction from irrelevant cues. Thus, the more exogenously controlled attention becomes, the greater the need to employ complementary cognitive processes such as inhibition and selective attention to regulate behavior. With gains in basic attention, other processes such as inhibition and selective attention must also improve. The IOWA task has been used to assess alerting, orienting, and executive attention in infancy, but has not been applied beyond this age.

One common assessment of attention during *early childhood* (i.e., 36–60-month-olds) is the Child Attention Network Task (ANT; Fan et al., 2002). In the ANT, a manual response task (Flanker task) is combined with properties of traditional oculomotor spatial cueing tasks to investigate how pre-target cues influence responses to the target item in the stimulus array. In the Flanker task, participants make manual left/right responses based on the direction of a centrally presented target stimulus. The central target stimulus can be flanked by distractor items that are either facing the same direction as the target stimulus (congruent) or the opposite direction (incongruent). Typically, the Flanker task is thought to provide a measure of *executive attention* based on the increase in reaction time (RT) and errors on incongruent trials compared to congruent or neutral trials in which no distractor items are presented. To make the ANT more engaging for children, its stimuli has been modified to consist of animals facing either left or right (Fan et al., 2002; Rothbart et al., 2007). In this version, children are instructed to feed the central animal by pressing a button on the side that the animal is facing.

By using spatial pre-cues, the ANT also manipulates the dynamics of attention prior to the presentation of the Flanker stimulus array. In traditional oculomotor spatial cueing tasks such as the IOWA task, participants are presented with peripheral target objects and the latency and directional accuracy of the initial saccade are measured. Different types of cues can be presented just before the target to measure the dynamics of attention. Using this same logic, the ANT provides pre-cues that can influence the deployment of attention for the Flanker array. For example, *attentional alerting* can be measured with decreases in response latency when providing a preparatory cue along another sensory modality (e.g., auditory cue). This manipulation removes the temporal ambiguity regarding when a stimulus is to be presented, allowing the attentional system to be ready to detect the target. As a result, responses are faster compared to when no cue is provided. Further, *attentional orienting* can be manipulated by providing a spatial cue that indicates the location where a target stimulus will be presented. Responses are faster on these trials compared to the preparatory cue trials mentioned above, suggesting attention is oriented to the target location before the target is presented. Alerting and orienting scores in the ANT show improvement from 4–7 years old (e.g., Berger et al., 2000). Further, Rueda et al. (2004) demonstrated that gains in performance (i.e., faster RTs, fewer errors) specific to conflict resolution (i.e., differences between congruent and incongruent trials) were also evident during this age range. Finally, the ANT is sensitive not only to developmental changes in visual attention efficiency from childhood to adulthood, but also to efficiency declines in aging populations (Jennings et al., 2007).

Despite its utility, the ANT has several limitations for implementation in toddlers. First, it does not independently assess oculomotor and manual measures of attention. Specifically, oculomotor attention is manipulated via the spatial pre-cues, but performance is measured by a manual response. Second, the ANT has only been used as early as 3.5 years of age. In fact, the ANT task may be too difficult for toddlers to complete. Specifically, the integration of spatial and featural attention in the toddler years might further complicate the paradigm's applicability in this age group. The ANT involves complex dynamics which may make it difficult for toddlers to prioritize spatial or featural information when they are equally likely to be relevant. That is, 2- and 3-year-olds are likely to struggle with attending to the center item when there are flanking distractors while also receiving spatial cues to the location of the array (Rivière & Brisson, 2014).

Taken together, an infant task scaled for toddlers, or an early childhood task scaled down for toddlers is unlikely from the ANT without modification. In addition, it remains unclear if the IOWA will be engaging enough for toddlers or if ceiling performance will be reached in this age group. Finally, the question remains on the comparability of measurable and observable behaviors used in these two paradigms as they pertain to toddlers. That is, should eye-tracking, motor responses, or both be used to test toddlers? We argue that the best way to address the factors contributing to the toddler data desert, is to combine infant and early childhood measures to answer these initial fundamental questions. Thus, the present study, we instead assessed these two components of the ANT (e.g., Flanker suppression and spatial cues) in different tasks, thereby increasing the likelihood that toddlers would be able to perform the tasks and allowing us to address our central questions regarding the nature of attention engaged by oculomotor and manual behaviors. In addition to these complexities, the ANT task taxes working memory generally as it requires participants to remember more complex rules due to the added task dynamics from spatial cueing and multiple potential target locations. In contrast, the Flanker task only requires participants to respond to the middle item on each trial. Thus, conflict is created by target arrays rather than spatial cueing in addition to target arrays. A final component yet to be discussed is if similar neural mechanisms are underlying performance in these two types of paradigms if applied together to toddlers. Moreover, triangulating multi-methods to address these questions would allow for more robust interpretation of findings that are translatable to task development efforts. We further explore this component of the current study next.

1.2. Cortical areas involved in visual attention in early development

Bilateral frontal and parietal cortices have been implemented in attention development over the first five years of life. Specifically, changes in activation within cortical areas associated with attention development's three systems (alerting, orienting, and executive attention) over the course of development reflect the emergence of three distinct and often interwoven neural circuitries (e.g., Johnson et al., 2013; Petersen & Posner, 2012; Posner & Petersen, 1990). Alerting is lateralized to the right hemisphere and involves cortical projections to frontal and parietal cortex from the brainstem, involving the subcortical to cortical regulation system of tonic and phasic preparedness to respond. Orienting is localized to the dorsal and ventral streams in frontal, temporal, and parietal cortices. The orienting system, initially thought to primarily involve parietal cortex, has since been expanded with more recent work on orienting and executive functions. For example, Posner and Petersen (1990) suggested that the pulvinar and superior colliculus projections to parietal cortex were responsible for attentional functioning related to orienting. However, responding in these posterior areas is now thought to be dependent on long range connections with frontal cortex. Processing in parietal cortex has since been pushed to include functions outside of attentional orienting, with parietal cortex being implemented in both bottom-up and top-down processing within dorsal and ventral attention systems in the brain. For example, the orienting network also includes the dorsal (i.e., frontal eye fields (FEF) and intraparietal sulcus/superior parietal lobe) and ventral attention systems (i.e., temporoparietal junction and ventral frontal cortex); that is, top-down visuospatial attention and bottom-up reorienting of that attention (e.g., Bush, Luu, & Posner, 2000; Fan, Flombaum, Mccandliss, Thomas, & Posner, 2003; Feair et al., 2007; Sridharan, Levitin, & Menon, 2008; Sridharan, Levitin, Chafe, Berger, & Menon, 2007; for a review see also Vossel, Geng, & Fink, 2014).

Lastly, areas implicated in executive attention, such as the anterior cingulate, show stronger connections with bilateral frontal and lateral parietal areas over the first two years of life (e.g., Tau & Peterson, 2010). Over the same time scale, bilateral parietal cortical areas show stronger connectivity with lateral and medial prefrontal areas (Petersen & Posner, 2012). In addition, the orienting and alerting neural systems develop more rapidly than the executive attention neural system; thus, it is possible these systems interact with one another to further tune the emerging fronto-parietal executive attention system. Inhibition of distracting visual information is a skill that continues to develop throughout early childhood. Specifically, regions of parietal cortex give bottom-up processing commands to prioritize selectivity while networks forming between frontal and parietal cortex give rise to more top-down goal-oriented regulation where selectivity and rule-based attention can be deployed (i.e., Abundis-Gutierrez et al., 2014). Although these works together suggest overlapping neural regions across early attention abilities, transitional involvement of these regions of cortex during the toddler years have yet to be linked as priors to these attentional abilities in early childhood due to a lack of systemic exploration for suitable tasks to measure these associations at age 2-years-old.

