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Bilingualism alters infants' cortical organization for attentional orienting mechanisms

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Abstract

A bilingual environment is associated with changes in the brain's structure and function. Some suggest that bilingualism also improves higher-cognitive functions in infants as young as 6-months, yet whether this effect is associated with changes in the infant brain remains unknown. In the present study, we measured brain activity using functional near-infrared spectroscopy in monolingual- and bilingual-raised 6- and 10-month-old infants. Infants completed an orienting attention task, in which a cue was presented prior to an object appearing on the same (Valid) or opposite (Invalid) side of a display. Task performance did not differ between the groups but neural activity did. At 6-months, both groups showed greater activity for Valid (> Invalid) trials in frontal regions (left hemisphere for bilinguals, right hemisphere for monolinguals). At 10-months, bilinguals showed greater activity for Invalid (> Valid) trials in bilateral frontal regions, while monolinguals showed greater brain activity for Valid (> Invalid) trials in left frontal regions. Bilinguals' brain activity trended with their parents' reporting of dual-language mixing when speaking to their child. These findings are the first to indicate how early (dual) language experience can alter the cortical organization underlying broader, non-linguistic cognitive functions during the first year of life.

KEYWORDS
bilingualism, brain development, covert attention, fNIRS, infants, orienting

1 | INTRODUCTION

Infants acquire language effortlessly, yet bilingual-raised babies must learn many more linguistic features (e.g. phonetic sounds, words) than infants in monolingual environments. Some theoretical frameworks suggest that a bilingual environment heightens and possibly improves performance on higher cognitive functions that support the management of two languages (Bialystok, 2015, 2017; Kroll & Bialystok, 2013). Specifically, these abilities transfer from the linguistic domain to non-linguistic higher cognitive functions (i.e., attention, inhibitory control, memory). Nevertheless, evidence for this conclusion is not consistent (De Bruin & Della Salla, 2019; Paap, 2019): while some studies show better task performance by bilinguals, others do not show differences between bilinguals and monolinguals. Despite the absence of differences in task performance, bilinguals engage brain regions associated with language areas when performing a non-linguistic higher cognitive function task, suggesting that demands from a dual-language environment may alter how cognitive systems develop and functionally organize (Arredondo et al., 2017, 2019; DeLuca et al., 2020; Garbin et al., 2010; Marian et al., 2014; Mohades et al., 2014; Pierce et al., 2015). The developmental nature of bilingual brain differences, including whether they are evident during early life, remains largely unstudied. The present research addresses this gap by investigating whether early bilingual experience impacts non-linguistic attentional orienting mechanisms in the preverbal infant brain.

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1.1 | Attentional orienting and bilingualism

RESEARCH HIGHLIGHTS

- The present study is the first to offer evidence that bilingualism may impact attentional orienting in the infant brain.
- Bilingual and monolingual infants perform similarly in an attentional orienting task.
- Neuroimaging results show that bilingual and monolingual infants differ in how they engage cortical brain regions for attentional orienting.
- Bilinguals' brain activity showed a trend with parents' report of dual-language mixing.

Language acquisition relies upon and interacts with multiple aspects of infants' early cognition. Attentional orienting (i.e., the ability to engage, disengage and shift focus to sensory events) is one example of domain-general abilities integral for language acquisition (Tenenbaum et al., 2014). For instance, prior to 8-months, infants tend to orient their attention to a speaker's eyes, and then tend to shift their attention to a speaker's mouth when listening to a talking face (Lewkowicz & Hansen-Tift, 2012). The mouth-over-eyes preference presumably supports infants in perceiving the linguistic cues of their native language(s) (Lewkowicz & Hansen-Tift, 2012). The amount of time that infants spend orienting their attention to a speaker's mouth over the eyes also predicts their later language development (Tenenbaum et al., 2014; Tsang et al., 2018). In comparison to monolingual-raised infants, bilinguals look longer at a speaker's mouth than the eyes (Pons et al., 2015; see also Ayneto & Sebastián-Gallés, 2017). By 8-months, bilingual infants are also more likely than their monolingual counterparts to succeed at distinguishing—just by watching silent talking faces—when a speaker switches to speaking another language (Sebastián-Gallés et al., 2012; Weikum et al., 2007). At 24-months, bilingual-learning toddlers are better able than monolinguals to retain a newly learned word in a fast mapping task, with the strength of the bilinguals' performance correlated with the amount they look to the mouth of the talking face (Weatherhead et al., 2021). These findings suggest that bilingual-raised infants are utilizing attentional orienting abilities at an earlier age and to a greater extent than monolingual-raised infants, and possibly doing so to exploit visual cues and detect the linguistic features linked to each of their languages.

The greater number of linguistic features in bilingual environments, along with the need to track those features separately for each language, may create an additional demand for attentional orienting processes during language acquisition. The Bilingual Adaptation hypothesis suggests that bilingual environments enhance domain-general cognitive functions and these improved abilities stem from dual-language use (Bialystok, 2015, 2017; see also Kroll & Bialystok, 2013). Several studies report that as early as 6 months of age, bilingual-raised infants perform better than monolingual-raised infants on memory generalization (Brito & Barr, 2014), encoding and recognition (Singh et al., 2015), and inhibitory control (Comishen et al., 2019; Kovács & Mehler, 2009, 2009ab). Until recently, most contradictory findings on the "bilingual cognitive advantage" were exclusively with older (speaking) children and adult samples (e.g., Antón et al., 2014; Hilchey & Klein, 2011; Nichols et al., 2020). New evidence with larger infant samples (D'Souza et al., 2020; Kalashnikova et al., 2020) failed to replicate the bilingual advantage previously seen with infants on inhibitory control (Comishen et al., 2019; Kovács & Mehler, 2009a; 2009b). However, the new evidence does suggest that bilingual-learning infants disengaged from stimuli and shifted their attention faster than monolinguals; both abilities are associated with attentional orienting processes (D'Souza et al., 2020). One possibility is that bilingual infants' increased reliance on attentional orienting during language acquisition (e.g., increased focus on the mouth) crosses the linguistic domain into the non-linguistic domain, and in accordance with the Bilingual Adaptation hypothesis, bilingual-learning infants may show advanced performance in attentional orienting, particularly of visual events.

The vast majority of the work on attentional orienting is in the visual modality; it assesses how visuo-spatial events engage and shift the participant's attention across their visual field (Petersen & Posner, 2012). To test the Bilingual Adaptation hypothesis, the present study employed a simplified version of a spatial cueing task, in which infants are briefly shown a cue either on the center-left or center-right side of a visual display and then a Target object either in the same location (valid trials) or on the opposite side of the screen (invalid trials) at which the cue originally appeared. This spatial cuing procedure is utilized as a measure of covert attention (Hood, 1993, 1995; Johnson, 1990; Posner, 1980; Posner & Cohen, 1984; Richards, 2000, 2001, 2005). Covert orienting of attention occurs when sensory information is processed regarding a peripheral location in the visual field without the individual having moved their eyes (e.g., peripheral cue location; Hood, 1993; Richards, 2000, 2001, 2005). Developmentally, infants' eye movements begin as reflexive during the first months of life (exogenous attention), and become more goal-oriented (endogenous attention) at 4 months (Johnson, 1990, 1995).

