Functional Specialization for Language Processing in Inferior Frontal Regions During Early Childhood: Evidence from functional near-infrared spectroscopy individual functional channels of interest approach

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Studies Statement:

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RESEARCH HIGHLIGHTS

- Validated language localizer task in fNIRS using individual functional Channel of Interest approach, enabling reliable investigation of early language networks.
- Demonstrated a double dissociation between neural processors in inferior frontal gyrus for language and domain-general cognition (cognitive load) in children as young as 2.
- Supports early neural specialization for language processing rather than gradual emergence from domain-general networks.

Abstract

Early language acquisition represents a fundamental achievement in cognitive development, yet the neural mechanisms underlying this process remain debated. Using functional near-infrared spectroscopy (fNIRS) with an innovative functional Channel of Interest (fCOI) approach, we investigated the functional specialization for language processing in bilateral inferior frontal regions during early childhood. In two experiments involving adults (N=20) and toddlers (N=22, ages 2-4 years), participants completed language processing and cognitive control tasks. Results demonstrated early functional specialization in the language-selective region of left inferior frontal gyrus, which showed selective responses to linguistic content while remaining insensitive to cognitive demand manipulations in both age groups. However, language selectivity in the homologous right hemisphere region was present only in adults, suggesting continued development of language organization beyond early childhood. The MD regions showed complementary patterns, with right-hemispheric selectivity for cognitive control emerging early. These findings provide evidence for early neural specialization of language processing in the left hemisphere, while revealing ongoing development in right hemispheric organization. Our results support models of early language-specific neural circuits rather than gradual differentiation from domain-general mechanisms, while highlighting the protracted development of language organization.

KEYWORDS : cognitive load, development, fNIRS, language, multiple demand

Introduction

Language acquisition in early childhood represents a remarkable achievement of human cognitive development, occurring naturally through exposure without formal training (Sharp & Hillenbrand, 2008). A fundamental question in developmental cognitive neuroscience is how the brain supports early language acquisition. One of the most debated aspects of language development is whether the brain contains specialized circuits for language processing from early in life, or whether these circuits emerge gradually over development. Specifically, there are two competing hypotheses about the neural mechanisms underlying language processing in young children. One possibility is that language processing relies on domain-specific neural mechanisms from early on, suggesting an early neural specialization for language that is distinct from other cognitive functions (Chomsky, 2005; Spelke & Kinzler, 2007). Alternatively, language processing might initially emerge through domain-general cognitive processes, such as working memory and executive function, with specialized language circuits developing gradually through experience (Johnson, 2011; Karmiloff-Smith, 2015).

Studies in adults have identified two distinct neural networks potentially relevant for understanding language development: the 'core language network' and the 'multiple demand' (MD) network. The language network, which includes regions primarily in left frontal and temporal areas, shows consistent engagement during language processing with limited activation during non-linguistic tasks (Fedorenko et al., 2011; Fedorenko et al., 2024; Vigneau et al., 2006). In contrast, the MD network, comprising bilateral frontal, parietal, cingulate, and insular regions, responds to increased cognitive demands across various cognitive tasks (Duncan, 2010; Fedorenko et al., 2013). The relationship between these networks and their respective roles in language processing have been debated. Some researchers argue that language processing relies substantially on domain-general cognitive

mechanisms implemented in the MD network (Hagoort, 2014; Novick et al., 2005), while others propose more distinct functional roles (Fedorenko & Blank, 2020). Recent adult neuroimaging evidence provides insights into how these networks contribute to language processing. Despite apparent similarities between mental operations involved in language comprehension (such as memory retrieval, prediction, and structure building) and those required by other cognitive domains, the MD network's role in basic language comprehension appears more subtle than initially theorized (Blank et al., 2014; Fedorenko & Shain, 2021; Mineroff et al., 2018). By contrast, the MD network displays more robust engagement when language tasks introduce extra cognitive demands, such as retaining information in working memory or answering comprehension questions (Diachek et al., 2020; Quillen et al., 2021; Wehbe et al., 2021). This can be understood as the language network implementing core computations for linguistic structure and meaning, while MD areas are recruited when task requirements demand increased cognitive control (Fedorenko & Shain, 2021; Fedorenko & Varley, 2016). This dissociation is supported by evidence from multiple methodologies, including functional connectivity analyses (Blank et al., 2014; Paunov et al., 2019), studies of patients with focal brain lesions (Woolgar et al., 2018), and investigations using naturalistic language stimuli (MacGregor et al., 2022; Shain et al., 2020). These findings suggest that while the language network may implement certain computations on linguistic representations somewhat independently, it likely interacts with domain-general circuits in the MD network when tasks require additional cognitive control (Campbell & Tyler, 2018; Fedorenko & Varley, 2016).