1.3. Improving assessment of attention in toddlers via a multi-method approach

The current study aims to address the lack of multi-modal data in the attention literature on toddlers by measuring neural responses along with oculomotor and manual behaviors in the same group of toddlers. Specifically, this study will examine the relationship between oculomotor (IOWA) and manual (Flanker) measures of attention that are typically used at different ages within the toddler transitional period. While collecting oculomotor and manual data with the IOWA and Flanker tasks, we measured cortical responses with functional near-infrared spectroscopy (fNIRS). Simultaneous recordings of brain and behavior allow us to examine the neural mechanisms associated with performance during these two tasks. Consequently, we can assess whether common neural regions are engaged in these tasks and in which regions activation is associated with variations in performance. The IOWA and Flanker tasks allow us to connect visual attention, as assessed by oculomotor measures, with behaviors obtained in a manual response selection task. By comparing behavioral and neural measures from these tasks, we can examine the relationship between different forms of attention that are often studied at different points in development during the transitional toddler years.

1.4. Hypotheses

It is important to link toddler data into developmental timescales. That is, to compare any toddler data to either an infant or early childhood population where more data are available, and thus more is known about assessing and disentangling cognitive processing associated with attention.

First, we hypothesized that developmental differences in attention development would be evident between 2- and 3-year-olds as these foundational attentional skills integrate with higher order cognition (i.e., executive functioning). We first predicted that behavioral performance (accuracy, RT) and attentional efficiency (indexed by composite scores) in the IOWA task and performance (accuracy, latency of motor response) in the Flanker task would be correlated with age. Second, we predicted older children would perform faster and more accurately than younger children on trials in which distractors were present (Flanker: congruent and incongruent trials; IOWA: invalid).

Second, we hypothesized associations between oculomotor and manual behavioral measures across the two tasks. Specifically, we predicted the composite attention score of conflict from the IOWA task would be positively associated with the conflict score from the Flanker task.

Our third hypothesis pertains to the underlying neural dynamics for the behavioral and oculomotor differences predicted in hypotheses 1 and 2. Specifically, we first predicted that unique dynamics present in each task would lead to differential recruitment of frontal cortex during these tasks. We expected that children would engage right lateralized regions of the frontal cortex during the IOWA task whereas they would engage bilateral frontal regions during the Flanker task. Second, we anticipated that both measures of attention would engage regions of cortex associated with conflict resolution in the context of featural and spatial visual attention. Specifically, children would recruit parietal cortex similarly during incongruent (Flanker task) and invalid (IOWA task) trial types. In contrast, we predicted that children who perform poorly in both tasks would have weaker recruitment of this area compared to children who perform well on these tasks.

2. Method

2.1. Participants

A total of 69 children, thirty-seven 2.5- (*M* age = 2.53 years, Female = 21) and thirty-two 3.5-year-olds (*M* age = 3.52 years, Female = 15), were recruited and tested within ± 6 weeks of 2.5 or 3.5-years. Tasks were presented in a fixed order, with IOWA given first and Flanker given second. Due to the complexity of the multi-modal approach, attrition was high in our sample. A post-hoc power analysis of power was conducted using G*Power version 3.1.9.7 (Faul et al., 2007). Sample size estimation for a large effect size was.80, using Cohen's (1988) criteria. With a significance criterion of $\alpha = 0.05$ and power = 0.80, the minimum sample size needed with this effect size is $N = 70$, with 35 in each group, for an independent samples t-test of performance (high, low) on any given channel in the current probe. Given the high attrition in the study, robust statistical tools within the AnalyzIR NIRS Toolbox (i.e., false-discover-rate [FDR] and Bonferroni corrections) were applied while whole head statistics were employed instead of a channel-by-channel approach. In addition, the nature of fNIRS recordings (i.e., multiple samples per person, per condition) allowed us to be adequately powered to detect an effect with even the lowest sample size found in our statistical analyses ($N = 45$), after pre-processing and exclusionary criteria were applied (e.g., Anderson et al., 2017). Proactive measures such as bathroom breaks, a fitted highchair with straps to reduce motion, and engaging cartoon videos while capping and placing the eye-tracking sticker mitigated many of the challenges in testing toddlers. In the analyses below, we included the 50 children who completed both tasks. This sample included twenty-seven 2.5- (*M* age = 2.54 years, Female = 17) and twenty-three 3.5-year-olds (*M* age = 3.51 years, Female = 10).

In this first attempt at multi-modal data collection in toddlers, we ran into a few specific reasons for attrition and data loss in this population ($N = 19$). Six children did not continue after the IOWA task due to boredom or fussiness. Seven children refused to participate in any of the tasks beyond capping once the videos ended. Three children refused to wear the fNIRS cap during the procedures, and one child would not wear the sticker required for the collection of eye-tracking data. One child would not push the buttons

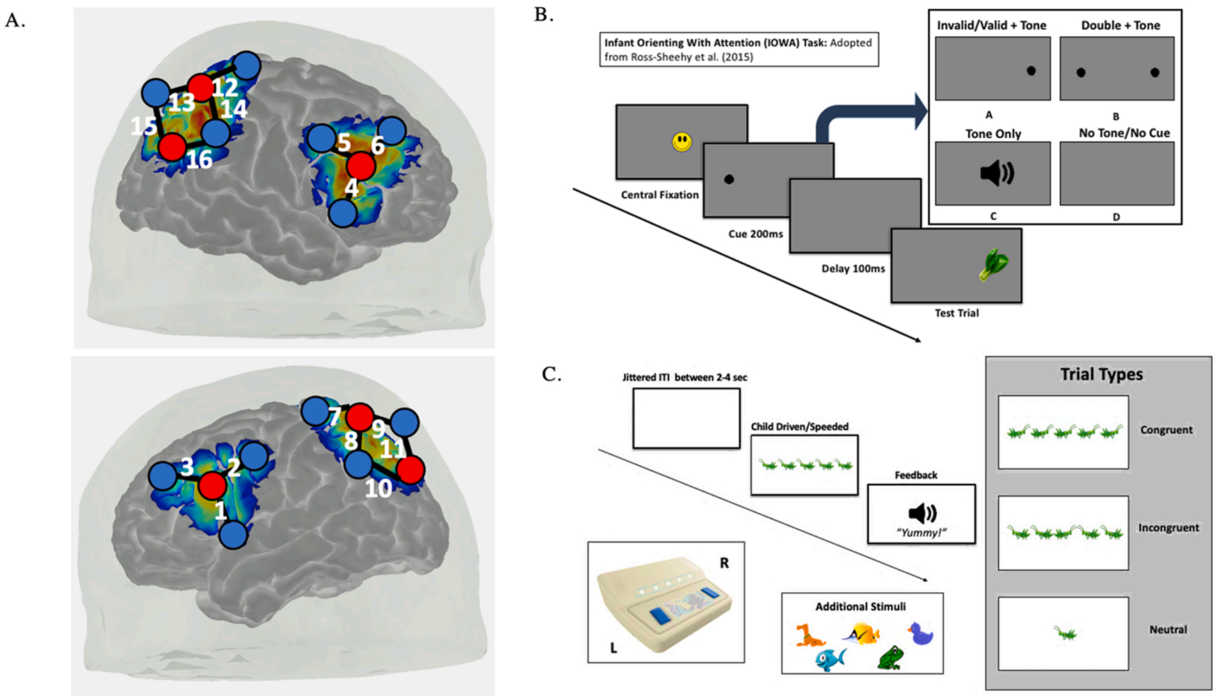

Fig. 1. *Sensitivity Profile and Task Structure for Current Study, Note.* A. depicts the sensitivity profile for the current probe design over bilateral frontal and parietal cortex. B. is an example of the sequence of events in an invalid trial during the IOWA task used in the current study. C. demonstrates the sequence of events during a congruent trial in the Flanker task. At the bottom middle, all possible animal stimuli are shown. On the bottom left, the serial response box used is shown.

during the Flanker task. Finally, one child had a neurological abnormality reported by the parent in session.

