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Do children's brains function differently during book reading and screen time? A fNIRS study

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Research Highlights

- Functional near-infrared spectroscopy (fNIRS) measured preschool-aged children's brain function during book reading with a live experimenter and screen time.
- Book reading elicited activation in the right temporal parietal junction (TPJ) while screen time did not.
- Brain response during book reading was greater in right hemisphere than left hemisphere, while brain response during screen time was similar across hemispheres.
- Findings provide further insight into how children's brains function during dyadic vs solitary activities and when using print vs digital media.

Abstract

Previous research suggests that book reading and screen time have contrasting effects on language and brain development. However, few studies have explicitly investigated whether children's brains function differently *during* these two activities. The present study used functional near-infrared spectroscopy (fNIRS) to measure brain response in 28 typically developing preschool-aged children (36-72 months old) during two conditions – a book reading condition, in which children listened to a story read by a live experimenter while viewing words and pictures in a book, and a screen time condition, in which children listened to a story that was played via an audio recording while viewing words and pictures on a screen. Analyses revealed significant activation in the right temporal parietal junction (TPJ) during the book reading condition only, which may reflect social cognitive processes (e.g., joint attention, mentalizing). Across regions of interest, brain response during the book reading condition was greater in the right hemisphere than the left hemisphere, while brain response during the screen time condition was similar across hemispheres. Findings suggest that the lateralization of preschool-aged children's brain function differs during book reading and screen time, which provides a neurobiological explanation for why book reading and screen time impact language development in such different ways. Findings provide important insights into how children's brains function during different types of activities (dyadic vs solitary) and when using different types of media (print vs digital).

Keywords: preschool, fNIRS, book reading, screen time, language, live

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The impact of book reading on language and brain development

Across a variety of cultures, book reading is one of the earliest activities within the home environment in which children are exposed to language (Dickinson, Griffith, Golinkoff, & Hirsh-Pasek, 2012; Fletcher & Reese, 2005). Book reading provides children with opportunities to learn the meaning of words (Flack, Field, & Horst, 2018), develop phonological and print awareness (Lefebvre, Trudeau, & Sutton, 2011), engage in conversation (McArthur, Adamson, & Deckner, 2005), integrate auditory and visual sensory information (Neumann et al., 2012), practice social and emotional skills (Baker, 2013; Sato & Uchiyama, 2012), and bond with their caregivers (Merga & Ledger, 2018). It is therefore unsurprising that book reading has such a positive impact on children's language development. Indeed, children who are read to more frequently, and who are exposed to higher quality language and reading strategies during book reading, have stronger language skills (see Noble et al., 2019 for review). Additionally, interventions supporting book reading practices at home lead to improvements in children's language skills (Dowdall et al., 2020; Fitton, Mcllraith, & Wood, 2018; Lorio, Ciera, & Romano, 2022; National Early Literacy Panel, 2008; Pillinger & Vardy, 2022).

Book reading also appears to have a positive impact on children's brain development. More frequent book reading is associated with increased myelination in white matter tracts responsible for language processing and production (i.e., arcuate fasciculus and superior longitudinal fasciculus; Davison et al., 2023; Hutton et al., 2020), and increased resting-state functional connectivity between regions of the brain involved in language and literacy development (i.e., visual word form area, inferior frontal gyrus, inferior temporal gyrus, and angular gyrus; Horowitz-Kraus & Hutton, 2018), which may reflect more efficient neural

signaling. Additionally, the quality of reading strategies that children experience during book reading has been linked to greater functional activation in regions of the brain associated with language processing (i.e., left inferior frontal gyrus, left temporal pole, left parietal-temporal-occipital association cortex, right superior temporal gyrus; Hutton et al., 2017; Hutton et al., 2015; Powers et al., 2016). In all, the research to date suggests that experiencing frequent and high quality book reading at home is associated with higher language skills and more efficient neural signaling.

The impact of screen time on language and brain development

Societal advances in technology have introduced other activities into the home environment, such as screen-based media use or "screen time," which may be monopolizing time that was once devoted to developmentally beneficial activities, like book reading (Khan et al., 2017; McArthur et al., 2021; Ramírez, Hippe, & Shapiro, 2021). Over the past decade, children's screen time has doubled to nearly three hours per day (Chen & Adler, 2019), despite the American Academy of Pediatrics' recommendation of less than one hour of screen time per day for children under 5 years of age (Council on Communications and Media, 2016). During the recent COVID-19 pandemic, children's screen time increased to over six hours per day (Hedderson et al., 2023). Reports of these rising rates have generated concern amongst parents and medical professionals (Council on Communications and Media, 2016; C.S. Mott Children's Hospital, 2023; Ponti, 2023), as research has shown that too much solitary screen time (as opposed to interactive screen time/joint media engagement/co-viewing; Dore et al., 2020; Mendelsohn et al., 2010) can negatively impact children's language development (Jannesar, Davenport, & Gietzen, 2023; Muppalla et al., 2023; Ponti, 2023). For preschool-aged children in

particular, increased screen time is associated with language delays (see Duch, Fisher, Ensari, & Harrington, 2013 and Madigan et al., 2020 for review).

Screen time has also been adversely linked to children's brain development (Horowitz-Kraus, Magaliff, & Schlaggar, 2024; Wu, Dong, Liu, & Li, 2023). Hutton and colleagues (2020) reported that preschool-aged children who use screen-based media for over one hour per day had lower myelination in white matter tracts involved in language processing and production (i.e., arcuate fasciculus and superior longitudinal fasciculus; Hutton et al., 2020). Other studies of school-aged children found associations between increased screen time and lower resting-state functional connectivity between language and literacy regions of the brain (i.e., visual word form area, inferior frontal gyrus, inferior temporal gyrus, and angular gyrus; Horowitz-Kraus & Hutton, 2018) and attention and cognitive control regions of the brain (i.e., dorsal attention and salience networks; Meri et al., 2023). Together these findings suggest that frequent screen time is associated with lower language skills and less efficient neural signaling.

In summary, existing research to date has demonstrated that book reading and screen time have contrasting effects on children's language and brain development. However, few studies have explicitly investigated whether children's brains function differently *during* book reading and screen time. Finding significant differences in the strength and localization of functional brain response during book reading and screen time will offer a neurobiological explanation for why these two activities impact children's language development in such different ways. Studying children's brains function during book reading and screen time will also improve our understanding of how children's brains function during dyadic vs solitary activities and when using print vs digital media.

Measuring children's brain function during screen time and book reading

In traditional neuroimaging studies, auditory and visual stimuli are presented using audio recordings and screens. Consequently, findings from these studies can provide some insight into how children's brains function during screen time. Studies on language processing more specifically have shown that children process audio recordings of language in the bilateral superior and middle temporal gyri and the left inferior frontal gyrus (see Enge, Friederici, & Skeide, 2020 for review); this activation becomes more left-lateralized as children enter adolescence and adulthood (Enge, Friederici, & Skeide, 2020; Olulade et al., 2020). Studies that have used more naturalistic movie viewing tasks (See Redcay & Moraczewski, 2020 and Vanderwal, Eilbott, & Castellanos, 2019 for review), which inherently involve the processing of language from audio recordings and visuals from screens, have reported that children show more widespread activation across a variety of brain regions responsible for processing language, visual, and social information (e.g., inferior, middle, and superior temporal gyri, inferior, middle, and superior frontal gyri, occipital gyrus, and supramarginal gyrus; Tansey et al., 2023).