While studies with adults have suggested relatively clear dissociation between language-specific and domain-general networks, documenting this dissociation in adults alone is insufficient for understanding the origin of uniquely human cognitive abilities. Several competing developmental trajectories could lead to the same adult organization:

cortical regions might start as domain-general and gradually specialize through competitive interactions (Johnson, 2011), with language regions initially participating in broader cognitive functions like working memory before gaining linguistic selectivity. Alternatively, domain-general processes might bootstrap the development of language abilities (McMullen & Saffran, 2004; Rakison & Yermolayeva, 2011; Saffran & Thiessen, 2007). A third pattern could be that there is an innate proto-organization of domain-specificity. Understanding how and when these networks dissociate during development is therefore critical for distinguishing between these possibilities and illuminating the origins of human cognitive architecture. Recent fMRI studies have demonstrated that this selective and specific language network is already established in children as young as 4 years of age, showing adult-like functional dissociation from domain-general cognitive processes (Hiersche et al., 2024; Schettini et al., 2023). However, due to the methodological constraints of fMRI, particularly the requirement for participants to remain still, the emergence and organization of these networks in even younger children remains largely unexplored. To the best of our knowledge, there is no existing exploration of the double dissociation of language and domain-general cortex in children younger than 4.

To address this gap, we employ functional near-infrared spectroscopy (fNIRS), which allows measurements while participants move relatively freely. fNIRS uses absorption of near-infrared light between emitters and detectors placed against the scalp to measure changes in oxygenated and deoxygenated hemoglobin concentrations that reflect neural activity (Gervain et al., 2011). This method has been successfully used to study early language processing in infants. Several studies have demonstrated that newborns already show specialized neural responses to speech in temporal and frontal regions (May et al., 2018; Pena et al., 2003; Sato et al., 2012), while later work has suggested that language-specific responses continue to develop throughout infancy (Minagawa-Kawai et al., 2011). While

these studies provide evidence for differential neural responses to speech versus reversed or degraded speech stimuli, they have not fully characterized the functional architecture of language processing in the developing brain. Specifically, showing greater activation to speech than non-speech does not establish whether these regions are specialized for language processing or serve more domain-general functions that happen to be engaged during speech processing. As Kanwisher (2010) emphasizes, in studies of functional specificity, demonstrating true specialization requires not only evidence of preferential responses to one category but should also test whether regions are exclusively engaged in processing that category. For example, the right temporoparietal junction (rTPJ) activates selectively when thinking about others' thoughts, but not during closely related tasks like processing physical appearances or even other mental states such as hunger or pleasure. In additional to these conceptual challenges, mapping fNIRS measurement channels to specific cortical regions presents several methodological challenges, particularly in developmental populations. These challenges arise from anatomical variability in the relationship between external landmarks and underlying cortical structures, developmental variations in head size affecting measurement array coverage, and practical constraints in precise optode placement (Powell et al., 2018). Moreover, even when measurement channels can be accurately mapped to specific anatomical regions, this anatomical localization does not guarantee functional correspondence. A given anatomical region often contains multiple functionally distinct sub-regions that vary in size and precise location across individuals (Amunts et al., 1999; Wang et al., 2015).

To overcome these methodological challenges, we employ a functional Channel of Interest (fCOI) approach for analyzing fNIRS data (Powell et al., 2018). Unlike traditional approaches, which assume that measurement channels correspond to the same cortical regions across participants, the fCOI method identifies channels of interest by examining

each individual's functional activation patterns. This approach recognizes that the same channel position relative to scalp landmarks may measure different cortical regions across individuals due to variations in array placement, head size, and the relationship between surface landmarks and underlying cortical anatomy - a particularly important consideration in developmental research. The fCOI approach offers several key advantages for developmental studies (Liu et al., 2023): it accounts for individual variability in brain anatomy and functional organization (Kabdebon et al., 2014), reduces noise from neighboring regions with different functional profiles, and provides a principled way to limit multiple comparisons while maintaining statistical power. This approach has been validated across multiple domains of cognitive development, including face processing and theory of mind (Hyde et al., 2018; Powell et al., 2018; Richardson et al., 2021).