2.2. fNIRS data collection

fNIRS data were collected at 25 Hz using a TechEn CW7 system with wavelengths of 830 nm and 690 nm. Light was delivered via fiber optic cables that terminated in an array compiled of six sources and 12 detectors. The probe was organized into an array of 16 channels in which the source and detector were 3 cm apart. Placement of sources was relative to the 10–20 system over left and right frontal cortex (AF3–4; F5–6) and left and right parietal cortex (CP1–4; P1–4; PO3–4; see Fig. 1A). Data were synchronized via timestamps delivered at trial onsets.

2.3. Eye-tracking data collection

Participants were seated approximately 65 cm from a 24″ LED computer monitor (1280 ×960 resolution; refresh rate of 100 Hz) where an EyeLink 1000 Plus eye tracker was mounted. A target sticker was placed on the fNIRS probe hat above the participant's left eye or in the middle of the forehead, depending on where it was easiest to place without the child becoming aware of the sticker. At the beginning of each task and as needed throughout the experiment, the participant's right eye was calibrated with a five-point calibration method using the EyeLink software. Eye data were recorded online at 500 Hz during each task. Stimuli presentation and behavioral response collection were controlled using E-Prime 3.0 software (Schneider et al., 2002). A video camera positioned behind the child's head recorded each session with a view of both the response space (i.e., child and monitor) and the researcher.

2.4. Stimuli and procedure

2.4.1. IOWA task

During the IOWA task, children were first presented with a smiley face subtending 1.9 × 3.4 degrees of visual angle (DVA) in the center of the screen during which drift correction was applied. Once the child fixated on the smiley face, the researcher initiated the trial. The background was set to a neutral gray (RGB: 136, 136, 136; see Fig. 1B). The visual cue consisted of a black circle that subtended approximately 0.4 × 0.4 DVA. The auditory cue was a 500 Hz pure tone.

The task involved four cue conditions: single cue + tone, double cue+ tone, no cue + tone, and no cue + no tone. For all conditions, the trial started with a 200-ms cue with or without a tone (see Fig. 1B), followed by a 100-ms blank delay, and then the presentation of the target until fixation or until 250 ms had passed. For the single cue condition, the cue was presented at approximately 6.4 DVA from the center of the screen, either to the left or right side. For the double cue condition, the cue was presented at both the left and right locations. On no cue trials, participants were presented with a blank screen for 200 ms. In contrast, a tone was played for 200 ms for the auditory cue trials. After the brief delay, target stimuli were presented on either the left or right side of the screen. Based on cue type and target location combination, there were five trial types: auditory cue, no cue, valid cue (i.e., target where cue was presented), invalid cue (i.e., target opposite of cue presentation), and double cue. Trial types were randomized with a total of 10 trials per condition, resulting in a total of 50 trials.

We modified the instructions to keep toddlers both engaged with the task and aware of what was expected of them. To achieve this, the researcher gave the following instructions: "You are going to see a smiley face appear on the screen. Then you will see silly objects pop up on the sides of the screen. These are smiley's toys. You need to use your eyes to help find smiley's toys by looking at them. Are you ready?" Then the researcher redirected the child to the screen, repeating these instructions as many times as needed throughout the task. For inclusion in the eye-tracking analyses, children were required to have usable data on at least four trials. This requirement eliminated eight children from the IOWA task dataset. However, these children have already been listed as excluded in the participants section above.

2.4.2. Flanker task

Stimuli consisted of six different animals (frog, cricket, dog, duck, and two types of fish; see Fig. 1C), subtending approximately 5.8 DVA. A researcher instructed each child to press a button that corresponded to the direction that the center-screen stimulus was facing. Three trial types were administered in random order: congruent, incongruent, and neutral. Neutral trials presented only a single central stimulus. Congruent trials featured four additional stimuli, two on each side, that faced the same direction as the central stimulus. Incongruent trials featured four additional stimuli, two on each side, that faced the opposite direction as the central stimulus. Each stimulus was used two or three times in each type of trial, including at least once in both the right and left orientations. For example, the duck stimuli appeared at least six times, once facing the left and once facing the right for each of the congruent, incongruent, and neutral trial types. An initial practice phase of six trials, followed by 45 test trials, totaled 51 trials in all. Though all six stimuli were used during the test trials, only the cricket stimuli were used during the practice trials. In each test trial, only one type of animal was shown for all five stimuli in the left and right orientations.

Prior to practicing the task, a researcher gave the children the following instructions: "You are going to see animals on the screen. Sometimes they will be alone and sometimes they will have friends with them. I want you to pay attention to the animal in the middle of the screen. The animal in the middle is hungry, so your job is to feed it by pressing the blue button that matches the way the animal is facing. When you feed the animal, it will say, 'Yummy.' Pay attention to the animal in the middle. Is he facing this way (*point to the right*) or this way (*point to the left*)? If he is facing this way (*point to the right*), press this button (*point to the right button*). If he is facing this way (*point to the left*), press this button *(point to the left button*)." During practice, the researcher oriented the child to the task and pointed to the correct response if the child struggled to understand the rules. Further, they explained the rules as many times as needed during the practice trials. After the practice trials, the researcher did not provide the correct answer regardless of the child's performance; however, they did give the following instructions as many times as needed: "Remember, to feed the animal in the middle (*pointing to the middle*), you push this button (*pointing to the right button*) if they are going this way (*pointing right*) and this button (*pointing to left button*) if they are going this way (*pointing to the left*)." The researcher also encouraged the children to go as quickly as they could while trying to be accurate. In both the practice and test phases, a female voice exclaimed, "Yummy!" to provide positive feedback only.

2.5. Behavioral and eye-tracking analyses

For the IOWA task, we used saccadic RT (i.e., time measured from the presentation of the target until the eyes landed on the target object) as the main measure. We calculated scores according to Ross-Sheehy et al. (2017); see Table 1). Note that each composite score was normalized by each child's individual baseline RT (i.e., no-cue RT). Children were excluded if they failed to have eye data for at least four trials per condition. If the first saccade was made to the target in under 70 ms, the trial was excluded, as this typically meant the child's eyes were already on the target from fixating on the cue. For the Flanker task, RTs and accuracy were calculated for each condition in each age group. Average fixation and looking times to the middle and flanking items were calculated by trial type for each age group. The proportions of time spent looking at the middle item versus the flanking items were calculated as the average proportion of time looking to each region normalized by the total time spent looking on the screen. Any saccades made off screen were subtracted from this total before normalizing the data. We used normalized scores from the IOWA task to determine attentional efficiency and proportion of time spent looking during the Flanker task as a measure of how children's looking behavior related to their manual behavioral performance (i.e., does looking drive processing and responding).