Little is known about the developmental and functional nature of the attentional orienting system during the first year of life. Using event-related potentials (ERP), Richards (2000, 2001, 2005, 2008) found that, similar to adults, three to 6 months old infants engage the posterior attention system. The brain regions involved in the posterior attention system include the parietal cortex, pulvinar, superior colliculus, and fontal eye fields (Posner, 1995; Posner & Petersen, 1990; Rothbart & Posner, 2001). With age, infants show an increasing P1 component and this is likely due to a more mature parietal cortex and frontal eye fields involving endogenous attention (Richards, 2000, 2001, 2005). Crucially, electrophysiological recording is limited in its spatial resolution in comparison to hemodynamic imaging methods. Thus, the underlying cortical systems for attentional orienting in the infant brain remain largely unknown, including whether these networks are enhanced due to early bilingual environments.

There is growing evidence that bilingualism alters the brain structures and networks for dual-language processing, as well as domain-general cognitive functions that support dual-language use (e.g., Pliatsikas & Luk, 2016, 2020). For instance, monolingual and bilingual children (7-12 years-old), who completed a non-verbal attentional control task showed differences in brain activity in the frontal lobe (Arredondo et al., 2017). Monolingual children engaged right frontal regions, as seen previously with adults, while bilingual children engaged left frontal "language" regions. Bilinguals' left frontal activity was also related to second-language competence; those who had greater competence showed reduced activation (Arredondo et al., 2017; see also Costumero et al., 2015; DeLuca et al., 2020; Garbin et al., 2010; Rodriguez-Pujadas et al., 2013). It remains unknown, however, whether brain differences could emerge for attentional orienting during the first year of life when preverbal infants are only beginning to distinguish linguistic cues and recognize words in their native language(s). Several studies report that bilingual experience is associated with changes in infant brain structure, function, and connectivity during language processing (Ferjan Ramírez et al., 2017; Garcia-Sierra et al., 2016; Petitto et al., 2012). Thus, one hypothesis is that any differences in the brain among bilinguals and monolinguals are specific to the language domain (e.g., Arredondo et al., 2019; García-Pentón et al., 2014; Marian et al., 2014; Pierce et al., 2015), and would not cross over to the non-linguistic domain. The goal of the present research is to provide a more complete description on whether bilingual environments alter task performance and underlying brain systems of non-linguistic attentional orienting, during a period of rapid brain development and language acquisition.

1.2 | The present research

Attentional processes show dramatic development during the first year of life, but continue their development steadily through childhood and into young adulthood (Colombo, 2001; Oakes & Amso, 2018). The present study investigates whether early bilingual experience alters the development of attentional orienting mechanisms and their functional cortical organization in the preverbal infant brain. We used an infant-version of a visuo-spatial cueing task to assess attentional orienting (Hood, 1993; Posner, 1980; Richards, 2000, 2001, 2005; Ross-Sheehy et al., 2015). We employed functional near-infrared spectroscopy (fNIRS) to measure changes in cortical activation among bilingual-learning and monolingual-learning infants at 6-months and 10-months of age.

In accordance with the Bilingual Adaptation framework, we hypothesized that bilinguals may outperform monolinguals. Alternatively, bilingual- and monolingual-learning infants may not show task performance differences during a non-linguistic attentional orienting task. The neural correlates of bilingual effects on attentional processes during the first year of life remain largely unexplored. Prior work investigating differences on cognitive control (attentional and inhibitory) among bilinguals and monolinguals has focused on speaking children and adults, thus the present neuroimaging work is largely exploratory in nature. Nevertheless, below we provide several plausible hypotheses based on prior research with adults and children: First, neural responses of the infant brain may mirror those observed in the mature attentional system, and thus infants (regardless of bilingualism) will show brain activity in frontal and parietal cortical regions (Colombo, 2001; Corbetta & Shulman, 2002; Johnson, 2002; Oakes & Amso, 2018; Petersen & Posner, 2012; Richards, 2008). Alternatively, it is possible that a mature cortical network (frontal and parietal brain activity) may emerge later in development (at 10-months) rather than earlier (at 6-months). Specific to the bilingual experience, prior evidence from older bilingual samples (e.g., Arredondo et al., 2017) also lead us to hypothesize that monolingual and bilingual infants may show different patterns of cortical brain organization for attentional orienting, and these patterns may emerge in the frontal lobe. Furthermore, these patterns may be associated with measures of bilingualism (such as proportion of dual-language exposure, dual-language mixing) and/or better task performance. Alternatively, differences in performance and brain activity between bilingual- and monolingual-learning infants may not emerge at either age.

2 | METHOD

2.1 | Participants

Participant criteria included: (a) meeting either the monolingual (i.e., exposure to a primary language for at least 90% of their lifetime) or the bilingual language criteria (i.e., exposure to a primary and secondary language for at least 20% in their daily life) as recommended by prior infant research (Byers-Heinlein, 2015; Byers-Heinlein et al., 2019), (b) completion of the first four blocks in the task to ensure sufficient data for data analysis, and (c) gestation at ≥37 weeks with no history of vision or health problems. Families were recruited from advertisements in Facebook, and from the University of British Columbia Early Development Research Group database which recruits new parents at a maternity ward (in Vancouver, BC, Canada) at the time of the infant's birth.

Forty-nine 6-month old infants (age range: 5-months, 18-days to 6-months, 22-days; 20 females, 29 males) were included in the final sample: of which 24 were being raised bilingual and 25 monolingual from birth. Forty-four 10-month old infants[1] (age range: 10-months, 1-day – 11-months, 9-days, 22 females, 22 males) were included in the final sample: of which 20 were being raised bilingual and 24 monolingual since birth. See Table 1 for parents' demographics. An additional 16 6-month olds and 13 10-month olds were tested, but excluded from analysis due to poor signal quality, a large number of motion artifacts contaminating the fNIRS data, and/or more than 50% of fNIRS channels deemed unreliable (see below for details).

2.2 | Procedure

Infants were tested in a dimly lit, sound-attenuated room at an infant laboratory. Infants underwent fNIRS brain imaging while seated on

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[1] Five bilingual and seven monolingual infants from the 6-months old sample returned for a second visit at 10-months.