In the present study, we investigate the functional organization of language and domain-general networks in toddlers aged 2-4 years using fNIRS with the fCOI approach. Following Kanwisher (2010)’s framework for establishing functional specificity, our experimental design carefully contrasts responses across cognitive domains rather than simply identifying regions that respond preferentially to language. We focus on bilateral inferior frontal gyrus (IFG) regions given their well-documented heterogeneity in adult neuroimaging studies (Fedorenko & Blank, 2020). Specifically, prior research has established that Broca's area within the left IFG contains two functionally distinct regions: a language-selective region responding specifically to linguistic input, and a domain-general region responding to diverse cognitive demands (Fedorenko & Blank, 2020). While anatomically adjacent, these regions belong to different networks - the left-lateralized frontotemporal language network and the bilateral frontoparietal multiple-demand (MD) network, respectively. Moreover, IFG's anatomical characteristics (e.g. minimal hair interference, relatively thin skull in this region, proximity to cortical surface, Hoshi et al., 2003) maximize

fNIRS signal quality. Therefore, IFG provides an optimal starting point for investigating whether specialized circuits emerge in core regions before extending to broader networks. Our experimental design includes a child-friendly language localizer adapted from Scott et al. (2017) that contrasts responses to auditorily presented engaging narrative clips versus acoustically degraded versions of the same stimuli. This localizer has been demonstrated to reliably identify language-selective regions across 45 languages from 12 language families, showing consistent activation patterns in the fronto-temporal language network regardless of the specific language being processed (Malik-Moraleda et al., 2022). The passive listening nature of this task makes it particularly suitable for young children who may have difficulty with reading or cognitively demanding tasks with the confounding effects of task difficulty being controlled. The narrative stimuli can be easily customized with age-appropriate content to maintain children's attention. For the cognitive control task, we used a spatial working memory task to engage the MD network for adults, as this paradigm has been consistently shown to be the most reliable and widely used task for localizing the MD network across numerous studies (e.g. Fedorenko et al., 2013; Woolgar et al., 2018). Using the same paradigm allows us to directly compare our fNIRS findings with the extensive fMRI literature. For children, we employed a Go/No-go task that probes inhibitory control - another key component of executive function that has been shown to engage the MD network (Duncan & Owen, 2000). While these tasks tap different aspects of executive function (working memory versus inhibitory control), both have been demonstrated to reliably activate the MD network and show similar patterns of increased activation under higher cognitive demands (Duncan, 2010; Fedorenko et al., 2013). We implemented two conditions in the Go/No-go task: an easier condition with only "go" trials and a more demanding condition mixing "go" and "no-go" trials, paralleling the easy versus difficult manipulation in the adult working memory task. This modification was necessary as young children are unable to

perform complex spatial working memory tasks (Pena et al., 2016) but can engage with the more developmentally appropriate Go/No-go paradigm (Simpson et al., 2006) while still allowing us to probe domain-general cognitive control functions supported by the MD network. Through this approach, we aim to investigate whether these regions show distinct functional profiles for language processing versus domain-general cognitive demands in young children.

To validate our methodology, we first applied the individual fCOI approach to fNIRS data analysis in a sample of adults in experiment 1, ensuring that our source-detector array was capable of detecting activation from known functional regions in adult cortex. Then, in experiment 2, we examined whether the same language-preferring regions with functional profiles matching those established in the adult literature (i.e., selective responses to linguistic content and insensitivity to cognitive demands) could be observed in toddlers between 2-4 years of age using the same approach of identifying fCOIs in individual participants.

Experiment 1

Method

Participants. Twenty adults (between 18 and 26 years, 10 female) were recruited from the student population at Sichuan University. All participants had normal or corrected to normal vision, no history of neurological or psychiatric disorders, head trauma, seizures, or current use of psychoactive medications. None reported physical impairments that could affect task performance. All were right-handed and gave written informed consent.

Procedure. Participants were seated in front of a 68 cm monitor at a distance of approximately 50 cm. Each participants completed (1) an auditory language localizer task (Scott et al., 2017); (2) one spatial working memory task (Fedorenko et al., 2011).