2.6. fNIRS event-related data analysis

We used the AnalyzIR NIRS Toolbox for all pre-processing and statistical analysis of data (Santosa et al., 2018). Data were first converted to an optical density (OD) measure. A wavelet-based motion artifact removal tool was used to correct motion artifacts by removing then smoothing physiological and environmental noise trial by trial, concatenating trial data across each condition to then calculate an average hemodynamic response curve for each condition at the subject level. Next, data were band-pass filtered before we converted them to absolute concentration values for oxygenated (HbO) and deoxygenated (HbR) hemoglobin using the modified Beer-Lambert equation (Derived Partial Pathlength Factor, DPF = 6). Recent work has advised on the best DPF, and partial pathway factor (PPF) values based on physiological and anatomical differences in the human skull and brain based as children age (i.e., skull thickness, anatomical differences, etc.). Notably, Whiteman et al. (2017) conducted a systemic comparison of stepped PPF values in children ages 5–11 years old and concluded values ranging between 5.66 and 6.33 were differential appropriate for measuring from most all cortical regions of interest (ROI) via fNIRS where wavelengths ranged from 690 to 850 nm. Given this range of values, an average DPF value of 6 was chosen to best represent the ROIs targeted via the current study's probe to reduce the overcleaning of neural data that would result from a more stringent value. After motion and physiological artifact removal/smoothing, signal to noise ratio (SNR) ≥ 0.8 criteria were applied. At the conclusion of preprocessing, 38/42 children for the IOWA task and 44/50 children for the Flanker task remained and were included in subsequent group level analyses. Average HbO and HbR were calculated in a time window of 0–6 s post stimulus presentation for both tasks.

To address the current hypotheses as well as thoroughly explore the richness of these data, a series of linear mixed models were employed. In all statistical analysis models' corrections for multiple comparisons using an algorithm to reduce false discovery rate (FDR) were applied to decrease the rate of false positives (Santosa et al., 2017). Only trials that met behavioral and eye-tracking inclusion criteria at the subject level, as outlined above in the behavioral methods, were analyzed in subsequent event-related analyses of neural data. For ease, the 2 statistical models utilized for each task are numbered and described below.

Model 1: Mixed-effects models were used to compute activation during each task by comparing the average total change in HbO to the average total change in HbR for each channel and condition. For the Flanker task, a 2 (Hemoglobin: HbO, HbR) x 16 (Channels:1–16) x 3 (Congruency: congruent, incongruent, neutral) x 2 (Age: 2.5 years, 3.5 years) mixed design was used where Age was a between-subjects factor, and the remaining variables were within-subjects. For the IOWA task, a 2 (Hemoglobin: HbO, HbR) x 16 (Channel: 1–16) x 5 (Condition: valid, invalid, double, no tone, tone) x 2 (Age: 2.5 years, 3.5 years) mixed design where age was a between-subjects factor, and the remaining variables were within-subjects. This analysis was done to test whether the main effects age, and/or any subsequent interaction between age and condition, best explained variation in activation at the group level regardless of performance.

Model 2: Next, we ran Model 1 again with behavioral performance as a between-subjects factor. This analysis was done to test whether a main effect of performance, as well as subsequent interactions between performance and activation, best explained variation

Table 1
Composite Attention Scores.

Mean RT	Cue Facilitation	Cue Interference	Cue Competition
average RT of all conditions	(tone - valid)/tone	(invalid - tone)/tone	(double - valid)/ tone

in neural activation.

3. Results

3.1. Behavioral

To examine performance on the IOWA task, 2 (Age: 2.5-year-old, 3.5-year-old) x 5 (Condition: valid, invalid, double, tone, no tone) mixed ANOVAs were run on the saccadic RT and percent correct data separately (Fig. 2A–B). When assumptions of sphericity were violated, we used Greenhouse-Geisser corrections. Forty-two children (twenty 2.5-year-olds and twenty-two 3.5-year-olds) provided data in all five conditions. For saccadic RT, we found a significant main effect of condition, F (3, 122) = 3.16, p = .027, η_p^2 = .073. Pairwise comparisons showed that participants performed significantly slower on invalid trials compared to no cue (p = .012) and tone cue (p = .017) trials. We found no other significant differences. Neither the main effect of age nor a Condition x Age interaction was significant, F (1, 40) = 2.32, p = .136, η_p^2 = .055, and $F < 1$, respectively. To test the effect of age on attentional facilitation, inhibition, and competition, we ran separate independent samples t tests (Fig. 2C). The results showed no age-related differences on any of these scores ($t < 1$ for all scores).

Similarly, the main effect of condition was significant for accuracy, F (3, 103) = 4.53, p = .002, η_p^2 = .102. Pairwise comparisons showed that participants were significantly more accurate on no cue trials than double cue (p = .022), invalid ($p < .001$), and valid (p = .033) trials, indicating that visual cues had a distracting effect on accuracy. Further, participants were more accurate in tone cue trials than invalid cue trials (p = .008), again showing the distracting effects of visual cues. The main effects of age and Condition x Age interaction were not significant, $F < 1$ for both.

Next, we ran 2 (Age: 2.5-year-old, 3.5-year-old) x 3 (Condition: congruent, incongruent, neutral) mixed ANOVAs on accuracy and RT data (Fig. 3A-B) during the Flanker task. Fifty children (twenty-seven 2.5-year-olds and twenty-three 3.5-year-olds) provided data for all three conditions. For accuracy, the main effects of condition and age and the Condition x Age interaction were all significant, F (2, 96) = 13.76, $p < .001$, η_p^2 = .223, F (1, 48) = 28.56, $p < .001$, η_p^2 = .373, and F (2, 96) = 13.45, $p < .001$, η_p^2 = .219, respectively. The main effects of age and condition showed that 3.5-year-olds were overall significantly more accurate than 2.5-year-olds. Further, pairwise comparisons reveal that 1) participants overall were less accurate on incongruent trials compared to both congruent (p = .004) and neutral trials ($p < .001$), and 2) no significant differences emerged between age groups on neutral and congruent trials (p = .331) when collapsing across age. To interpret the Condition x Age interaction, we ran separate independent samples t tests on accuracy for each condition comparing the two age groups. Results showed that 3.5-year-olds were significantly more accurate on congruent, t (48) = 5.03, $p < .001$, and neutral trials, t (48) = 6.27, $p < .001$, compared to 2.5-year-olds. However, we found no significant difference between age groups for the incongruent trials, $t < 1$. Overall, these results indicate that the older group was generally better at response selection, but both age groups were equally susceptible to distraction and have difficulty with resolving

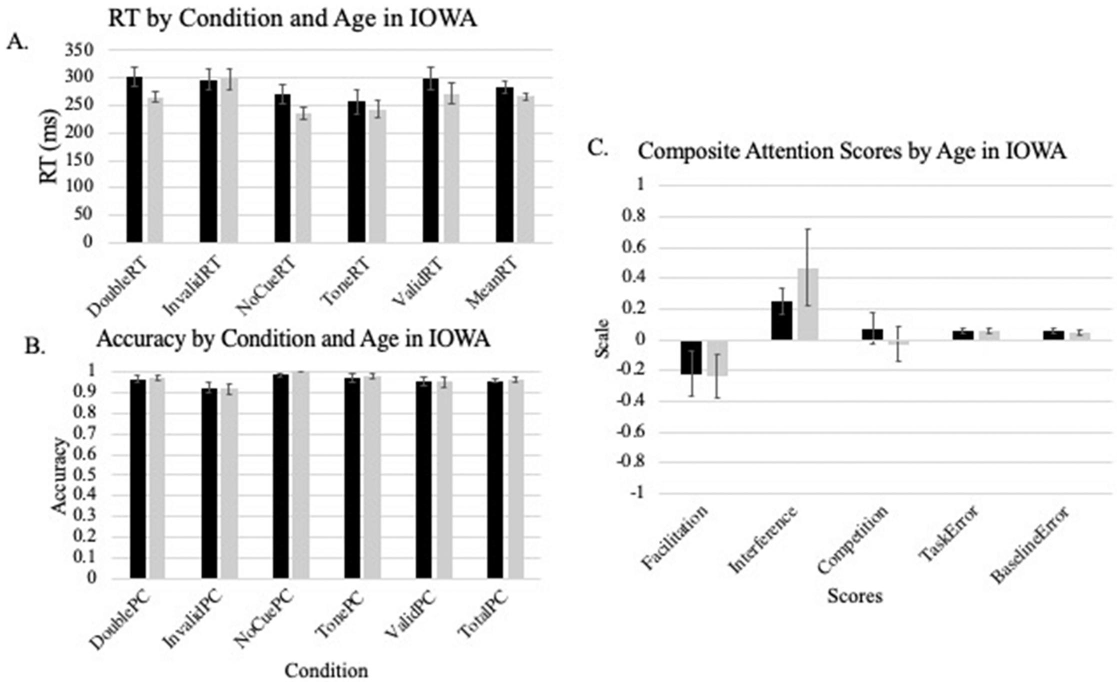

Fig. 2. *Oculomotor Scores, Note.* All three graphs consider age, with 2.5-year-olds in black and 3.5-year-olds in gray. The graphs use standard error bars.