Several studies have investigated the neural bases of independent reading and story comprehension in school-aged children (Houdé, Rossi, Lubin, & Joliot, 2010; Martin, Schurz, Kronbichler, & Richlan, 2015; Schmithorst, Holland, & Plante, 2006). These studies have found that independently reading text on a screen activates primarily left-lateralized regions of the brain (e.g., left inferior and middle frontal gyri, left inferior, middle, and superior temporal gyri, left superior parietal lobule, and left inferior occipital gyrus; Houdé et al., 2010; Martin et al., 2015), while listening to audio recordings of stories activates bilateral regions of the brain (e.g., superior temporal gyrus and angular gyrus; Schmithorst, Holland, & Plante, 2006). However, very little is currently known about how the brains of younger, preschool-aged children function during live book reading interactions. In fact, preschool-aged children remain an understudied

age group in the neuroimaging literature, despite the fact that the preschool years are considered to be a sensitive period in language, literacy, and brain development (Brown & Jernigan, 2012; Dickinson, McCabe, & Essex, 2006; Kuhl, 2010). This gap in the literature is likely due to the methodological limitations of using more traditional neuroimaging methods, such as functional magnetic resonance imaging (fMRI), which do not allow for live, in-person social interactions. Functional near-infrared spectroscopy (fNIRS) is a newer functional neuroimaging technology that is exceptionally well-suited for measuring children's brain function while they are awake, seated upright, and interacting with a live social partner (Lloyd-Fox, Blasi, & Elwell, 2010; McDonald & Perdue, 2018). fNIRS uses near-infrared light to estimate changes in the concentration of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) on the cortical surface of the brain. Increases in HbO and corresponding decreases in HbR reflect increases in blood volume to brain regions that are experiencing increased neuronal activity (Obrig & Villringer, 2003). Previous work has shown that the hemodynamic response measured by fNIRS is highly correlated with the BOLD signal measured by fMRI, supporting fNIRS as an alternative neuroimaging method to fMRI (Sassaroli et al., 2006).

fNIRS has been successfully used to study how the brains of infants and children function during live, play-based parent-child and experimenter-child interactions (Hakuno et al., 2018; Hakuno et al., 2020; Lloyd-Fox, Széplaki-Köllőd, Yin, & Csibra, 2015; Su, Culotta, Tsuzuki, & Bhat, 2022; also see Alonso, McDorman, & Romeo, 2024 for review of parent-child hyperscanning studies). These studies, which assessed the neural bases of a variety of social and cognitive processes during live social interactions, reported activation in primarily right-lateralized regions of the brain, including the temporal parietal junction (TPJ; Hakuno et al., 2018; Hakuno et al., 2020; Lloyd-Fox et al., 2015; Su et al., 2022). However, only one fNIRS

study to date has measured children's brain function during a live book reading interaction (Ohgi, Loo, & Mizuike, 2010; although also see hyperscanning study by Zhai et al., 2023). Ohgi and colleagues (2010) collected fNIRS data from a sample of fifteen toddlers (18-30 months old) during a live parent-child book reading interaction. Parent-child dyads also interacted while co-viewing a digital version of the story (i.e., audio recording of experimenter reading the story with visuals presented on a screen). Results showed that toddlers' brain response in the bilateral prefrontal cortex was greater during book reading than video co-viewing (Ohgi, Loo, & Mizuike, 2010). Findings from this study are limited in that researchers measured toddlers' brain response in the prefrontal cortex only. Thus, the extent to which more posterior regions of the brain, such as the TPJ, are active during book reading is currently unknown. Measuring TPJ function during a live book reading interaction will provide critical insights into the social cognitive processes occurring during book reading, given the role that the TPJ plays joint attention (Mundy, 2018; Redcay & Saxe, 2013) and mentalizing (Frith & Frith, 2003; Krall et al., 2015).

Present study

The present study aimed to address existing gaps in the literature by utilizing fNIRS to measure preschool-aged children's brain function during book reading with a live experimenter and screen time. We measured children's functional brain response during two conditions – a book reading condition, during which children listened to a story read by a live experimenter while viewing words and pictures in a book, and a screen time condition, during which children listened to a story that was played via an audio recording while viewing words and pictures on a screen.

Our first aim was to identify which regions of the brain were active during the book reading condition and the screen time condition. We hypothesized that the bilateral temporal gyri

and left frontal gyrus would be active during both conditions, given that both conditions involved language processing and reading (Enge, Friederici, & Skeide, 2020; Houdé et al., 2010; Martin et al., 2015). We also hypothesized that the TPJ would be active during the book reading condition, based on the findings of previous fNIRS studies that documented TPJ activation in infants and children during live social interactions (Hakuno et al., 2018; Hakuno et al., 2020; Lloyd-Fox et al., 2015; Su et al., 2022). Our second aim was to compare the strength of brain response during the book reading condition and the screen time condition. We hypothesized that the strength of brain response would be greater during the book reading condition compared to the screen time condition in the bilateral frontal gyri based on the findings of Ohgi and colleagues (2010).

Methods

Participants

Children between 36 and 72 months of age were recruited from a local database of families who expressed interest in contributing to research on child development, in addition to social media posts and flyers shared in the Greater Boston area. Children who had a history of developmental, behavioral, speech, language, or seizure disorders, genetic syndromes, severe head injury, or pre-term birth were ineligible to participate in the present study. Children who had a family history of autism in any first-degree relatives were also ineligible to participate. Because fNIRS stimuli and parent-report measures were presented in English, all children were from predominately English-speaking households (i.e., heard English >50% of the time at home), although 39% of children in the final sample (N=11) were from multilingual households. The final sample included 28 children (10 female, 18 male) between the ages of 3 years 1 month 21 days and 5 years 11 months 28 days (M=4.21 years old, range=3.14-5.99 years old). Behavioral data were collected from one additional participant who was excluded from the final sample

because they could not tolerate wearing the fNIRS cap. Demographic information for the final sample is provided in Table 1. All study procedures were conducted according to the guidelines of the Declaration of Helsinki, including informed consent and assent prior to study inclusion, and approved by the Institutional Review Board at Boston University (protocol #5334).

fNIRS task

For the fNIRS task, each child listened to two different stories. The stories, which were called "Winter" and "Summer," were created by the first author and reviewed by two speech language pathologists to ensure that they were matched on number of words, syntax, vocabulary, content/sequence of events, and number of characters. One story was presented in the book reading condition and the other story was presented in the screen time condition (Figure 1).

During the book reading condition, a live female experimenter initiated interaction with the child by reading them one of the scripted stories from a printed book. While listening to the story, the child was seated next to the experimenter so that they could see each page of the book, which was placed on a stand in front of the child. Each page of the book, which served as one trial, included one simple illustration and typed text that matched what the child was hearing. The book reading condition was designed to simulate the household activity of book reading. To ensure that consistent prosody and pacing was used across trails in the book reading condition, the experimenter shadowed a pre-recorded version of the story that was presented to her through earbud headphones that could not be seen or heard by the participant.

During the screen time condition, the child listened to a pre-recorded audio recording of the same female experimenter reading the other scripted story. Each trial included one simple illustration and typed text that matched what the child was hearing. For this condition, trial visuals were presented using a computer screen instead of a printed book. The computer screen

was placed in front of the child and an audio speaker was placed below the computer screen. In this condition, the experimenter remained seated next to the child, but did not initiate interaction with the child during the trials. The screen time condition was designed to simulate the household activity of screen time. This condition was also designed after more conventional neuroimaging tasks which present stimuli using audio recordings and screens. Audio and visual stimuli were presented using the E-prime 3.0 software (Psychology Software Tools, 2016).