In the language localizer task, participants listened to blocks of intact meaningful sentences and acoustically degraded speech following the procedure introduced in Scott et al (2017). All the materials for this localizer were adopted to Mandarin from Gweon et al (2012) and read by a native female speaker. We used female speakers because children tend to pay attention to female voices (Wolf, 1963). Thirty-two audio clips were created, consisting of 24 intact clips and 8 degraded clips (see the full list of stimuli in supplementary material). Each clip was 19-20 seconds in duration. Degraded speech clips were created from the intact versions using the procedure described below, resulting in muffled speech where the linguistic content was no longer intelligible. The degraded versions were created by first applying a low-pass filter (350 Hz pass-band) to the intact audio clips, then creating a noise track by randomizing the time-points of the original audio and multiplying it by the amplitude envelope of the intact clip. The noise track was low-pass filtered (8,000 Hz pass-band, 10,000 Hz stop frequency) to soften the highest frequencies and added to the filtered speech at a level that rendered it unintelligible. Each block lasted around 20 seconds. Each run included three blocks corresponding to three language conditions plus one block of degraded speech condition, with 10-second fixation blocks between blocks and additional fixation blocks at the beginning and end of the run [1]. There are a total of eight runs. Participants were told that they would listen to some fun audio clips and some clips that were distorted in a way that makes it impossible to understand what the speaker is saying. They were instructed to listen attentively. Prior to the experiment, it was ensured that the volume level was sufficiently loud yet comfortable.

In the MD localizer task, participants performed a spatial working memory (WM) task involving a 3x4 grid. During each trial, squares appeared in different locations on the grid, either one at a time (easy condition) or two at a time (hard condition). Participants were required to remember these sequential locations. At the end of each trial, they were shown two sets of locations and had to select the set that matched the sequence they had just seen. They received feedback indicating whether their response was correct or incorrect (Fedorenko et al., 2011). Each trial followed a precise timing structure: beginning with a 500 ms fixation cross, followed by sequential grid presentations where each location was shown for 1000 ms. Participants then had up to 3750 ms to make their choice between the two location sets. After responding, they received feedback for 250 ms, followed by a fixation cross that filled the remaining time to ensure a consistent trial length (calculated as 4000 ms minus the response time minus 250 ms). Each run consisted of two blocks (one easy, one hard) with four trials per block, plus three 10-second fixation blocks interspersed at the beginning, middle, and end. Participants completed four runs in total. To ensure task comprehension, all participants completed a practice run before beginning the main experiment.

After each run the display paused until the participant initiated the next run by pressing a key on a keyboard located to his/her right. Participants were instructed to remain still and to focus on the screen throughout each run but were not asked to fixate on any point on the screen and could adjust their position between runs.

Data acquisition. fNIRS measurements were collected with a continuous wave system NirSmart (Danyang Huichuang Medical Equipment Co., Ltd., China) using wavelengths of 760 nm and 850 nm with a sampling rate of 11 Hz. 29 sources and 30 probes constituted 79 measurement channels of 3 cm (figure 1). The emitter and detector were placed according to the 10–20 system. The optodes were stabilized using a plastic holder and

then affixed to participants' heads over the frontal, temporal, occipital and parietal lobes in the left and right hemisphere using custom headgear. Prior to data collection, head circumference measurements were taken to ensure all participants fell within the suitable range for our standard cap size (54-58 cm). When wearing the optode cap, it was ensured that the Cz point of the electrode cap coincided with the Cz point of the scalp surface measurement. The spatial coordinates of sources, detectors, and anchor points (Nz, Cz, Al, Ar, lz, and other points from the international 10-20 system) were digitized using an electromagnetic 3D digitizer (Patriot, Polhemus, USA). These coordinates were then transformed into Montreal Neurological Institute (MNI) coordinates and mapped onto the MNI standard brain template using the spatial registration method in NirSpace (Danyang Huichuang Medical Equipment Co., Ltd, China).

Data preprocessing. Initial measurements of incident light reaching the detector for each channel were trimmed to remove excess time points from the beginning and end of data collection and were then preprocessed using the HomER NIRS processing package (Huppert et al., 2009). First, each run of the experiment was isolated from the continuous data and processed as a separate file to ensure that normalization of a given run was not skewed by more or less noisy portions of the data occurring at other times in the experiment (Hyde et al., 2018). Then, the negative intensity values resulting from noisy data were corrected using the hmrR_PreprocessIntensity_Negative function. Subsequently, channels were visually inspected and those lacking clear cardiac signal were manually excluded from individual participants' data sets. Raw intensity measurements were then converted to optical density changes (ΔOD). Then a linear fit function was used to further remove the baseline drift. Next, a Temporal Derivative Distribution Repair (TDDR) was used to filter out motion artifacts, which can effectively remove baseline shift and spike artifacts without the need for any user-supplied parameters (Fishburn et al., 2019). The resulting time courses were then band-pass