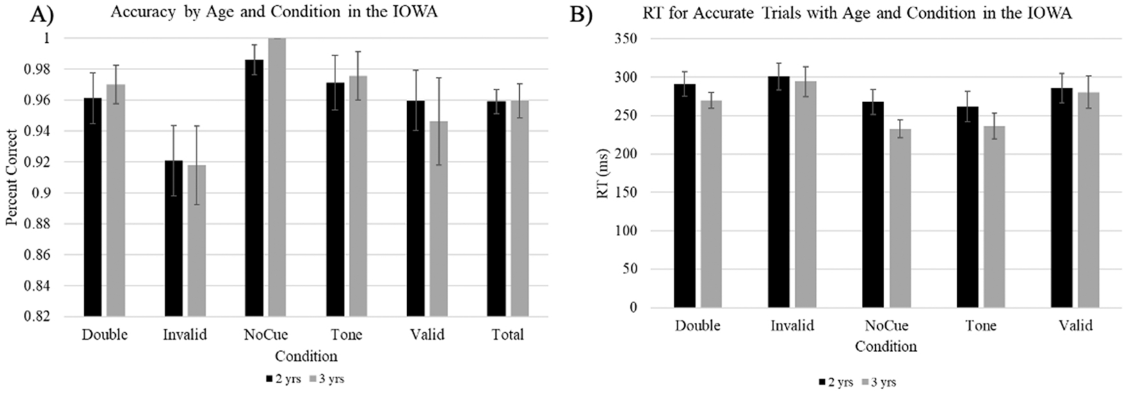

Fig. 3. *Performance in the IOWA task, Note.* This figure depicts performance during the IOWA task. Specifically, A) accuracy and B) RT during all five conditions. Both graphs use standard error bars.

response conflict (see Fig. 3A).

The same linear mixed models run on accuracy scores were also run for RT. Results revealed a significant main effect of condition and Condition x Age interaction, $F(2, 96) = 9.86, p < .001, \eta_p^2 = .170$, and $F(2, 96) = 5.48, p = .006, \eta_p^2 = .102$, respectively. The main effect of age was not significant, $F < 1$. Because there was no main effect of age, follow-up *t* tests collapsed across age demonstrating that overall children were slower on incongruent trials compared to both congruent ($p = .002$) and neutral ($p < .001$) trials. To interpret the interaction, we ran independent samples *t* tests on RT for each condition to test which condition demonstrated age differences. The results showed that older children were faster to respond during neutral trials, but not during congruent and incongruent trials, $t(48) = 2.15, p = .037$, $t(48) = 1.36, p = .181$, and $t < 1$, respectively. These results suggest that older children are faster only when there are no visual distractors.

Next, we tested whether eye movement behavior is related to performance in the Flanker task. To determine this, we collapsed data across age but analyzed correct and incorrect trials separately. As mentioned above, we only included participants who had eye data for at least four trials per condition *($N = 42$)*. Of these, six participants did not have any correct trials in at least one of the three

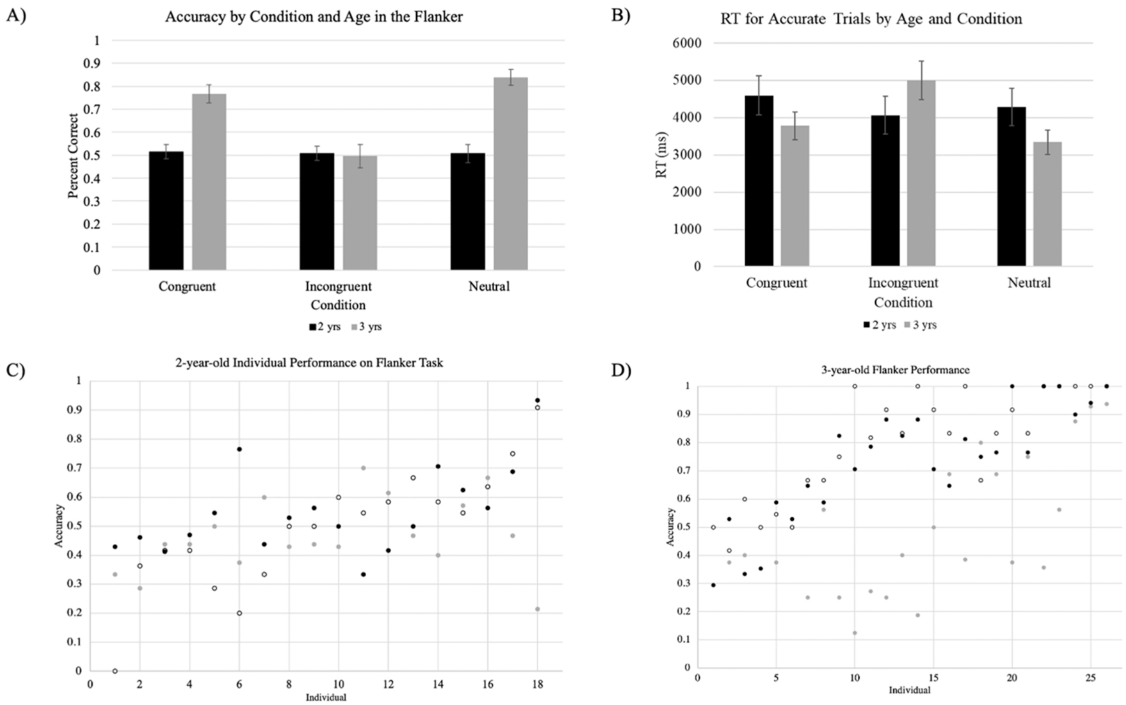

Fig. 4. *Performance in the Flanker Task, Note.* This figure depicts performance during the Flanker task. Specifically, A) accuracy and B) RT during all three conditions broken up by age. Both graphs use standard error bars. C) Depicts 2.5-year-old performance at the individual level while D) depicts individual performance for 3.5-year-olds. Solid gray points indicate incongruent, solid black indicate congruent, and hollow points indicate neutral performance scores respectively.

conditions, and 12 participants did not have any incorrect trials in at least one of the three conditions. Thus, 36 participants were included in the correct trial analysis, and 30 participants were included for the incorrect trials. We ran three factor (Condition: congruent, incongruent, neutral) repeated measures ANOVAs on correct and incorrect trials (see Fig. 4). The proportion of time looking was calculated for the target item for each trial and then averaged across trials for each participant. We found a significant effect of condition on proportion of time looking for correct trials, $F(2, 70) = 79.15$, $p < .001$, $\eta_p^2 = .693$. Pairwise comparisons reveal that participants spent more time looking at the target object in the neutral condition compared to both congruent ($p < .001$) and incongruent conditions ($p < .001$). This finding is likely because only the target appeared on screen during the neutral condition. Congruent and incongruent conditions did not differ ($p = .119$). We found similar results for the incorrect trials. The effect of condition was significant, $F(2, 58) = 68.46$, $p < .001$, $\eta_p^2 = .702$, with neutral trials resulting in more time looking at the target object compared to congruent ($p < .001$) and incongruent trials ($p < .001$). Again, the congruent and incongruent trials did not differ ($p = .805$).