Each story was divided to create 18 trials (e.g., pages of the story) that lasted 10 seconds each. Between each trial, a jittered fixation cross was presented for 10 to 15 seconds to ensure that the hemodynamic response returned to baseline before the next trial was manually triggered by the experimenter. 18 trials of one condition were presented during the first run, followed by a short break, and then 18 trials of the other condition were presented during the second run. The order of conditions, as well as the story used in each condition ("Winter" or "Summer"), were randomized and counterbalanced across participants so that each child received both conditions and listened to both stories. Each condition lasted between 8 and 10 minutes. The entire fNIRS task lasted no longer than 60 minutes, including time for set up, capping, and breaks.

The child remained seated next to the experimenter in a dimly lit room throughout both conditions of the fNIRS task. Children were instructed to look and listen to each story while keeping their voice quiet and their body still. Snacks or handheld fidget toys were used if the child became restless or attempted to take the fNIRS cap off. After excluding trials in which the experimenter made an administration error (e.g., did not turn page of book at the correct time, deviated from book script), children completed an average of 17.32 trials for the book reading condition (range: 10-18) and 18 trials for the screen time condition. Two children completed the book reading condition only and did not complete any trials for the screen time condition, as they

could not tolerate wearing the fNIRS cap long enough to complete both conditions of the task. To maximize our sample size, data from these two participants were included in analyses.

fNIRS system and cap

fNIRS data were collected using the TechEn CW7 fNIRS system operating at 690nm and 830nm wavelengths and a 50 Hz sampling frequency. The fNIRS cap included a probe of 16 light sources and 20 detectors to make up 48 channels with a distance of approximately 25mm. The probe was designed using the AtlasViewer toolbox (Aasted et al., 2015) so that detectors 4 and 14 covered the T7 and T8 landmarks, respectively. Channel placement over brain regions of interest (ROIs) was determined by visually inspecting the probe design projected onto a 4 year old brain atlas (Figure 2), in addition to projecting the probe design onto a resized adult brain atlas that provided the specific MNI coordinates for each channel. Channel placement and ROIs were cross referenced using the devfOLD toolbox (Fu & Richards, 2021). Channels bilaterally covered brain regions of interest (ROIs) in the frontal, temporal, and parietal lobes, including the inferior and middle frontal gyri (IMFG), the superior and middle temporal gyri (SMTG), and the temporal parietal junction (TPJ; including regions of the supramarginal gyrus and angular gyrus). These ROIs were broadly defined as the IMFG, SMTG, and TPJ, given the possibility of slight variation in probe placement across participants. ROIs were selected a priori based on previous studies that have demonstrated that these brain regions are involved in language processing, narrative comprehension, and social cognitive processes (Enge, Friederici, & Skeide, 2020; Horowitz-Kraus & Hutton, 2015; Mar, 2011). Cap sizes of 50cm or 52cm were used, depending on the child's head circumference.

To guide accurate and symmetrical placement of the fNIRS cap on each child's head, the distances between naison-inion (Nz-Iz) landmarks and left-right pre-auricular (LPA-RPA)

landmarks were measured. These distances were halved to locate the midpoints of Nz-Iz and LPA-RPA so that Cz could be identified and marked. The Cz mark on the fNIRS cap was aligned with Cz on each child's head during cap placement. The fNIRS cap was secured with a chin strap and a light attenuating shower cap was placed over the fNIRS cap to shield the detectors from possible light interference.

fNIRS data processing

fNIRS data were processed using Homer3 (v1.81.4; Huppert, Diamond, Franceschini, & Boas, 2009). First, channels with a poor signal to noise ratio in the raw signal were removed from analyses (*hmrR_PruneChannels*; dRange=1e3 1e7, SNRthresh=4; see Appendix Figure S.1 for information about excluded channels per participant). The raw signal from remaining channels was converted to optical density (*hmrR_Intensity2OD*) and motion artifact correction was performed using the spline interpolation with Savitzky–Golay filtering method (*hmrR_MotionCorrectSplineSG;* p=0.99, framesize=10; Jahani, Setarehdan, Boas, & Yücel, 2018). Next, a low pass filter was used to exclude high frequency fluctuations (*hmrR_BandpassFilt;* lpf=0.50). Then, optical density was converted into oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) concentration changes using the Modified Beer-Lambert law (*hmrR_OD2Conc;* ppf=1); pathlength correction was not applied and therefore signal changes are presented as the products of concentration changes and mean path length (M*mm; Yücel et al., 2021). Finally, the hemodynamic response function (HRF) was estimated over the time range of -2 to 18 seconds using general linear modeling (GLM) with the least-squares method for estimating the weights of consecutive Gaussian functions (*hmrR_GLM*; glmSolveMethod=1, idxBasis=1, driftOrder=3). To remove global systemic physiology from the signal (i.e., physiological noise), we used the average of all channels as a regressor in the GLM

(i.e., common average reference method; Klein et al., 2023). After data processing, average HbO and HbR concentration values from 0 to 10 seconds (i.e., trial length) were calculated and used for analyses.

Preschool Language Scales, Fifth Edition (PLS-5)

Children completed the fifth edition of the PLS (Zimmerman, Steiner, & Pond, 2011), a comprehensive developmental language assessment that evaluates two domains of language – expressive communication and auditory comprehension. The PLS-5 includes items that behaviorally assess a range of pre-verbal, phonological, syntactic, semantic, and early literacy skills in children under 8 years of age. Total language scores are reported in Table 1.

Analyses

All analyses were conducted using HbO concentration values and carried out using SPSS (v 27.0).

Channel analyses

For channel analyses, we first conducted one-sample t-tests to identify channels that showed significant activation (i.e., HbO concentration values significantly greater than zero baseline) or deactivation (i.e., HbO concentration values significantly less than zero baseline) during each condition. We next conducted paired sample t-tests to determine whether HbO concentration values significantly differed during the book reading condition compared to the screen time condition in each channel. For channel analyses, the Benjamini-Hochberg method was used to correct for multiple comparisons (false discovery rate=.10; Benjamini & Hochberg, 1995).

ROI analyses

For region of interest (ROI) analyses, we first calculated "ROI averages" by averaging HbO concentration values across all channels covering each ROI (see Figure 2 for specific channel numbers in each ROI). Using these ROI averages, we conducted a 2 × 3 × 2 factorial ANOVA – Hemisphere (Left, Right) × Region (IMFG, SMTG, TPJ) × Condition (Book reading condition, Screen time condition). Significant interaction effects were explored using simple effects post-hoc testing with Bonferroni correction.