TABLE 1 Demographic information, average (standard deviation) for task performance, analysis information, and language exposure measures, for 6- and 10-month old infants

	6-month old		10-month old	
	Monolinguals	Bilinguals	Monolinguals	Bilinguals
Demographics: Parents' education[a]				
High school education	4.00%	4.17%	12.50%	2.50%
Some college or trade degree	30.00%	20.83%	31.25%	17.50%
Bachelor's degree	28.00%	37.5%	25.00%	40.00%
Master's degree	26.00%	28.83%	12.50%	15.00%
Doctoral/professional degree	12.00%	12.5%	18.75%	20.00%
Work Status: Parents' education[b]				
Full time (incl. paid temp leave)	82.00%	83.33%	83.33%	65.00%
Part time	10.00%	4.17%	8.33%	10.00%
Student, stay-at-home, unemployed	8.00%	8.33%	8.33%	20.00%
Demographics: Parents' ethnic/racial descent[c]				
European	64.00%	27.08%	72.92%	25.00%
Asian	22.00%	50.00%	22.92%	50.00%
Other	10.00%	14.58%	0.00%	15.00%
Attentional Orienting Task Performance				
Congruent accuracy (%)	88.08 (10.04)	91.69 (5.97)	90.01 (10.40)	91.99 (7.04)
Congruent latency (ms)	239.04 (36.52)	239.45 (50.75)	157.88 (34.97)	180.50 (52.92)
Incongruent accuracy (%)	73.51 (14.31)	78.10 (14.35)	54.90 (22.62)	56.63 (24.97)
Incongruent latency (ms)	343.00 (48.52)	342.11(37.65)	321.93 (65.40)	317.44 (66.63)
Data Analysis Information[d]				
Total trials analyzed	54.36 (8.24)	53 (10.07)	46.04 (12.13)	48.10 (11.92)
Congruent trials	21.45 (5.83)	22.38 (5.06)	20.29 (6.15)	21.50 (6.27)
Incongruent trials	19.14 (5.58)	20.38 (6.51)	17.92 (5.76)	20.65 (6.82)
Trials removed	14.68 (8.55)	10.92 (7.77)	8.63 (5.68)	6.65 (5.34)
Primary language exposure (%)	98.64 (2.10)	64.66 (10.13)	98.59 (2.54)	64.10 (10.95)
Language mixing score	–	4.00 (1.50)	–	4.54 (1.61)

Notes. .

[a] Proportions include all responses, including those who chose not to respond. In the bilingual sample, two parents in the 6-month old sample and two parents in the 10-month old sample chose not to respond.

[b] Proportions include all responses, including those who chose not to respond. In the bilingual sample, four parents in the 6-month old sample and four parents in the ten-month old sample chose not to respond. In the monolingual sample, two parents in the six-month old sample and two parents in the 10-month old sample chose not to respond. In the Other racial/ethnic category, parents reported African, Aboriginal, Arab, Latin American backgrounds, and Pacific Islander.

[c] Proportions include all responses, including those who chose not to respond. In the bilingual sample, two parents in the 6-month old sample and two parents in the 10-month old sample chose not to respond.

[d] Number of trials that were analyzed for performance and fNIRS analysis, as well as trials that were removed for overt attention (looks where the child looked away from the screen, never shifted to the Target object, or shifted their gaze to a direction prior to onset of the Target object).

their parent's lap. The infant faced a computer monitor at an approximate distance of 65-cm. The parent wore opaque glasses to reduce bias. During testing, a baby lullaby song (with tones, no spoken language) played in the background at 50-db to soothe the infant. After the testing session, parents completed language and demographic reports. At the end of their visit, infants received an honorary degree certificate, a lab newsletter, and a small gift (baby t-shirt) as a thank you for their participation.

2.3 | Measures: parent reports

2.4 | Demographics

Parents reported on their child's health, birth weight, sex, and gestational age. Parents also reported their level of education (ranging from primary school to professional degree), racial or ethnic background, and work status (full-time employee, part-time, student, stay-at-home parent, and/or on paid temporary parental leave).

2.5 | Language and ethnic background questionnaire

Modified from Bosch & Sebastián-Gallés, 1997; see also Orena et al., 2019. Parents completed a one-on-one questionnaire with the experimenter, in which they reported on their infant's typical daily and weekly language exposure in the months following birth until the testing date; these included information about speakers who spent significant time with the child (e.g. at home, daycare, library, playgroups). This assessment thus allowed a calculation of how often each infant was exposed to English and other languages.

2.6 | Language mixing scale (Byers-Heinlein, 2013)

Using a seven-point Likert scale (1 = very true, 7 = not at all true), parents reported how frequently they switched languages in the same sentence, when speaking to their child. A total of four items were presented and averaged for data analysis. Sample items include, "I often start a sentence in English and then switch to speaking [Other language]", "I often borrow an English word when speaking [Other language]" (Cronbach's alpha = .75).

2.7 | Non-linguistic spatial cueing task

Infants completed a spatial cueing attention task (Hood, 1993; Posner, 1980; Richards, 2000, 2001, 2005; Ross-Sheehy et al., 2015). For each trial, an attention getter (i.e., a yellow smiley face) was displayed (1000-ms) to focus the infant's gaze to the center of the screen. Then, a cueing asterisk appeared (150-ms), either on the center-left or center-right side of a visual display. A brief delay period followed (100-ms), in which a blank screen was presented. Finally, a Target image was displayed (1500-ms) either in the same location as where the cue originally appeared (Valid condition) or on the opposite side of the screen (Invalid condition); see Figure 1A.

The task employed a blocked design consisting of 12 experimental blocks, of which half were Valid and the other half were Invalid. Blocks were pseudo-randomized, such that the first four blocks always included two blocks of each condition. By this rule, infants were included in the analysis if they completed at least the first four blocks, and the NIRS data were free of significant motion artifacts (as detailed below). Each block consisted of five trials, and was comprised of either only Valid or Invalid trials. The side of the cue and target image was pseudo-randomized, and no more than three trials appeared on the same side of the screen. Each trial lasted for 2,750-ms, and each block lasted approximately 14-s. A 13-s resting period, in which infants watched a spinning waterwheel, was included before and after each block. The resting period was included to allow the hemodynamic response to return to baseline. The total length of the task was approximately 5½-min.

2.8 | Stimuli and apparatus

The task was presented using SMI Experiment Suite 360 software on a Dell Precision laptop, which was connected to a 22″ LCD color display monitor. A SONY AX33 4K Handycam camcorder was placed either on the top or bottom of the monitor screen to record the infants' eye movements and looking behavior in real time. Similar to Ross-Sheehy et al. (2015), all events were presented on a grey background (RGB:136,136,136). Targets consisted of six colorful objects: a yellow banana, a red shoe, a pink Sippy cup, a yellow rubber ducky, a cookie, and a ball. One object was presented in all five trials for a Valid block and for an Invalid block.