filtered with cut-off frequencies of 0.01–0.09 Hz to further remove slow drifts and high frequency and physiological noise (Pinti et al., 2019, butter filter 3 order for lowpass, 5 order for high pass). After that the ΔOD values were transformed into changes in oxyhemoglobin (HbO2) and deoxyhemoglobin (HHb) concentration according to the modified Beer-Lambert law (hmrOD2Conc, ppf = [1.0 1.0]). Then, the global components were removed using a principal component analysis spatial filter (σ=46 deg; Zhang et al., 2016; Zhang et al., 2017), which is comparable to using short-source channels when the coverage of the measurement is much larger than the regions of interest (Noah et al., 2021). And the concentration of each block is baseline corrected by 2s prior to the onset of stimuli.

Data analysis. We focused our analysis on changes in oxygenated hemoglobin concentration, as it has been demonstrated to be a more sensitive and reliable measure compared to deoxygenated or total hemoglobin concentration changes, which do not provide additional information beyond HbO2 (Luke et al., 2021). For each participant and channel, we computed the mean change in HbO2 concentration during each block, beginning 2 seconds post-stimulus onset to account for hemodynamic response lag. The analysis window extended to 25 seconds post-onset for the language localizer task and 38 seconds post-onset for the spatial working memory task, since different tasks' blocks have different durations. (Luke et al., 2021; Yücel et al., 2021). The differences in these responses across conditions were then analyzed using the fCOI approach.

First, we selected a set of channels ("search space") (Powell et al., 2018) that plausibly covered regions of the scalp plausibly overlaying bilateral inferior frontal lobe across participants (see table 1 for probabilistic mapping of selected fNIRS channels to underlying cortical regions).

The leave-one-run-out cross-validation procedure (Hyde et al., 2018) was implemented within each search space, which has demonstrated better sensitivity than other selection methods (Liu et al., 2023). For each participant, one run was held out while the remaining runs were averaged. Within the predefined search space, we identified the eligible channel showing maximum contrast between intact speech and degraded speech for Language fCOI, and maximum contrast between hard and easy conditions for MD fCOI. This process was repeated iteratively for each run and participant. The identified channel was used as the fCOI definition to extract response values for each condition from each held-out run.

Our fCOI selection method does not guarantee the identification of reliably preferential channels in either search space. If none of the available channels recorded from cortex exhibited distinct responses between conditions, the selection process would just operate on random noise, resulting in no consistent response patterns in the independent data (Powell et al., 2018). In other words, in cases where no robust preferential activation emerges during fCOI selection, any subsequent analyse may be driven by random variance rather than reflecting a true functional specialization, warranting cautious interpretation.

To compare the functional profile across the two networks, we also estimated the responses of the fCOIs to conditions that were not used to define them (i.e., hard and easy WM for the language fCOI, intact speech and degraded speech for the MD fCOI). For this analysis, we used all runs from the localizer task to define the fCOIs and all data from the other task to estimate their responses.

fCOIs were excluded from analyses if more than one-third of the channels in their search space were excluded (consistent with previous studies e.g. Richardson et al., 2021). Participants were excluded if they had fewer than 2 runs.

Our main analysis addressed three primary questions. First, regarding functional selectivity, we examined whether identified language fCOIs show selectivity to the properties of high-level language, specifically stronger activation in response to intact versus degraded speech (Scott et al., 2017). Second, for functional specificity, we investigated whether language fCOIs exhibit specificity to language. A lack of difference in the language fCOI between the Easy and Hard conditions of the spatial working memory task , or a reverse pattern showing stronger responses to the Easy than the Hard condition, would suggest that the language network is not selectively engaged in this working memory task. Third, concerning domain-general processing, we needed to verify that the language fCOIs' lack of response to cognitive load was not simply due to a failure of our tasks to engage domain-general function (Aslin, 2012). Therefore, we tested whether the MD fCOIs in our sample exhibited the expected selectivity and specificity for cognitive demands.

We employed a generalized linear mixed-effects model (GLMM) on individual trials to account for the unbalanced nature of the dataset (different numbers of runs across participants due to exclusion criteria) and individual differences in global signal strength. The analysis was implemented using MATLAB's "fitglme" function with Maximum Penalized Likelihood (MPL) method. Our model structure was: HbO data ~ condition + (1|subject) where condition represented the experimental conditions (intact vs degraded speech for language task; hard vs easy for cognitive/MD task). While inclusion of random slopes for condition by subject would be theoretically appropriate (Barr et al., 2013), attempts to include these led to convergence failures. Separate models were run for two fCOI types in each search space (LIFG language, RIFG language, LIFG MD, RIFG MD) of two experiment contrasts (Intact > Degraded; Hard > Easy). To account for multiple comparisons, we applied Bonferroni correction separately for each task (language vs. cognitive control). In each task,

the left and right IFG fCOIs formed a single family of two comparisons, yielding a family-wise threshold of $\alpha = 0.025$ (0.05/2).