Results

Channel analyses

Channels showing significant change in HbO during the book reading condition

Three channels within the left hemisphere showed evidence of significant deactivation during the book reading condition (Figure 3). HbO concentration values were significantly less than zero in channel 2 ($t(16)=-2.391$, $p=.029$, $M_{diff}=-.000010$, 95% CI: [-.000019, -.000001]; Cohen's d=-.580, 95% CI: [-1.088, -.057]) and channel 8 ($t(14)=-2.563$, $p=.023$, $M_{diff}=-.000012$, 95% CI: [-.000022, -.000002]; Cohen's d=-.662, 95% CI: [-1.214, -.091]) which covered the left IMFG, and channel 18 which covered the left TPJ ($t(18)=-4.763$, $p<.001$, $M_{diff}=-.000018$, 95% CI: [-.000026, -.000010]; Cohen's d=-1.093, 95% CI: [-1.656, -.511]). Three channels within the right hemisphere showed evidence of significant activation during the book reading condition. HbO concentration values were significantly greater than zero in channel 43 ($t(11)=2.852$, $p=.016$, $M_{diff}=.000022$, 95% CI: [.000005, .000039]; Cohen's d=.823, 95% CI: [.150, 1.470]) and channel 44 ($t(11)=2.603$, $p=.025$, $M_{diff}=.000024$, 95% CI: [.000004, .000044]; Cohen's d=.751, 95% CI: [.093, 1.384]) which covered the right SMTG, and channel 41 which covered the right TPJ ($t(18)=3.161$, $p=.005$, $M_{diff}=.000021$, 95% CI: [.000007, .000035]; Cohen's d=.725, 95% CI: [.210, 1.225]). One channel within the right hemisphere showed evidence of

significant deactivation during the book reading condition. HbO concentration values were significantly less than zero in channel 25 which covered the right IMFG ($t(16)=-4.013$, $p=.001$, $M_{diff}=-.000017$, 95% CI: [-.000027, -.000008]; Cohen's d=-.973, 95% CI: [-1.544, -.382]). For all other channels, HbO concentration values during the book reading condition did not significantly differ from zero (Table 2). After correction for multiple comparisons, HbO concentration values remained significantly different from zero in channels 18, 25, and 41.

Channels showing significant change in HbO during the screen time condition

Two channels within the left hemisphere showed evidence of significant deactivation during the screen time condition (Figure 4). HbO concentration values were significantly less than zero in channel 1 ($t(21)=-5.305$, $p<.001$, $M_{diff}=-.000021$, 95% CI: [-.000029, -.000013]; Cohen's d=-1.131, 95% CI: [-1.662, -.584]) and channel 2 ($t(20)=-2.963$, $p=.008$, $M_{diff}=-.000014$, 95% CI: [-.000024, -.000004]; Cohen's d=-.647, 95% CI: [-1.112, -.168]) which covered the left IMFG. Two channels within the right hemisphere showed evidence of significant activation during the screen time condition. HbO concentration values were significantly greater than zero in channel 48 which covered the right SMTG ($t(10)=2.671$, $p=.023$, $M_{diff}=.000015$, 95% CI: [.000002, .000027]; Cohen's d=.805, 95% CI: [.105, 1.477]), and channel 41 which covered the right TPJ ($t(15)=2.429$, $p=.028$, $M_{diff}=.000014$, 95% CI: [.000002, .000027]; Cohen's d=.607, 95% CI: [.064, 1.134]). One channel within the right hemisphere showed evidence of significant deactivation during the screen time condition. HbO concentration values were significantly less than zero in channel 25 which covered the right IMFG ($t(18)=-2.290$, $p=.034$, $M_{diff}=-.000015$, 95% CI: [-.000029, -.000001]; Cohen's d=-.525, 95% CI: [-1.00, -.038]). For all other channels, HbO concentration values during the screen time condition did not significantly differ from zero

(Table 2). After correction for multiple comparisons, HbO concentration values remained significantly different from zero in channel 1 only.

Channels showing significant difference in HbO between conditions

When comparing HbO concentration values during the book reading condition and the screen time condition, one channel a showed significant difference in HbO between conditions (Figure 5). HbO was significantly greater during the screen time condition compared to the book reading condition in channel 18 which covered the left TPJ ($t(17)=2.455$, $p=.025$, $M_{diff}=.000013$, 95% CI: [.000002, .000025]; Cohen's d=.579, 95% CI: [.071, 1.072]). This statistically significant difference did not survive correction for multiple comparisons. For all other channels, there were no significant differences in HbO concentration values between conditions (Table 2).

ROI analyses

The 2 × 3 × 2 factorial ANOVA (Hemisphere × Region × Condition) revealed a significant two-way interaction effect for Hemisphere × Condition ($F(1, 14)=6.704$, $p=.021$; partial $\eta^2=.324$; Figure 6). Bonferroni corrected post-hoc tests showed that during the book reading condition, HbO concentration values were greater in the right hemisphere than the left hemisphere ($p<.001$). During the screen time condition, HbO concentration values did not significantly differ between hemispheres ($p=.836$). Additionally, HbO concentration values were greater during the screen time condition compared to the book reading condition in the left hemisphere ($p=.023$). HbO concentration values appeared to be greater during the book reading condition compared to the screen time condition in the right hemisphere, although this difference was not statistically significant ($p=.158$). Main effects of hemisphere ($F(1, 14)=4.248$, $p=.058$; partial $\eta^2=.233$), region ($F(1.28, 17.91)=3.864$, $p=.056$; partial $\eta^2=.216$), and condition ($F(1, 14)=.088$, $p=.771$; partial $\eta^2=.006$) were non-significant. Hemisphere × Region $F(2, 28)=.081$,

p=.922; partial η^2=.006), Region × Condition *F*(2, 28)=.607, *p*=.552; partial η^2=.042), and Hemisphere × Region × Condition (*F*(1.39, 19.41)=.786, *p*=.426; partial η^2=.053) interaction effects were also non-significant.

Discussion

The present study used fNIRS to measure preschool-aged children's functional brain response during two conditions – a book reading condition, in which children listened to a story read by a live experimenter while viewing words and pictures in a book, and a screen time condition, in which children listened to a story that was played via an audio recording while viewing words and pictures on a screen. Channel analyses revealed significant activation in the right TPJ during the book reading condition only, which may reflect the occurrence of social cognitive processes like joint attention and mentalizing. ROI analyses demonstrated that brain response during the book reading condition was greater in the right hemisphere than the left hemisphere, while brain response during the screen time condition was similar across left and right hemispheres. These findings indicate that for preschool-aged children, lateralization of brain function differs during book reading and screen time. These differences in functional brain response may help to explain why book reading and screen time impact children's language development in such different ways, as book reading may provide children with additional opportunities to process socially relevant information while screen time may be more cognitively demanding.

Right TPJ activation during book reading only

Channel analyses demonstrated that after correction for multiple comparisons, channel 41, which covered the right TPJ, showed evidence of significant activation during the book reading condition only. Channel 41 also showed evidence of activation during the screen time

condition, although this finding did not survive correction for multiple comparisons. Previous fNIRS studies of infants and children have similarly documented right TPJ activation during live play-based parent-child and experimenter-child interactions (Hakuno et al., 2018; Hakuno et al., 2020; Lloyd-Fox et al., 2015; Su et al., 2022). Together these findings suggest that the right TPJ plays an important role in children's brain function during live social interactions.

Researchers have argued that the TPJ serves as a zone of convergence for a variety of processes related to memory, attention, language, and social cognition (Carter & Huettel, 2013). One of these social cognitive processes is joint attention, defined as the intentional sharing of attention between two social partners and a common object of interest (Mundy, 2018; Redcay & Saxe, 2013). Both fMRI studies (Caruana, Brock, & Woolgar, 2015; Oberwelland et al., 2016; Redcay et al., 2010; Redcay, Kleiner, & Saxe, 2012) and fNIRS studies (Dravida et al., 2020; Hakuno et al., 2018) have reported right TPJ activation during tasks that elicit joint attention in toddlers, school-aged children, and adults (also see Mundy, 2018 and Redcay & Saxe, 2013 for review). The TPJ is also active during mentalizing, a social cognitive process that involves thinking about the "mental states" (i.e., goals, beliefs, and intentions) of a social partner (Frith & Frith, 2003; Krall et al., 2015). The right TPJ seems to play a more important role in implicit/spontaneous mentalizing than the left TPJ (Boccadoro et al., 2019; Kovács et al., 2014), which may help to explain why we observed significant activation in the right TPJ but significant deactivation in the left TPJ during the book reading condition, which did not include any explicit prompts for mentalizing. A recent meta-analysis by Fehlbaum and colleagues (2022) reported that the right TPJ is involved in mentalizing throughout various developmental stages, including childhood, adolescence, and adulthood. A fNIRS study by Hyde and colleagues (2018) showed

that the right TPJ was active during an implicit theory of mind task in 7 month old infants, suggesting that this region is involved in mentalizing from very early in development.