The total score (i.e., average accuracy across all condition types) does not represent the many combinations of condition performance demonstrated in Fig. 4C&D as many children had one or two conditions they did well while they struggled in the third condition (see also Table S1). Interestingly, the condition they struggled with during this transition was not always the incongruent condition. Additionally, some children systemically responded to the flanking items rather than the middle item on both congruent and incongruent trial types resulting in performance well below chance.

Lastly, we examined associations between the composite attention scores from the IOWA and accuracy on the Flanker task. Depending on the compared conditions, either 44 or 45 participants had data from both tasks for this analysis. Facilitation scores significantly predicted accuracy on neutral trials ($N = 45$), $r = -0.365$, $p = .014$. Specifically, higher facilitation scores were associated with decreased accuracy on neutral trials. Additionally, competition scores were significantly associated with accuracy on incongruent trials ($N = 45$), $r = 0.338$, $p = .023$. That is, higher competition scores in the IOWA task were associated with higher accuracy on incongruent trials. Together, these associations suggest a continuum along which children went from being off task (i.e., high facilitation on the IOWA task and decreased accuracy on the Flanker task when no task irrelevant information was present) to being in an attentionally controlled state (i.e., slowing down when competing pre-cues were present in the IOWA and performing better when incongruent information was present on the Flanker task).

3.2. fNIRS results

fNIRS measures both oxygenated (HbO) and deoxygenated (HbR) hemoglobin. Neural activation is typically thought to be reflected by increases in HbO values for a given condition or group (Yücel et al., 2021). However, both HbO and HbR are factors in our models, while we only report HbO in our tables. The AnalyzIR Toolbox (Santosa et al., 2018) was used to conduct mixed effects models to compare activation across conditions in the IOWA and Flanker tasks. Participants were categorized into high and low performing groups. For the IOWA task, we performed a median split on facilitation score. As discussed above, facilitation score is computed as the difference in saccadic RT on valid cue trials and no cue trials. We coded children with low facilitation scores as high performers, and children with high facilitation scores as low performers. In the Flanker task, we performed a median split on accuracy in incongruent trials. Tables 2 and 3 summarize the statistical results from these mixed effects models. *T* values indicate which conditions produced activation that was different from 0 or channels in which activation was related to performance. Positive *t* values indicate higher HbO levels for the group with low facilitation scores (IOWA task) or higher accuracy on incongruent trials (Flanker task).

In the IOWA task (see Table 2), the hemodynamic response (HbO) significantly differed between groups on tone, valid, and no-tone trials in the left frontal cortex (lPFC; channel 1). Here, IOWA performance is dummy coded to group individuals into low (0) and high (1) groups. During these trials, we observed larger hemodynamic responses in the low performing group relative to the high performing group. However, HbO values on valid trials were below zero, while HbR values were above zero, indicating that there was no significant neural activation in lPFC for the valid condition. The hemodynamic response also differed between groups in the right frontal cortex (rPFC) on no-tone trials (channels 4 and 5) and double cue trials (channel 6). On no-tone trials and double-cue trials, we found significantly larger HbO levels for the low performing group relative to the high performing group (see Fig. 5A). Finally, the hemodynamic response on no-tone trials also differed between groups in the right parietal cortex (rPC). In this region, the low performing group showed significantly larger HbO levels relative to the high performing group (see Fig. 5B). Thus, the high performing group produced stronger activation in rPFC during trials with high inhibitory demands. The low performing group, however, produced stronger activation in rPFC and rPC on no cue trials that involved simple reactions to the onset of the stimulus.

Table 2
Activation for Condition Type in IOWA in Relation to Performance.

Channel	Region	Effect	*t*	*p*[a]
1	lPFC	Tone X IOWA Performance	-3.81	< 0.001
1	lPFC	Valid X IOWA Performance	-3.00	0.002
1	lPFC	NoTone X IOWA Performance	-2.75	0.004
4	rPFC	NoTone X IOWA Performance	-3.80	< 0.001
5	rPFC	NoTone X IOWA Performance	-2.97	0.003
6	rPFC	Double X IOWA Performance	2.62	0.007
12	rPC	NoTone X IOWA Performance	-2.27	0.025

Note. rPC = right parietal cortex; rPFC = right prefrontal cortex; lPFC = left prefrontal cortex.
[a] False-discovery rate corrected *p* values.

Table 3
Main Effect of Condition and Condition x Performance Interactions During Flanker Task.

Channel	Region	Effect	*t*	*p*[a]
3	lPFC	Congruent X Flanker Performance	2.74	0.007
6	rPFC	Congruent	-2.62	0.010
4	rPFC	Congruent	-2.07	0.040

Note. rPFC = right prefrontal cortex; lPFC = left prefrontal cortex.
[a] False-discovery rate (FDR) corrected *p* values