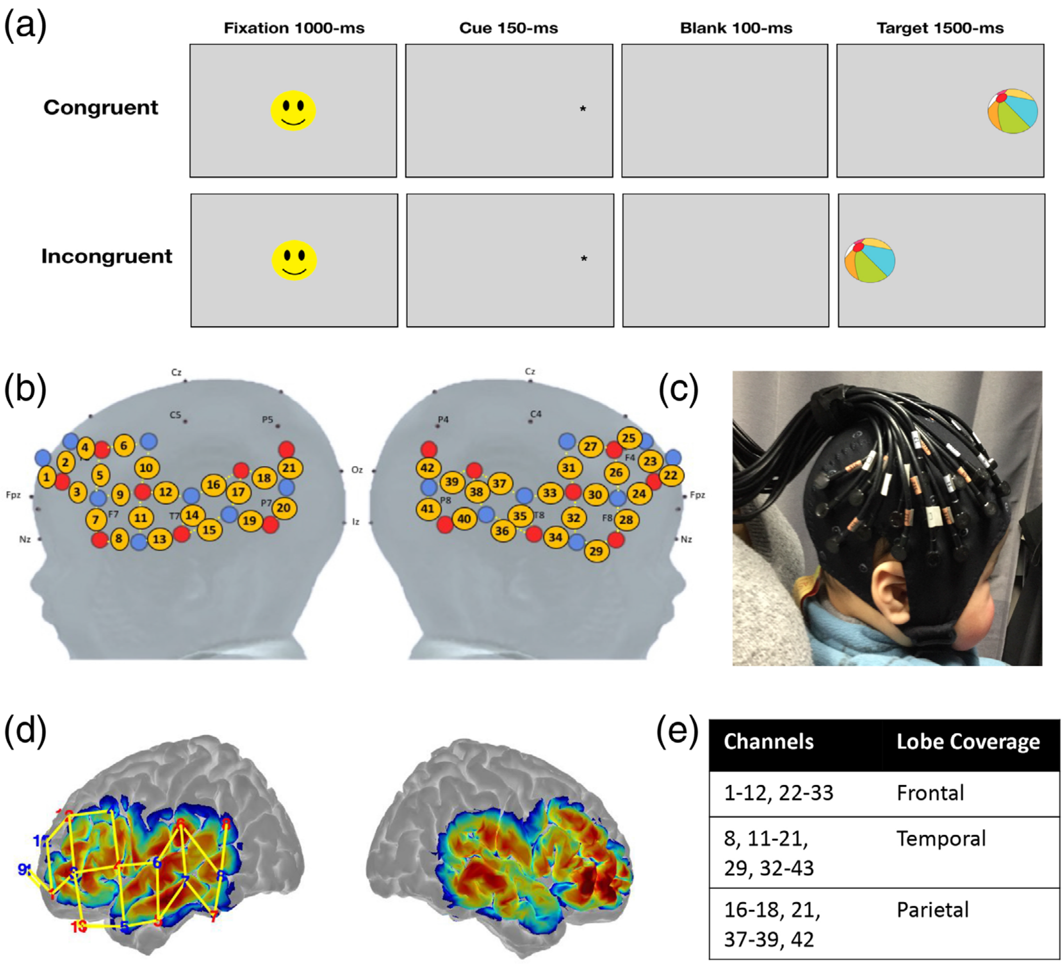
2.9 | Gaze coding

The coding guidelines were modeled after Richards (2001, 2005) and Ross-Sheehy et al. (2015) in which infants' ability to shift their gaze to the side of the Target image served as a measure of orienting attention. The videos were captured at a rate of 30 fps or 33-ms per frame. Each trial was coded for latency in directional response (center, left, right, away).

First, each trial was coded for whether the infant was looking to the center of the screen when the cue first appeared. During this portion of the coding, a trial was removed from the analyses, if the infant's eyes were not centered or were closed when the cue was first displayed, including if the infant looked away or their head was turned away from the screen during cue display, and/or if the infant was crying. Next, each trial in which the infant was looking to the center of the screen was coded for a directional response of the first gaze shift. During this portion of the coding, trials were coded as "left" or "right."

If the infant shifted their fixation to the target object following target onset, the trial was marked as correct and reaction time was calculated for the trial. In the case that the infant produced a gaze shift to the opposite side (left or right) of the object following target onset, the trial was marked as incorrect. However, in the case that the infant's first gaze shift was incorrect, the second gaze shift was also coded and reaction time for the (correct) second shift was calculated. Trials were included in the fNIRS analysis if the first or second gaze shifts (following target object onset) were to the correct side. Summaries for gaze shift accuracy (first gaze shifts) and response times were calculated and analyzed. See Table 1.

Behaviors in which the infant does not shift their gaze (left or right) to a side of the screen following the onset of the Target object can be associated with inattention. If the infant did not shift their fixation from the center of the screen following onset of the target object, the trial was marked as an error and removed from the fNIRS and reaction time analysis. In addition, if the infant shifted fixation to the cue (or cue location) prior to cue offset or to onset of the target object, then the data for the trial was marked as an error and removed from fNIRS and



Channels	Lobe Coverage
1-12, 22-33	Frontal
8, 11-21, 29, 32-43	Temporal
16-18, 21, 37-39, 42	Parietal

FIGURE 1 (a) Example trials for the attentional orienting task: Valid trial on top row, Invalid trial on bottom row. (b) NIRS probe configuration. Head image on the left panel is a representation of the probe placed on the left hemisphere, head image on the center panel is a representation of the probe placed on the right hemisphere. Red circles = sources/emitters of light, blue circles = detectors, orange circles = channels (connections between sources and detectors). Head image was designed on AtlasViewer GUI following Aasted *et al*. (2015), using a 7½ month-old MRI infant template from the NIH Pediatric MRI database (NIHPD; Almli *et al*., 2007; Richards *et al*., 2016). (c) Image on the right panel is an image of a 6-month old infant wearing the NIRS cap and probes. (d) Monte-Carlo simulation of the near-infrared light propagation in a 6-month old infant brain (Aasted *et al*., 2015). (e) Summarized table with approximations of the brain lobes that are likely measured by each channel. Appendix A includes a complete detailed list of channel approximations by lobe and region for each channel in a 6-month old and 10-month old infant probe

behavior analysis. If the infant looked away from the screen (e.g., to look at the parent) following a fixation from the center of the screen (i.e., infant does not shift to the left or right side of the screen), the trial was marked as an error and removed from fNIRS and reaction time analysis. Summaries for overt attention behaviors are reported in Table 1 as trials removed.