Considering the role that the right TPJ plays in these social cognitive processes, finding significant activation in a channel covering this region suggests that children may have been engaged in joint attention and/or mentalizing during the book reading condition. Indeed, studies have shown that book reading provides children with opportunities for joint attention (Farrant & Zubrick, 2012; Fletcher, Perez, Hooper, & Claussen, 2005; Sato & Uchiyama, 2012) and mentalizing (Adrián, Clemente, & Villanueva, 2007; Dyer, Shatz, & Wellman, 2000; Symons et al., 2005). Other researchers have suggested that simply interacting with a live social partner can elicit activation in the right TPJ, even without explicit prompts for mentalizing (Redcay et al., 2010). In all, our findings suggest that for preschool-aged children, book reading engages the right TPJ, even in the absence of explicit bids for joint attention or prompts for mentalizing.

IMFG deactivation during book reading and screen time

Channel analyses also revealed that the IMFG showed evidence of significant deactivation during the book reading condition and the screen time condition. After correction for multiple comparisons, this deactivation was localized to the right IMFG during the book reading condition and the left IMFG during the screen time condition. Previous fNIRS studies have similarly reported that infants show deactivation in the bilateral frontal gyri when viewing socially relevant stimuli (Grossmann & Johnson, 2010; Xu et al., 2017), listening to communicative sounds (McDonald et al., 2019), and interacting with a live social partner (Behrendt, Konrad, Perdue, & Firk, 2020; Naoi, Minagawa, Yamamoto, & Kojima, 2022). This deactivation may simply be the result of blood flow moving away from anterior regions of the brain towards more posterior regions of the brain that showed evidence of activation (e.g., right

TPJ). Alternatively, deactivation of the frontal gyrus may reflect changes in the default mode network, a baseline pattern of brain function that is attenuated during tasks that require attentional control and other goal-directed behaviors (Raichle et al., 2001). Thus, deactivation of the IMFG could simply indicate that children were attentive and engaged during both conditions of the task.

Right-lateralized brain response during book reading and bilateral brain response during screen time

Contrary to our hypotheses, there were no channels that showed a significant difference in strength of brain response between conditions after correction for multiple comparisons. However, ROI analyses demonstrated that the strength of brain response during the screen time condition did not significantly differ between hemispheres; this finding is in line with previous studies that have measured preschool-aged children's brain response to audio recordings and have found activation in both hemispheres of the brain (Hutton et al., 2015; Hutton et al., 2017; Sroka et al., 2015; also see Enge, Friederici, & Skeide, 2020 for review). In contrast, the strength of brain response during the book reading condition was significantly greater in the right hemisphere than the left hemisphere. Together these findings indicate that for preschool-aged children, lateralization of brain function differs during book reading and screen time. Book reading elicits right-lateralized brain response, while screen time elicits bilateral/non-lateralized brain response.

The right hemisphere of the brain serves a dominant role in the perception and evaluation of socially relevant information (Rajimehr et al., 2022). For example, studies of infants, children, and adults have reported greater right hemisphere activation than left hemisphere activation when processing different types of socially relevant information, including faces (Nakato et al.,

2009; Otsuka et al., 2007), eye contact (Noah et al., 2020; Pelphrey, Viola, & McCarthy, 2004), social contingency (Hakuno et al., 2020; Redcay et al., 2010), biological motion (Lloyd-Fox et al., 2011), emotional prosody (Zhang et al., 2017), and dyadic social interactions more generally (Bosseler et al., 2024; Semrud-Clikeman, Goldenring Fine, & Zhu, 2011). Thus, one explanation for why we observed this right-lateralized brain response during the book reading condition is that this condition may have included more socially relevant information than the screen time condition, given that language was coming directly from a live experimenter rather than an audio recording. Another explanation could be that the language used in the book reading condition was perceived to be more "human-like" than the language used in the screen time condition. fMRI studies conducted with adults have found that right-lateralized regions of the brain, including the right IFG, MFG, TPJ, and superior temporal sulcus (STS; a subregion of the TPJ), respond more strongly to videos and photos of humans than cartoon characters and virtual avatars (Gobbini et al., 2011; Kegel et al., 2020; Mar, Kelley, Heatherton, & Macrae, 2007), suggesting that the right hemisphere is preferentially responsive to human animacy.

The right hemisphere is also involved in processing functional aspects of language, including pragmatics, discourse, and prosody (Fonseca, Scherer, Oliveira, & Parente, 2009; Wildgruber, Ackermann, Kreifelts, & Ethofer, 2006). There is evidence that this right hemisphere dominance for processing functional aspects of language is present during infancy and early childhood (Chen et al., 2023; Homae et al., 2006; Wartenburger et al., 2007). Given these findings, the right-lateralized brain response that we observed in the present study may indicate that children were focused on processing these functional aspects of language more so during the book reading condition when language was coming directly from a live experimenter as opposed to the screen time condition when language was coming from an audio recording.

Additionally, the right hemisphere is responsible for more basic cognitive functions, such as attention (Corbetta & Shulman, 2002; Langner & Eickhoff, 2013). For example, the right ventral frontoparietal network, which includes regions of the TPJ, STG, IFG, and MFG, is involved in attentional control (Corbetta & Shulman, 2002). The right TPJ specifically is also involved in attention reorienting (Decety & Lamm, 2007; Krall et al., 2015; Mitchell, 2008). Thus, greater activation in the right hemisphere during the book reading condition could be the result of children dividing their attention between the words and pictures in the book and the socially relevant information (e.g., face, social contingency, biological motion, prosody) provided by the live experimenter.

Sustained or "vigilant" attention also involves primarily right-lateralized regions of the brain, including the TPJ, IFG and MFG (Langner & Eickhoff, 2013). In fact, neuroimaging studies conducted with adults have shown that simpler cognitive tasks with less attentional demands activate right-lateralized regions of the brain, while tasks with greater attentional demands recruit additional regions in the left hemisphere as a way to gain "processing power" (Helton et al., 2010; Hughes, Upshaw, Macaulay, & Rutherford, 2016; Klingberg, O'Sullivan, & Roland, 1997; Langner & Eickhoff, 2013). In other words, brain response appears to be right-lateralized during less cognitively demanding tasks, but bilateral/non-lateralized during more cognitively demanding tasks. While further research is needed to confirm whether this phenomenon also occurs in children, these findings suggest that the screen time condition may have been more cognitively demanding than the book reading condition, given that the screen time condition resulted in similar brain response in both hemispheres while the book reading condition resulted in greater brain response in the right hemisphere. In support of this interpretation, an EEG study conducted by Zivan and colleagues (2023) found that school-aged

children showed higher power in lower frequency bands when reading text on a screen compared to reading text on paper, which suggests that using screen-based digital media is more cognitively demanding for children than print media (Zivan et al., 2023).