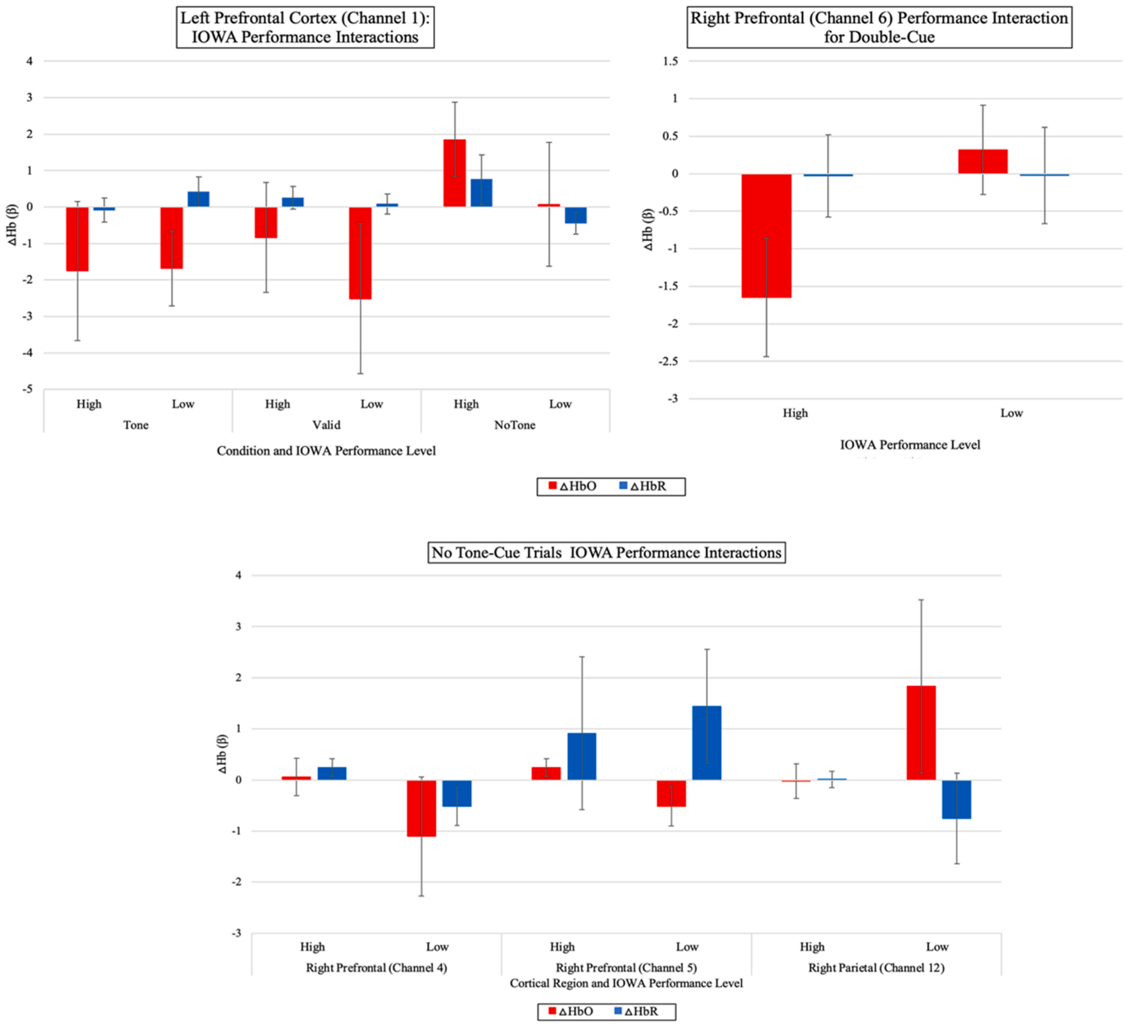

Fig. 5. *Event-Related Activation Across Trial Types of Interest in the IOWA Task, Note.* These graphs depict the beta (β) values of HbO and HbR for interactions and main effects found in the GLMs for the IOWA Task.

In the Flanker task (see Table 3), the hemodynamic response differed between groups in lPFC (channel 3) on congruent trials. Children in the high performing group showed significantly larger HbO levels relative to children in the low performing group (see Fig. 6). Although we found a significant effect of the congruent condition in rPFC (channels 6 and 4), the HbO levels were negative, while HbR values were also negative, indicating that there was no neural activation.

4. Discussion

This is the first recorded study to simultaneously assess eye-tracking, fNIRS, and manual responses to better understand visual attention in toddlers. We collected simultaneous neural recordings (using fNIRS), eye-tracking data, and behavioral responses in 2.5- and 3.5-year-olds to examine the neural and behavioral associations between these skills. Results reveal that oculomotor facilitation in

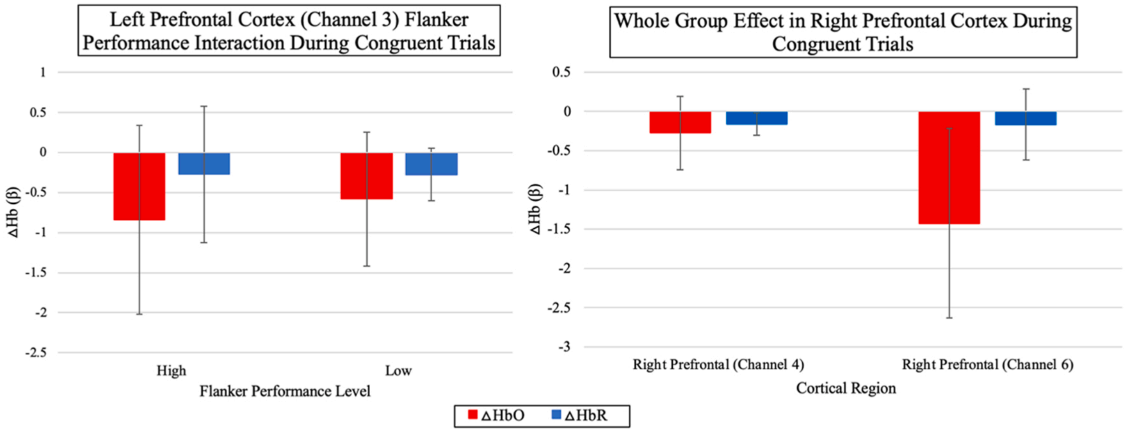

Fig. 6. *Event-Related Activation Across Trial Types of Interest in the Flanker Task, Note.* These graphs depict the beta (β) values of HbO and HbR for interactions and main effects found in the GLMs for the Flanker Task.

the IOWA task was negatively associated with accuracy on neutral trials in the Flanker task. Second, conflict scores between the two tasks were positively associated. At the neural level, however, the tasks showed distinct patterns of activation. lPFC was engaged during the Flanker task, whereas rPFC and rPC were engaged during the IOWA task. Activation during the IOWA task differed based on how well children could control oculomotor behavior during the task. Children with high levels of stimulus reactivity activated the parietal cortex more strongly, but children with more controlled oculomotor behavior activated the frontal cortex more strongly. These results provide an initial link between early developing attentional processes assessed with oculomotor behavior and later developing conflict resolution assessed with manual behavior.

Integrating oculomotor and manual response tasks is critical for bridging our understanding of attention from infancy through early childhood. Specifically, this work highlights the limitations we currently face from current methods of measuring attention in the toddler years. That is, this initial study brings to light many new considerations we must make when addressing the toddler data desert. For example, one primary gap in our understanding regards the relationship between measures of attention that involve oculomotor behavior and measures of attention that involve manual responses during the toddler years and beyond. Even when behaviors are correlated behaviorally, and methods carefully triangulated to bridge developmental gaps in assessment, the neural mechanisms underlying those behaviors still might differ. Thus, we are left with more questions that must be addressed such as "What transitions in neural mechanisms of attention converge during the toddler years as priors to later executive functioning in early childhood?" The current study begins to systematically probe toddler attention via multiple methods to begin to address the *toddler data desert*. However, our findings expose the need for future work should take these data and design new innovative measures of attention in toddlers that best fit the needs of this population while remaining scalable to older and/or younger populations. As a first attempt to address this gap in the literature, we administered two known measures of attention in infancy (IOWA task) and early childhood (Flanker task) in a group of toddlers.

The neural data presented here demonstrate the critical role of the frontal cortex during these attention-driven tasks. Interestingly, high performing groups engaged different regions of the frontal cortex during each of the two tasks. During the IOWA task, children in the high performing group showed stronger activation in rPFC on a condition with high inhibitory demands (double cue trials) relative to children in the low performing group. On the Flanker task, however, children in the high performing group showed stronger activation in lPFC on congruent trials relative to children in the low performing group. The IOWA task also revealed differences in frontal and posterior activation as a function of performance grouping. Children in the high performing group showed stronger activation in rPFC on double cue trials, suggesting that these children engaged the frontal cortex when demands on inhibitory control were higher. However, children in the low performing group showed stronger activation in rPC on no-tone trials, suggesting that low performing children showed stronger posterior activity during trials that required simple stimulus reactivity.

We predicted significant age differences in performance for both tasks. However, we observed no age differences in behavioral performance on the IOWA task. The IOWA task has previously been used to examine developmental differences during infancy, which is likely the reason why we did not observe developmental differences between our older groups of children. In contrast, there were significant age differences for the Flanker task. Three-year-olds were better at basic response selection processes than 2.5-year-olds. That is, older children had higher accuracy and faster RTs on neutral trials. Older children were also more accurate than younger children on congruent trials. Both groups of children performed poorly on congruent trials, suggesting that both groups of children had trouble with distractor suppression. However, about half of the children performed better than 60% correct on the incongruent trials, indicating that executive attention is graded across these age ranges, and that a subset of children in both age groups can resist the most challenging condition in this task.