Three trained coders were randomly assigned videos for coding directional response during the first gaze shift (average inter-rater reliability was high = 97.46% for the 6-month old sample and 95.6% for the 10-month old sample). One of the three coders reviewed all videos (following feedback from reviewers) ensuring that only trials in which the participant was facing centered were considered in the analysis, and that second gaze shifts were also coded for directional response. Average reaction time for the correct gaze shift, and proportion of correct responses were computed for each condition and for each participant. Videos from three monolingual infants were deemed inadmissible for coding due to equipment failure, with the camera not focusing on the infant's face.

2.10 | Neuroimaging method and procedure

To measure hemodynamic brain responses, we used the LED-based NIRScout 16 × 16 functional Near-Infrared Spectroscopy (fNIRS) system by NIRx Medical Technologies LLC with 760 and 850 nm wavelengths. The data were sampled at 3.91-Hz. Prior to data collection, we measured the infant's head circumference, nasion-to-inion, and ear-to-ear. A black polyester-cloth EasyCap (a 42-cm, 44-cm, 46-cm, or 48-cm EEG head cap) was chosen based on the participating infant's head circumference, to hold the fNIRS probes during data collection. The probes included eight near-infrared lights and eight detectors per hemisphere. The source and detector channels were spaced 2-cm apart for the 42-cm and 44-cm cap, and 2.25-cm apart for the 46-cm and 48-cm cap. This slightly larger source-detector distance is scaled to head-size and therefore compensates for the slightly larger distance from the optodes on the scalp and the underlying cortical tissue. The probe yielded a total of 42 data channels (21 per hemisphere). Sources and detectors were mounted onto slit openings in the cap, prior to placing them on the infants' head for data collection. The probe configuration was designed to measure hemoglobin change (a correlated measure of brain activity) in bilateral frontal and posterior regions (see Figure 1(B-E) and Supplementary Information – Appendix A).

2.11 | NIRS data preprocessing and analysis

Data were preprocessed using Homer2 v2.3, a MATLAB-based GUI retrieved from the NITRC database (Huppert et al., 2009). First, the data went through a quality check, in which channels with very high or low optical intensity readings were excluded (using the enPruneChannels function set at 1e-03 to 1e+07, SNR threshold = 2). During this examination, participants whose data included more than 50% of channels with poor signal quality were excluded from further analysis. For the remaining participants, channels outside of this range were excluded from group data analysis.

The following preprocessing steps were carried out in the final dataset, as recommended for correcting motion artifacts in fNIRS infant data (Di Lorenzo et al., 2019). First, the raw time course data were converted into units of optical density (OD) change. The OD data went through motion artifact detection and correction using wavelet filtering (parameter value, iqr = 0.5). Next, the OD data went through a second quality control step for integrity and presence of motion artifacts in the signal, on a channel-by-channel basis (Scholkmann et al., 2010), to reject the remaining uncorrected motion artifacts in the data. Motion artifacts were defined as signal changes exceeding an amplitude greater than .5 mmol x mm threshold and/or a standard deviation of 15, over a period of a second (tMotion = 1, tMask = 1, STDEVthresh = 15, AMPthresh = .5). Trials with remaining motion were discarded if these appeared 2 s prior and 10 s after the motion artifact (tRange = −2.0 10.0). The remaining artifact-corrected OD data were then high and low band-pass filtered (hpf = .01 and lpf = .8). The OD data were then converted into hemoglobin concentration data using the modified Beer-Lambert law, yielding oxygenated (HbO) and deoxygenated hemoglobin (HbR) values.

To examine hemoglobin response, a General Linear Model (GLM; Barker et al., 2013; Poline & Brett, 2012) ordinary least squares (OLS) fit was applied, that modeled the dual-gamma canonical hemodynamic response function ranging from 0 to 16-s following stimulus onset. The GLM beta values for the Valid and Invalid conditions were estimated between 4–10 s, which incorporates the timing of the rise and peak of the response function. Next, a permutation analysis (Maris & Oostenveld, 2007) was conducted to identify clusters of channels in which significant activity (per hemoglobin) differed between Valid and Invalid conditions (at $p < .05$). Permutation analyses define regions of interest (ROIs) in a non-arbitrary and data-driven manner; this method is typical for infant neuroimaging data (Ferry et al., 2016; Benavides-Varela & Gervain, 2017; Kabdebon & Dehaene-Lambertz, 2019; Mahmoudzadeh et al., 2013; May et al., 2018). The cluster-based permutation required at least one other neighboring channel, and was implemented over 1000 simulations of the data. Given that our hypothesis is based on group differences, we carried out separate permutations for each language group and age group. Oxygenated hemoglobin (HbO) is the most robust signal of brain activation when using fNIRS with infants (Aslin, 2012; Gervain et al., 2011), therefore we present HbO in the analysis below (see Supplementary Information Appendix B for HbR results). Following the permutation analysis, we averaged the signal from significant channels making up the cluster, to compare brain activity between the conditions (Invalid versus Valid) within these regions. In the case that clusters in close proximity emerged across the two groups (which is to be expected if there is no effect of bilingualism), we planned between-sample t-tests to compare whether differences in brain activity emerge between the groups. Lastly, correlational analyses will help determine whether brain activity is associated with task performance (accuracy of the first gaze shift, and reactive latencies in each condition), proportion of the dual-language exposure, and parents' dual-language mixing reports.

3 | RESULTS

3.1 | Task performance

A 2 × 2 × 2 mixed-design ANOVA was performed on mean accuracy of the first gaze shift, with language group (monolingual, bilingual) as a between-participant factor, age group (6-months, 10-months) as a between-participant factor, and condition (Valid, Invalid) as a within-participant factor. The analysis revealed a main effect of condition, $F(1,86) = 113.21$, $p < .001$, $\eta p2 = .57$, showing that infants were more accurate during Valid trials (M = 90.43%, SD = 8.60) than Invalid trials (M = 66.02%, SD = 21.75). The analysis also revealed a main of effect of age, $F(1, 86) = 18.77$, $p < .001$, $\eta p2 = .18$, showing that younger infants (M = 82.93%, SD = 13.63) were more accurate than older infants (M = 73.30%, SD = 25.01). Finally, the analysis revealed a condition by age group interaction, $F(1,86) = 20.83$, $p < .001$, $\eta p2 = .20$, showing that 6-month-old infants were more accurate during Invalid trials (M = 75.90%, SD = 14.36) than the 10-month-old infants (M = 55.69%, SD = 23.45; $p < .001$), while both age groups performed similarly during Valid trials (6-months M = 89.96%, SD = 8.28, and 10-months M = 90.91%, SD = 8.99; $p = .60$). There was no main effect of language group or any other interactions, $p > .05$. See Table 1 for group performances.