Study limitations and contributions

The present study has several limitations to note. First, our statistical analyses were likely underpowered due to our sample size. Some participants did not have usable data from channels covering the temporal gyrus, which may help to explain why we did not observe significant activation in this region. Second, it is important to note that many children in our sample had above average language skills, as reflected by their PLS total language scores. Additionally, our sample was composed of children from predominately high socioeconomic backgrounds, as all children had at least one parent with a college or graduate degree. Therefore, findings should be considered preliminary and interpreted with caution until they can be replicated in a larger, more diverse sample.

Third, while our method for removing global systemic physiology from the fNIRS signal has been shown to improve signal quality over no correction, it can lead to a more conservative overcorrection of the signal compared to less conservative methods (e.g., regression of signal from short separation channels; Klein et al., 2023). This overcorrection may also help to explain why we did not observe significant activation in a greater number of our channels. While our original fNIRS cap included short separation channels, most children in our sample could not tolerate the tactile sensation of these additional channels, and so the short separation channels were removed from the cap. Future studies should utilize short separation regression to obtain better signal quality from the brain, while also ensuring that short separation channels are comfortable for young children. Fourth, we were unable measure regions of the occipital gyrus

given the technical constraints of our fNIRS system. It is likely that our task elicited activation in the occipital gyrus, given the inclusion of visual stimuli. Future studies should utilize fNIRS systems with whole-head coverage that allow for simultaneous measurement from all cortical brain regions so that we can examine whether children's brains process printed visual stimuli differently from screen-based visual stimuli.

Lastly, unlike previous studies that have measured children's brain function during book reading (Ohgi, Loo, & Mizuike, 2010; Zhai et al., 2023), the book reading condition in our task did not incorporate features of real-world book reading interactions that children experience in everyday life, such as eye contact, gesture, and the opportunity for conversational exchange between social partners. Our task was designed to minimize opportunities for conversational exchange; if the child made a comment or asked a question during the task, the experimenter did not respond. While this kept the task well-controlled, it somewhat limits the ecological validity of our task given that book reading interactions typically involve conversational exchange between the child and the adult reader. Unintentionally, the book reading condition may have felt less natural for children than the screen time condition, which could have impacted our findings. Future work should measure children's brain function during even more naturalistic tasks that allow for live, dyadic social interaction between social partners, such as unstructured parent-child book reading interactions. Future researchers may also want to explore children's brain function during joint media engagement/co-viewing, as interactive screen time has been shown to facilitate children's language acquisition (Strouse, Troseth, O'Doherty, & Saylor, 2018).

Beyond these limitations, the present study provides important contributions to the literature. This study provides proof of concept that fNIRS can be used to measure preschool-aged children's brain function during a live book reading interaction. Furthermore, this is one of

the first studies to demonstrate that children's brains function differently *during* book reading and screen time. This difference in brain function may help to explain why these two activities impact children's language development in such different ways.

Implications and insights

Current findings have implications for the types of activities and educational materials that we use to teach children at home and in the classroom. More specifically, findings provide important insights into how children's brains function during different types of activities (dyadic vs solitary) and when using different types of media (print vs digital). First, findings demonstrate that children's brains function differently during book reading, a dyadic activity, and screen time, a solitary activity. Dyadic activities like book reading may provide children with more opportunities to engage in social cognitive processes, which may ultimately strengthen the neural circuitry underlying language development. In contrast, solitary activities like screen time may not provide children with such opportunities to engage in social cognitive processes, which could lead to alternative trajectories in children's brain and language development. Further research is needed to determine whether functional brain response measured during these activities is related to children's language skills, as this will provide further evidence to suggest that book reading and screen time have different impacts on children's language development via changes in brain function.

Second, findings suggest that children's brains function differently when using print media during book reading (words and pictures in a book + live reader) and digital media during screen time (words and pictures on a screen + audio recording). Using digital media may be more cognitively demanding for children, which may impact their comprehension, engagement, and learning. Indeed, research has shown that children understand and learn more when reading

on paper compared to reading on screens, and learning outcomes improve when reading on paper occurs with a live adult reader (Furenes, Kucirkova, & Bus, 2021). Future research should explore whether the media format of educational materials influences children's learning, as well as their brain and language development, during the preschool years.

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Table 1. Sample demographics and descriptives

Child age (years)	
Mean (SD)	4.21 (.84)
Range	3.14 – 5.99
PLS total language standard scores	
Mean (SD)	127.22 (15.01)
Range	95.00 – 150.00
Child sex	
Female	35.70%
Male	64.30%
Child race	
Asian	10.70%
More than one race	32.10%
White	57.10%
Child ethnicity	
Hispanic or Latino	0.00%
Not Hispanic or Latino	100.00%
Parent education level	
Bachelor's degree	10.70%
Master's degree	50.00%
Doctorate or professional degree	39.30%
Annual household income	
$40k-$60k	3.60%
$60k-$80k	3.60%
$80k-$100k	7.10%
$100k-$120k	14.30%
$120k-$140k	3.60%
$140k-$160k	3.60%
$160k-$180k	10.70%
$180k-$200k	10.70%
More than $200k	35.70%
Prefer not to answer	7.10%
Language(s) spoken at home	
English only	60.71%
English and another language	39.29%

Note. Parent education level reflects the highest education level across both parents. While all participants were from predominately English-speaking households (i.e., heard English >50% of the time at home), some participants were from multilingual households in which they also heard one or more non-English languages at home (i.e., Spanish, Hindi, Marathi, Cantonese, Mandarin, Hainanese, Japanese, Korean, Bulgarian, German, and/or Italian). *N*=1 participant was missing data from the PLS. PLS=Preschool Language Scales

Table 2. Channels showing significant changes in HbO compared to baseline and significant differences in HbO between conditions