Consistent with our predictions, we found significant associations between composite conflict score from the IOWA task and performance on incongruent trials in the Flanker task. We also found an association between the composite facilitation score from the IOWA task and accuracy on neutral trials. These associations in performance between the two tasks implies that performance fell along a continuum of being more stimulus-driven to being more deliberative and controlled. Specifically, the facilitation composite score in the IOWA task was negatively associated with accuracy on neutral trials in the Flanker task. The facilitation score was calculated as the difference in saccadic RT between valid and no cue trials. High facilitation scores, then, are reflective of children who used the pre-cue to plan a saccade before knowing where the target would be located. On the Flanker task, children with a high number of errors on neutral trials were likely making responses without processing the stimulus because no distracting information was present on these trials. On the other hand, the conflict score on the IOWA task (double cue – valid cue) was positively associated with accuracy on incongruent trials in the Flanker task, suggesting both conflict score and performance in the Flanker task's incongruent trials are indices of controlled and regulated attention in the context of distracting information.

5. Limitations

In the IOWA task, we dropped many trials due to participants executing saccades during the period between the cue and the target object. Our data suggest the delay between the cue and target was too long for toddlers and young children. In comparison, Ross--Sheehy et al. (2017) found that infants do not typically execute a saccade during the delay period. Future studies may adapt the task by decreasing the delay time or decreasing the time the cue is on the screen. Additionally, performance varied greatly on incongruent trials in the Flanker task, suggesting that there is a wide range of abilities that develop from 30- to 40-months of age. Some children performed above 60%, showing they were able to consistently suppress the distractors. However, some children performed well below chance on the Flanker task (as low as 26% correct); they were more consistently responding to the distractors rather than the target object. The interplay between adaptively using feature or spatial attention strategies during the toddler years might have contributed to these distinct behavioral profiles of performance during the Flanker task. The current study used behavioral groupings (low, high) of performance in the statistical models to test the relationship between activation and performance. Although this approach was necessary to capture the robust shift in efficiency from toddlerhood to preschool, we acknowledge a more fined grained approach within each age group where the continuous performance score was explored would be informative. Specifically, future work with a larger sample size should build upon the current findings by identifying why these data lacked age effects at the neural level despite robust developmental differences at both the level of oculomotor and manual responding.

Although the 2.5-year-olds as a group did poorly on the Flanker task, their data were included in the same models as the 3.5-year-olds for three reasons. First, their eye-tracking data, specifically proportion of time looking, indicate that they understood the task instructions by looking more to the center item on correct trials than flanking items. Second, many toddlers' performance fell well below chance level, suggesting they were not randomly pushing buttons, rather they were systematically choosing the opposite or in the case of incongruent trials, responding to the flanking items. Finally, as can be deducted from the first two points, manual RT is not a good indicator of task performance in this population because there is a robust developmental shift in motor abilities from infancy to early childhood (Tieman et al., 2005). Although controlling for motor development for manual responding is an additional limitation of the current study, these data are still informative when collapsing across age because they demonstrate children in both age groups can be successful even when manually responding in the task is the outcome variable.

Taking these three findings together, we argue that the 2.5-year-old group understood the task and that the breakdown in low performance reflecting this was at both the neural and motor mapping levels. That is, even when toddlers could identify the correct side the animal was facing in each condition, they could not execute the motor command to the corresponding side on the button box. In contrast, when 2.5-year-olds were not able to be as selective in their visual processing of relevant information in contrast to 3.5-year-olds, oculomotor data indicate they were likely responding to flanking items. One possible explanation of this is that bottom-up processing of visual stimuli on the screen led to younger group responding to the larger number of stimuli on the screen during incongruent trials. In the context of Posner and Peterson's seminal works on attention networks, the current results suggest that the efficiency of visual attention processing in toddlers is heavily dependent on their ability to recruit frontal cortex adaptively (i.e., Peterson & Posner, 2012). This is consistent with previous studies that showed toddlers have difficulty integrating spatial and featural information to resolve conflict when aspect of a stimulus array has more bottom-up salience (Buss & Kerr-German, 2019). Future work should examine how performance in tasks that use working memory, such as the Dimensional Change Card Sorting (DCCS) task, compares to performance in the Flanker task. Specifically, if children are using bottom-up processing as a strategy (which would facilitate Flanker task performance on congruent but not incongruent conditions, then they should be more likely to perseverate in the DCCS task (Buss & Kerr-German, 2019). Multiple methods allow us to better interpret vast individual differences found in toddler performance during attentional tasks.

Due to the challenging nature of combining infant and early childhood methods to test toddlers, the current study utilized accuracy scores during the Flanker task rather than RT because motor developmental status was not controlled for. In contrast, accuracy was not used as an index of efficiency in the IOWA task because composite scores are calculated from saccadic latencies on accurate trials. One limitation of this analysis choice is that Flanker task conflict scores cannot be compared between toddlers and adults because Flanker task performance is traditionally calculated via RT differences in adult literature (Eriksen & Eriksen, 1974) while the developmental literature has utilized both RT and accuracy scores to calculate conflict (e.g., Ebert et al., 2019).

In the present study, children were given practice trials prior to the start of the task, during which they were prompted to point out the middle item before responding. Without this scaffold during the test trials, however, the influence of multiple irrelevant competing items in an array was too much for selective attention to overcome, leading to a lack of focus on the relevant item. The number of stimuli and the change in stimulus animal from trial to trial might have imposed additional demands on selective attention, which may have also challenged performance in this task. Changing the stimulus animal from trial to trial may have imposed additional demands on attention selection beyond the targeted manipulation of target-distractor congruency. While these limitations are significant, these findings are nonetheless important as they provide the first link between brain and behavior, highlighting the transition in attention development during the toddler years. Thus, these data are critical for addressing the toddler data desert in the literature while offering a way forward for others to do the same.

Due to the rate of attrition in the current study ($N = 19/69$; 27.5%), we have considered that our results might not be broadly generalizable. Despite this rate of attrition, the use of multiple methods on a challenging age to test is still impressive and valuable work to the literature. We acknowledge that these data demonstrating an association between foundational basic attention skills and executive attention might be self-selecting due to the rate of attrition. However, this is a common problem in development work and should not discourage continued work based on these findings geared at filling in the toddler data desert.

6. Conclusion

Despite some limitations, our results reveal that oculomotor and manual measures of attention are associated with one another during the toddler years and early childhood. These data suggest that measures of attention typically used during infancy may also be meaningfully related to measures of attention during early childhood. However, the neural systems engaged by these different measures of attention differ. The Flanker task revealed activation in lPFC associated with higher task performance, but the IOWA task revealed increased rPFC and decreased rPC activation associated with higher performance. We still face an open question regarding which neural mechanisms are involved with IOWA task performance during infancy and how these neural systems change across childhood as children improve in performance on attentional control tasks. Thus, our work cast some doubt on simply scaling existing tasks to cover the toddler years. Rather, new measures should be created with the limitations we bring to light in this work, to further assess attention during the toddler transition. These data create the groundwork for future research aimed at uncovering developmental trajectories of attention from infancy through childhood, identifying neural markers that are likely to be predictive of future attentional development in early childhood.

Data statement

Due to the sensitive nature of the questions asked in this study, survey respondents were assured raw data would remain confidential and would not be shared with identifying information. Deidentified neural and behavioral data will be shared upon request from Journal or for use in meta-analysis.

Ethics Statement

The research protocols used in this research were approved by the ethics committee of a southeastern university in the United States.

Conflict of Interest

There are no declared financial conflicts of interest from any of the authors involved in this manuscript.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cogdev.2022.101293.

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