A similar 2 × 2 × 2 mixed-design ANOVA was performed on mean reactive latencies for accurate trials (first and second gaze shifts). The analysis revealed a main effect of condition, $F(1,86) = 311.06$, $p < .001$, $\eta p2 = .78$, showing that infants were faster during Valid trials (M = 204.50 ms, SD = 56.87) than Invalid trials (M = 331.46 ms, SD = 55.74). The analysis also revealed a main of effect of age, $F(1, 86) = 35.48$, $p < .001$, $\eta p2 = .29$, showing that older infants

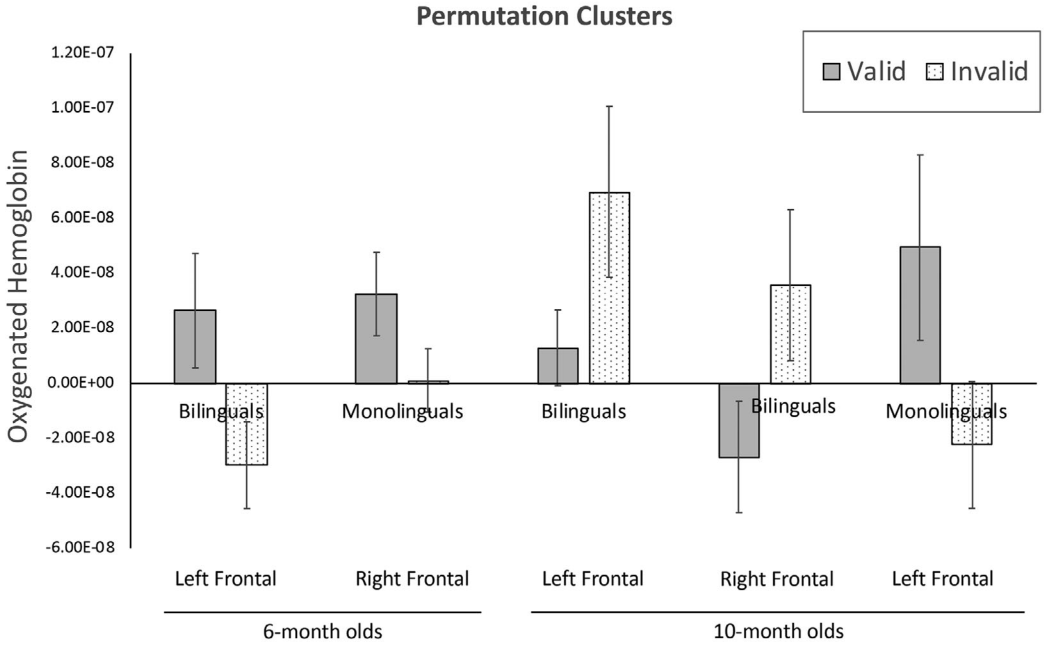


FIGURE 2 Increasing Oxygenated hemoglobin (HbO) activity for significant clusters that revealed condition differences for each group

were faster (M = 244.02 ms, SD = 94.46) than younger infants (M = 290.89 ms, SD = 67.50. Finally, the analysis revealed a condition by age group interaction, *F*(1, 86) = 10.75, *p* = .002, ηp2 = .11, showing that 10-month-old infants were faster during Valid trials (M = 168.16 ms, SD = 44.96) than the 6-month-old infants (M = 239.25 ms, SD = 44.03; *p* < .001), while both age groups performed similarly during Invalid trials (6-months M = 342.53 ms, SD = 42.70, and 10-months M = 319.89, SD = 65.22; *p* = .054). There was no main effect of language group or any other interactions, *p* > .05. See Table 1.

3.2 | Neuroimaging

3.3 | Bilingual 6-month-olds

On average, 1–2 channels (M = 1.58; SD = 2.34, range = 0-8) were removed per participant due to poor signal quality (see details above). The permutation analysis revealed one cluster of channels in the left frontal region (channels 4 and 5) showing increasing HbO for Valid trials relative to Invalid trials (see Figure 2); *t*(23) = 2.08, *p* = .049, d = 0.42. Bilinguals' brain activity for Invalid trials showed a trend with parents' dual-language mixing reports; *r*(20) = .42, *p* = .05 (see Figure 3). Specifically, infants showed greater HbO activity in the left frontal region during Invalid trials when their caregiver reported less likelihood of dual-language mixing. There was also a significant correlation between brain activity and reactive latencies for Valid trials; *r*(22) = -.45, *p* = .029. That is, bilingual infants who performed faster during Valid trials also showed greater HbO activity, while infants with slower reactive latency showed less HbO activity. There were no other significant correlations.

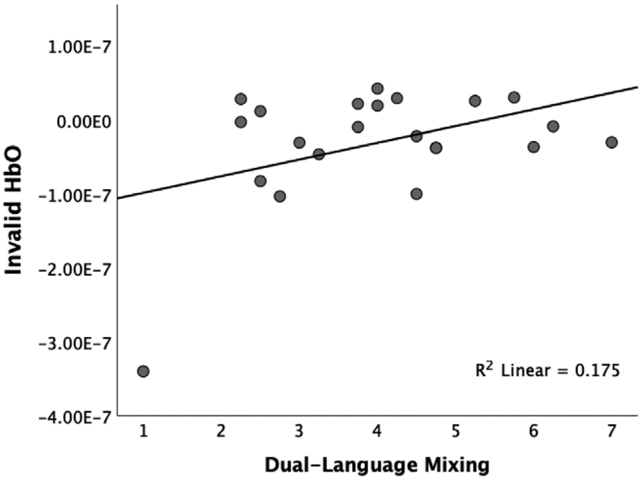


FIGURE 3 Correlation for bilingual 6-month-old infants' left frontal region. Specifically, there is a positive trend between parents' reporting of how often they mix both languages when speaking to their child (1 = very true, 7 = not at all true) and infants' oxygenated hemoglobin (HbO) during Invalid trials

3.4 | Bilingual 10-month-olds

On average, 1–2 (M = 1.30; SD = 2.05, range = 0-8) channels were removed per participant due to poor signal quality. The permutation analysis revealed two clusters of channels, one in left frontal region (channels 2, 3, 10, and 11) and the other in a right fronto-temporal region (channels 26, 27, 33, and 34). Both clusters showed increasing HbO for Invalid trials relative to Valid trials (Figure 2); *t*(19) = −2.48, *p* = .023, d = 0.55 and *t*(19) = −2.34, *p* = .030, d = 0.52, respectively). There were also significant correlations between HbO brain activity in the right cluster and performance during Valid trials; $r(18) = -.49$, $p = .03$ for accuracy and $r(18) = .57$, $p = .009$ for reactive latency. That is, bilingual infants who were more accurate and performed faster during valid trials showed less HbO activity in right anterior regions, while infants who committed more errors and had a slower reactive latency showed greater HbO activity during valid trials. There were no other significant correlations.