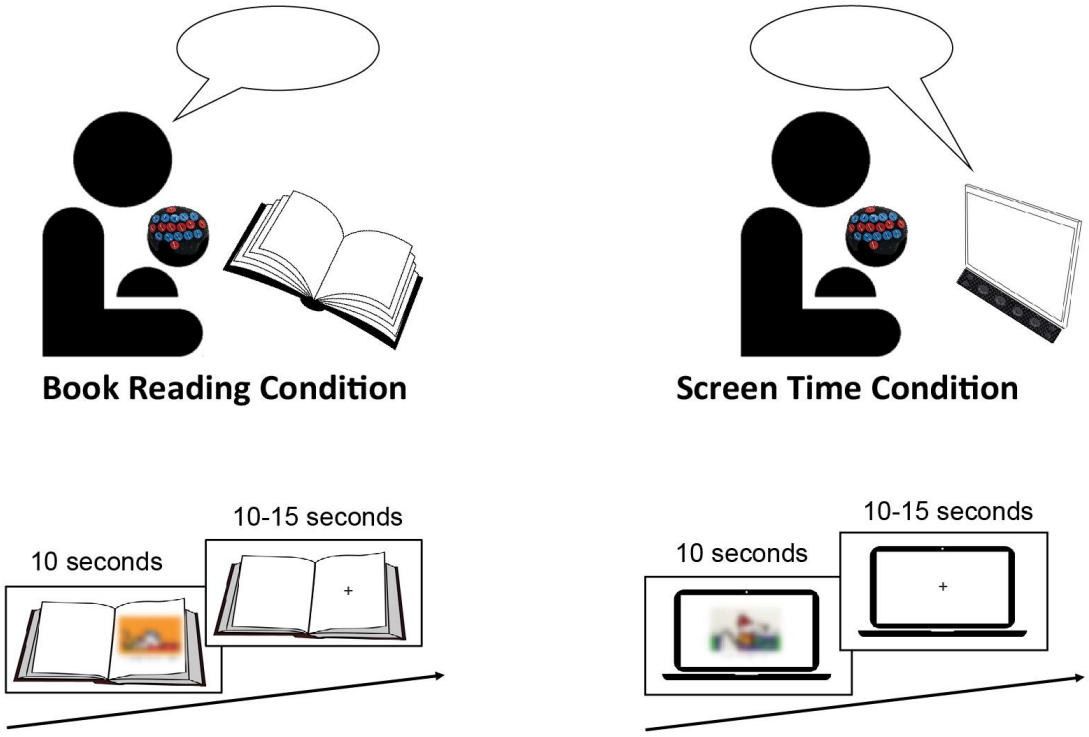
ROI	Channel #	*p*-value					
		Book Reading Condition vs. Baseline		*Screen Time Condition vs. Baseline*		*Book Reading Condition vs. Screen Time Condition*	
Left IMFG	1	.285		**<.001*** **	**(–)**	.086	
	2	.029*	(–)	.008**	(–)	.562	
	3	.473		.999		.629	
	4	.348		.620		.970	
	5	.934		.807		.885	
	6	.898		.871		.094	
	7	.329		.227		.260	
	8	.023*	(–)	.118		.898	
Left SMTG	13	.064		.127		.585	
	19	.984		.122		.165	
	20	.504		.735		.431	
	24	.405		.165		.751	
Left TPJ	15	.364		.202		.445	
	16	.380		.168		.280	
	17	.424		.130		.244	
	18	**<.001*** **	**(–)**	.312		.025*	ST>BR
Right IMFG	25	**.001****	**(–)**	.034*	(–)	.761	
	26	.661		.415		.156	
	27	.440		.761		.522	
	28	.879		.095		.266	
	29	.443		.647		.544	
	30	.990		.236		.399	
	31	.764		.464		.854	
	32	.853		.357		.891	
Right SMTG	43	.016*	(+)	.054		.444	
	44	.025*	(+)	.152		.358	
	47	.810		.303		.385	
	48	.324		.023*	(+)	.212	
Right TPJ	39	.845		.294		.298	
	40	.155		.743		.132	
	41	**.005****	**(+)**	.028*	(+)	.714	
	42	.368		.350		.813	

Note. * $p<.05$, ** $p<.01$, *** $p<.001$, before correction for multiple comparisons. Findings that survived correction for multiple comparisons are in bold. (+) represents a significant increase in HbO relative to baseline (i.e., activation) and (–) represents a significant decrease in HbO relative to baseline (i.e., deactivation). BR=Book

Reading, ST=Screen Time, ROI=Region of Interest, IMFG=Inferior and Middle Frontal Gyrus, SMTG=Superior and Middle Temporal Gyrus, TPJ=Temporal Parietal Junction

Figure 1.

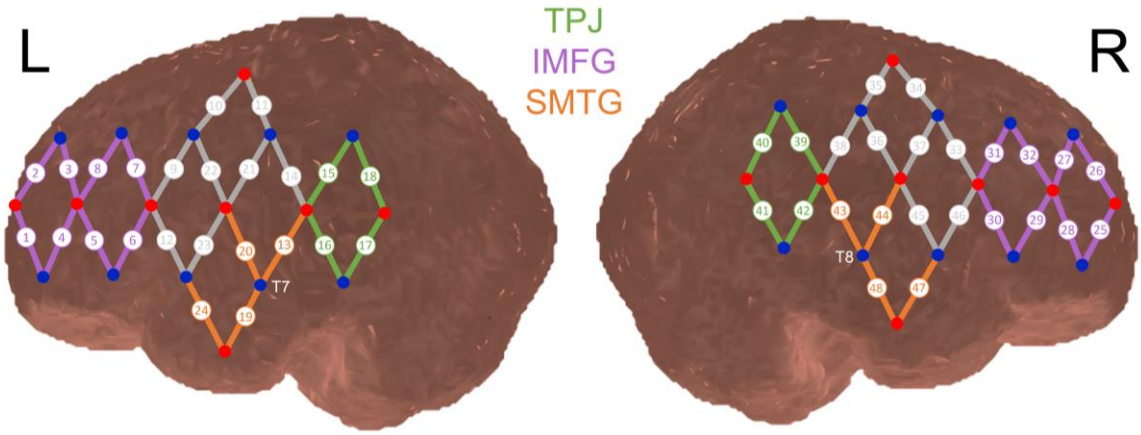
fNIRS task design



Note. The fNIRS task included two conditions – a book reading condition and a screen time condition. During the book reading condition, visual stimuli were presented using a printed book and the story was read by a live experimenter. During the screen time condition, visual stimuli were presented using a computer screen and the story was played via an audio recording. Each condition included 18 trials. Trials were presented for 10 seconds, followed by a jittered fixation cross for 10-15 seconds.

Figure 2.

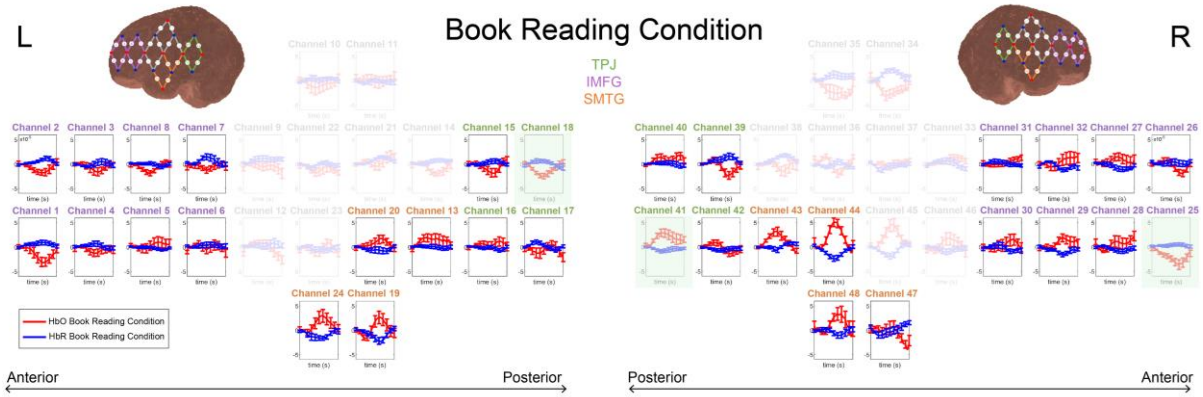
fNIRS probe design projected onto a 4 year old brain template



Note. Sources are depicted as red circles and detectors are depicted as blue circles. Channels are depicted as lines between source-detector pairs. The fNIRS probe was designed so that channels bilaterally cover regions of interest in the frontal and temporal lobes, including 8 channels over the inferior and middle frontal gyrus (IMFG), shown in purple, 4 channels over the superior and middle temporal gyrus (SMTG), shown in orange, and 4 channels over the temporal parietal junction (TPJ), shown in green. Detectors 4 and 14 covered the T7 and T8 landmarks, respectively. Channels shown in grey did not cover brain regions of interest and were thus excluded from analyses. Brain template provided by the Neurodevelopmental MRI Database (Richards, Sanchez, Phillips-Meek, & Xie, 2015).

Figure 3.