3.5 | Monolingual 6-month-olds

On average, 1–2 channels (M = 1.76; SD = 2.49, range = 0-10) were removed per participant due to poor signal quality. The permutation analysis revealed one cluster of channels in the right frontal region (channels 22 and 23) showing increasing HbO for Valid trials relative to Invalid trials (Figure 2); $t(24) = 2.01$, $p = .05$, d = 0.40. There were no significant correlations ($p > .05$), nevertheless brain activity and reactive latencies for Valid trials showed a positive trend; $r(20) = -.39$, $p = .07$.

3.6 | Monolingual 10-month-olds

On average, 1–2 (M = 2.00; SD = 3.23, range = 0-10) channels were removed per participant due to poor signal quality. The permutation analysis revealed one cluster of channels in the left fronto-temporal region (channels 2, 3, 5, and 13) showing increasing HbO for Valid trials relative to Invalid trials (Figure 2); $t(23) = 2.87$, $p = .009$, d = 0.58. There was also a negative trend between HbO brain activity and accuracy performance during Invalid trials; $r(22) = -.40$, $p = .05$: monolingual infants who were more accurate during Invalid trials showed less HbO activity, while infants who committed more errors showed greater HbO activity during Invalid trials. Otherwise, there were no significant correlations.

3.7 | Bilingual and monolingual 6-month-olds

Amount of HbO activity in bilingual and monolingual infants was not significantly different across Valid ($t(47) = .23$, $p = .82$) or Invalid trials ($t(47) = 1.59$, $p = .12$). As a group, a significant correlation between brain activity in their respective group clusters and reactive latencies for Valid trials emerged; $r(44) = -.43$, $p = .003$. That is, infants who performed faster during Valid trials also showed greater HbO activity, while infants with slower reactive latency showed less HbO activity during Valid trials. There were no other significant correlations.

3.8 | Bilingual and monolingual 10-month-olds

Amount of HbO activity in bilingual and monolingual infants was significantly different in the left frontal region, in which bilinguals showed greater HbO for Invalid trials than monolinguals; $t(42) = -2.42$, $p = .02$. There were no significant correlations for this group.

4 | DISCUSSION

The goal of the present research was to examine whether bilingual environments enhance task performance and alter the functional cortical organization for attentional orienting in the preverbal infant brain. We investigated 6- and 10-month old bilingual- and monolingual-raised infants' task performance and brain activity during a non-linguistic orienting of covert attention task. Guided by the Bilingual Adaptation framework, we hypothesized bilinguals would outperform monolinguals; however, this hypothesis was not supported. There were no differences in accuracy and gaze shift latency performance between bilingual- and monolingual-raised infants on attentional orienting. Despite the absence of group differences in performance, we found differences in performance by age and condition effects (i.e., better accuracy and faster latency for Valid than Invalid trials). Developmental differences in performance are likely due to a more mature system for visuo-motor control in the older infants. Similar results are also seen in Richards (2000, 2001, 2005) and Ross-Sheehy et al. (2015), with younger infants showing greater accuracy than older infants during Invalid cued trials, while older infants show faster performance than younger infants.

To date, most evidence that exists on the development of attentional orienting in the infant brain relies on electrophysiological evidence and looking behavior (see Richards, 2010) and little evidence exists on functional and cortical development. Between 3 to 7 months, the attentional system shows significant development (Hood, 1995; Richards, 2002, 2003). Many speculate that it follows the progression of myelination, by engaging occipital regions at 3-months, followed by the parietal lobe at 4-to-6 months, and frontal to temporal lobes from 6-to-8 months (Deoni et al., 2011; Oakes & Amso, 2018). Developmentally, we hypothesized that infants in the present study (regardless of bilingualism) would engage a mature attentional system that includes frontal and parietal cortical regions (Johnson, 2002). The present results provide functional neuroimaging evidence supporting that infants engage frontal regions at 6-months, as previously suggested by Gilmore and Johnson (1995; Johnson, 2002). Nevertheless, the neuroimaging probe was limited in its design as it did not maximally cover the parietal lobe (see Figure 1 and Appendix A). Given that the permutation analysis seeks to group channels where significant differences between the conditions emerge, it is plausible that parietal regions would be engaged with a different probe design and/or if the task were designed to engage increasing endogenous control mechanisms and planning behavior, such as long stimulus onset asynchronies between the cue and the target object, as seen in Richards (2000, 2001, 2005).

We were also guided by prior evidence on cortical differences in the bilingual brain (Arredondo et al., 2017; Costumero et al., 2015; DeLuca et al., 2020; Garbin et al., 2010; Pliatsikas, 2020; Rodriguez-Pujadas et al., 2013), and hypothesized that the impact of early-life bilingual experience would manifest as differences in brain activity in the frontal lobe. In part, this hypothesis was exploratory in nature, since little is known on infants' cortical specialization for attentional orienting and prior work focused on cognitive control (attentional and inhibitory) with bilingual-speaking children and adults. Here we found that bilingual-learning infants showed left frontal activity while monolingual-exposed infants showed right frontal activity at 6 months. One possibility is that these results are commensurate of bilingual hemispheric differences previously shown by Arredondo et al. (2017) in which bilingual-speaking school-age children activated left frontal regions for an attentional control task, while monolingual peers activated right frontal regions. At 10-months, however, monolingual infants engaged left frontal region, and bilinguals engaged bilateral frontal regions. Thus, beginning at infancy, it is evident that bilinguals rely on left frontal regions for attentional processes. Greater HbO activity for Invalid trials by the 10-month old bilingual group (in comparison to greater HbO activity by 6-month olds and 10-month old monolinguals) is another set of evidence showing developmental differences in attentional processing by the bilingual experience. Prior work by Richards (2000, 2005) revealed that infants (between 3.5-5.5 months) distinguish between Valid and Invalid trials by showing a larger P1 ERP component for Valid than Invalid trials, and suggesting that covert orienting of attention matures early in infancy. One possibility is that dual-language environments may adapt infants' functional neural responses for orienting attention, and the correlational evidence on task performance, which we turn to next, may begin to provide support for the interaction between language and attention processes.

Patterns of brain activity were associated with infants' performance, and these varied by developmental age. As a group, 6-month old infants showed greater activity during Valid trials when they also showed faster attentional orienting to the target. At 10-months, bilinguals also showed less HbO activity during Valid trials when they oriented faster and more accurately. Less activity for Valid and greater activity for Invalid trials in 10-month old bilinguals likely suggests a shift in which managing attentional orienting to a visuo-spatial location for Valid locations requires less cognitive effort, and greater cognitive effort for Invalid locations. This notion can be supported by the monolingual 10-month olds' trend, in which infants who committed more errors showed greater HbO activity for Invalid trials while those who had better accuracy showed less HbO activity for Invalid trials. Nevertheless, the correlation in the monolingual sample approached significance ($p = .05$), and the group averaged less brain activity for Invalid trials than Valid trials and group performance was equivalent across both language groups. Future research charting developmental differences of cortical organization by variations of language environments and with larger samples remains necessary, including whether brain activity for Invalid trials changes at later ages due to greater cognitive effort.

Bilinguals' greater activity for Invalid trials—a more effortful condition of attentional orienting—at 10-months may point to adapted cortical functions of attentional orienting capabilities, which may have emerged from managing dual-language experiences. Neuroimaging studies with adults on language processing find that highly-proficient bilinguals engage the left frontal cortex when adjudicating between competing words that share phonemic sounds across languages (e.g., "pear" and "perro [dog in Spanish]"), and this brain activity is associated with better inhibitory control performance (Marian et al., 2014). In the adult brain, left frontal regions are also known to support better performance during increasingly difficult conditions for attention tasks (Swick et al., 2008). Given that bilingual infants' brain activity (at 6-months) in left frontal regions trended with parents' reporting of dual-language mixing, one possibility is that bilinguals' increasing abilities in extracting linguistic features in both of their languages (i.e., an environment with less dual-language mixing) supports a more mature specialization of this region. Nevertheless, the correlation approached significance (at $p = .05$) and was possibly driven by an outlier (see Figure 3), thus future research is needed in charting the development of attentional functions and how a bilingual environment may adapt its response.

A large body of research reviewed in Werker (2012) shows that babies growing up in a bilingual environment differentiate the languages that are spoken in their environment, track the linguistic features of each language, and keep these representations separate. Indeed, Byers-Heinlein et al. (2017) revealed that dual-language switching is not restricted to the ability to produce language. In their study, bilingual toddlers heard language switches within a sentence and recognized the switches by showing a delay in word recognition and increased pupil dilation (Byers-Heinlein et al., 2017). Their study was the first to show that bilingual toddlers monitor and control both of their languages, in a similar manner as bilingual adults, and recognize when language switches happen within a sentence. Thus, one possibility is that pre-verbal bilingual infants can process language switches and likely employ attentional mechanisms to track their languages. We also carried out a post-hoc correlation between parents' reports on dual-language mixing and proportion of dual-language exposure to explore whether those who heard less mixing in their environment were also more likely to hear a primary language to a greater extent, however, the correlations were non-significant (at 6-months: $r(20) = .33, p = .14$, at 10-months: $r(17) = .06, p = .81$). Taken together, the trend between brain activity and reports on dual-language mixing may begin to suggest that early bilingual differences in the infant brain possibly stem from the child's home environment and languages spoken by primary caretakers. Nevertheless, the small sample and the correlational nature of this work limits its interpretation; future experimental work testing this hypothesis remains necessary.

5 | CONCLUSIONS

The present study provides evidence that bilingual and monolingual learning infants show different developmental patterns in the brain for orienting of covert attention, despite having similar performances. The different variations of brain adaptation between bilinguals and monolinguals despite similarities in behavior is not the first of its kind; this has previously been shown in neuroimaging work with children and adults (Arredondo et al., 2017, 2019; DeLuca et al., 2019; Pierce et al., 2015). Importantly, this work revealed how variability in the multilingual environment adapts how the brain becomes organized as a result of early experience. These findings not only provide foundational evidence for bilingual studies, but they prompt a consideration of the variability of bilingual experience and how this variability starts from early in development (Hernandez et al., 2018; Luk & Bialystok, 2013; Pliatsikas et al., 2020).

The present work does not provide direct support for the Bilingual Adaptation hypothesis because of the similar task performance among bilingual and monolingual infants. Attentional orienting is one aspect of higher cognitive functions, and differences in performance between bilingual and monolingual populations may be evident in other more complex non-linguistic tasks. Future work investigating brain differences during a variety of more complex cognitive tasks is therefore a future goal to further test the Bilingual Adaptation hypothesis. In this future work, a number of variables that quantify aspects of bilinguals' environments should be considered, including treating bilingualism as a continuous variable in order to better understand the root of any differences. In addition, future work with bilingual infants may investigate whether these effects hold with increasing endogenous attention mechanisms and planning behavior, such as long stimulus onset asynchronies between the cue and the target object, as seen in Richards (2000, 2001, 2005).

The present study has also demonstrated that the use of fNIRS technology is well-suited for addressing questions on functional activation with infants. However, the fNIRS technology is also the source of some limitations. This is especially the case for spatial resolution, in which the present study was unable to measure activity in small cortical areas and in subcortical regions that fall beyond the range of optical signals. Moreover, fNIRS signals cannot be precisely localized to specific anatomical regions in a given infant brain because of the absence of structural MRI images of each infant in the study. The use of brain templates within and across ages cannot account for subtle individual differences in the size and relative location of these cortical regions. Nevertheless, it is reassuring that some regions of brain activity were not only reliable across infants at a given age, but overlapped across age groups (see Appendix A), as revealed by condition differences that were consistent across ages.

Another important limitation of the study is that data collection took place in Canada, a country that identifies as bilingual and in which bilingualism is not associated with lower socioeconomic status. Specifically, the sample lived in Vancouver B.C., in which 52% of the population speaks a language other than English, and approximately 30% of the city's inhabitants have Chinese heritage (StatCan, 2017). Vancouver is composed of a large middle class (controlling for any negative effect socioeconomic factors that might otherwise be present in the data), offers universal healthcare, and shares cultural beliefs that encourage linguistic diversity. Thus, the study's findings may provide a baseline comparison for future studies investigating whether bilingualism mitigates negative effects of socioeconomic factors or varies by cultural contexts or backgrounds.

In summary, brain development varies as a function of age and maturation, but more importantly, it also varies as a function of experience. Attentional orienting emerges from sensory input, and it is a key mechanism across multiple domains including language, face perception, and episodic memory (Kanwisher & Duncan, 2004). During dual-language acquisition, bilingual infants allocate their attention to linguistic cues (e.g., discriminating phonemes across languages) and audio-visual information (e.g., mouth more than eyes) to distinguish and successfully acquire their languages; such dual-language experience may alter how attentional orienting mechanisms develop in bilinguals. The present work provides evidence that bilingual brain differences are present during the first year of life. Importantly, these differences are related to the amount of dual-language mixing that infants receive from primary language speakers. These findings provide critical insight into how language experience, especially bilingualism, shapes brain plasticity during early development. This finding suggests that bilingualism is a heterogeneous experience and its impact on attentional orienting (and possibly other higher cognitive functions) likely varies across individuals.

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CONFLICT OF INTEREST

The authors certify no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

DATA AVAILABILITY STATEMENT

Data is available upon request via Open Science – osf.io/q6cbv

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