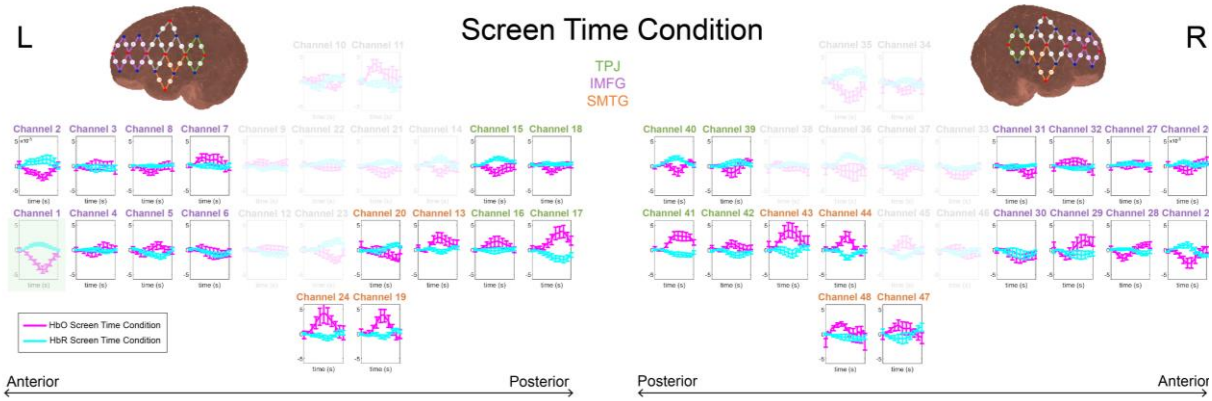
Average hemodynamic response from -2 to 18 seconds during the book reading condition



Note. HbO concentration values are shown in red and HbR concentration values are shown in blue. Channels highlighted in green showed average HbO concentration values over the analysis window (0 to 10 seconds) that were significantly different from a baseline concentration value of zero and survived correction for multiple comparisons. Error bars represent standard error values every 2 seconds. The y-axis shows a range of concentration values from -5.5×10^{-5} to 5.5×10^{-5} *M*mm*. Channels that are greyed out did not cover brain regions of interest and were thus excluded from one-sample t-test analyses. Channels covering the IMFG are labeled in purple, channels cover the SMTG are labeled in orange, and channels covering the TPJ are labeled in green.

Figure 4.

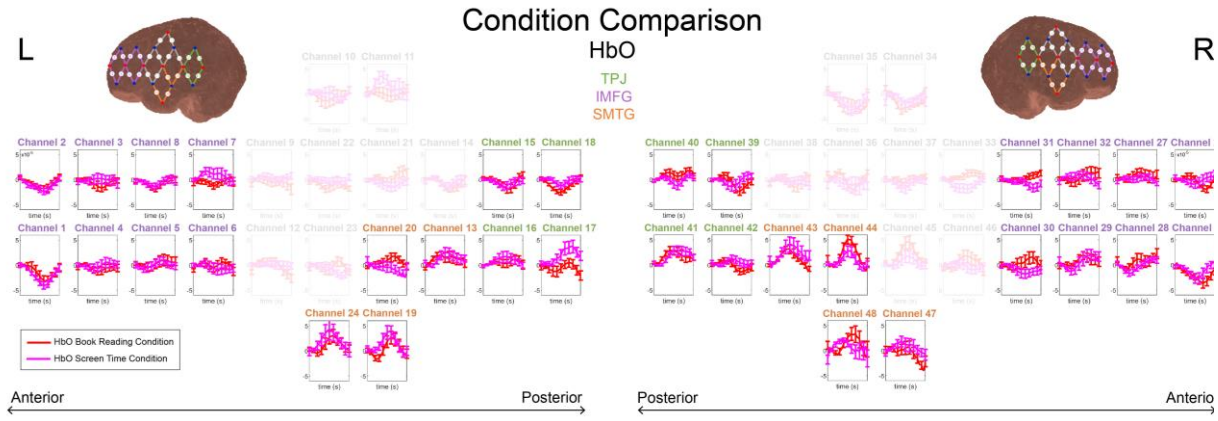
Average hemodynamic response from -2 to 18 seconds during the screen time condition



Note. HbO concentration values are shown in pink and HbR concentration values are shown in cyan. Channels highlighted in green showed average HbO concentration values over the analysis window (0 to 10 seconds) that were significantly different from a baseline concentration value of zero and survived correction for multiple comparisons. Error bars represent standard error values every 2 seconds. The y-axis shows a range of concentration values from -5.5×10^{-5} to 5.5×10^{-5} *M*mm*. Channels that are greyed out did not cover brain regions of interest and were thus excluded from one-sample t-test analyses. Channels covering the IMFG are labeled in purple, channels cover the SMTG are labeled in orange, and channels covering the TPJ are labeled in green.

Figure 5.

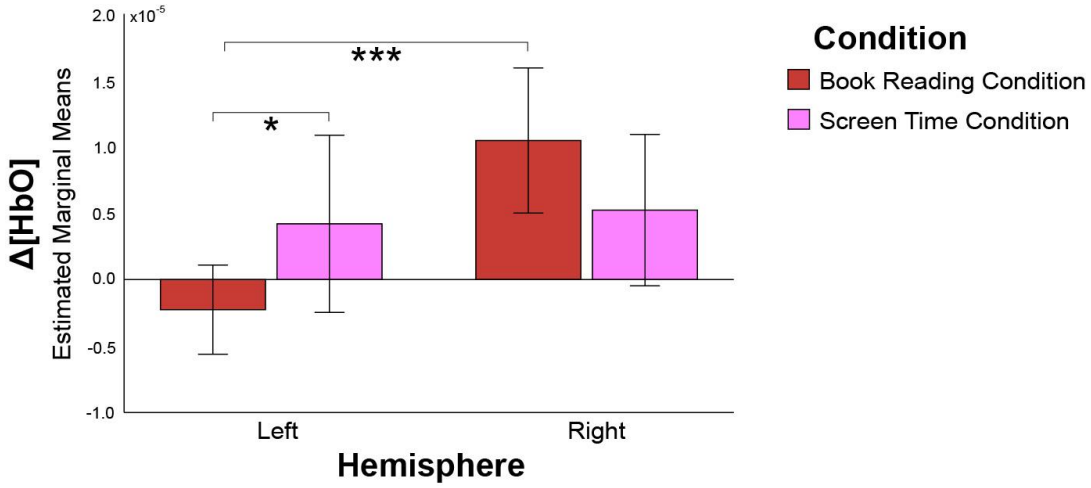
Average change in HbO concentration values from -2 to 18 seconds during the book reading condition and the screen time condition



Note. Book reading condition is depicted in red and screen time condition is depicted in pink. No channels showed average HbO concentration values over the analysis window (0 to 10 seconds) that were significantly different between conditions after correction for multiple comparisons. Error bars represent standard error values every 2 seconds. The y-axis shows a range of concentration values from $-5.5x10^{-5}$ to $5.5x10^{-5}$ *M*mm*. Channels that are greyed out did not cover brain regions of interest and were thus excluded from paired sample t-test analyses. Channels covering the IMFG are labeled in purple, channels cover the SMTG are labeled in orange, and channels covering the TPJ are labeled in green.

Figure 6.

Factorial ANOVA –Hemisphere × Condition interaction



Note. * $p<.05$, *** $p<.001$ simple effects post-hoc testing with Bonferroni correction. Error bars represent 95% CI.