Results

No participants were excluded based on our criteria for channel rejection and fCOI rejection. For the subsequent analyses, we included all data after removing the excluded noisy channel and any runs where noisy channels comprised more than one-third of the search space. Table 2 provides a summary of the available runs across participants for different fCOI types (See the distribution of identified channel for each type of fCOI in supplementary material in figure S4-S8).

The language fCOIs showed clear selectivity for language processing. In both hemispheres, these channels demonstrated significantly stronger responses to intact versus degraded speech. The LIFG language fCOI showed a significant effect of condition (β = -8.92e-06, SE = 3.04e-06, t = -2.9365, p = 0.0036), with higher activation for intact speech. Similarly, the right inferior frontal gyrus (RIFG) language fCOI exhibited a significant preference for intact speech (β = -1.18e-05, SE = 3.36e-06, t = -3.5248, p = 0.00049). Importantly, when tested on the spatial working memory task, neither the left nor right language fCOIs showed significant modulation by cognitive demand (LIFG: β = -4.66e-06, SE = 5.31e-06, t = -0.87838, p = 0.381; RIFG: β = -2.1894e-06, SE = 4.9866e-06, t = -0.43906, p = 0.661). This pattern suggests that the language fCOIs are specifically selective for language processing and do not respond systematically to increased cognitive load in non-linguistic tasks (figure 2a & 2b).

The MD fCOIs demonstrated a complementary pattern of activation. Both left and right MD fCOIs showed significant sensitivity to cognitive demand in the spatial working memory task. The LIFG MD fCOI exhibited stronger activation for harder versus easier

conditions (β = 1.34e-05, SE = 5.09e-06, t = 2.6279, p = 0.0095), as did the RIFG MD fCOI (β = 1.75e-05, SE = 5.26e-06, t = 3.3278, p = 0.0011). In contrast, when tested on the language task, neither MD fCOI showed significant differentiation between intact and degraded speech (LIFG: β = 5.04e-08, SE = 3.25e-06, t = 0.015523, p = 0.988; RIFG: β = 1.01e-06, SE = 3.25e-06, t = 0.31183, p = 0.756). This finding indicates that the MD network responds selectively to cognitive demand but not to linguistic properties per se (figure 2c & 2d).

These results demonstrate a double dissociation between the language and MD networks, with language fCOIs showing selectivity for linguistic processing but not cognitive demand, and MD fCOIs showing the opposite pattern.

Experiment 2

Method

Participants. Thirty-five children between 2 and 4 years of age were recruited from preschools in Shanghai. Thirteen children were excluded because of failing to follow the experimental instructions. Twenty-two children (mean: 3 years 6 months; range: 2 years 5 months–4 years 11 months; 14 male, 8 female) were finally included in the study. Two children were aged 2 years 5 months to 2 years 11 months, seventeen were aged 3 years 0 months to 3 years 11 months, and three were aged 4 years 0 months to 4 years 11 months. According to parent reports, all participants had no developmental disorders, had normal or corrected-to-normal vision and hearing, and could understand basic instructions in Mandarin. Additionally, all children were full-term births (≥37 weeks gestation) with no significant medical complications at birth. Parents or legal guardians provided written informed consent for their children's participation in accordance with the requirements of the Committee on the Use of Humans as Experimental Subjects.

Procedure. The procedure was similar to that of experiment 1 except that children under 3 years sat on their parents' laps while viewing the display, and the experiment was discontinued, either during or between runs, if the participant became fussy, inattentive or if the parent indicated their wish to end the experiment. Each participants completed an auditory language localizer task and a Go/no-go task.

In the language localizer task, participants listened to blocks of intact meaningful sentences and acoustically degraded speech following the same procedure described in experiment 1. The materials were adapted from experiment 1 by selecting a subset of the adult stimuli based on a pre-experiment assessment of comprehension in a separate group of toddlers (n=3). While the adult version contained three language conditions per run, we selected only the material that showed the highest comprehension rates in our pre-experiment (accurate responses to simple comprehension questions. E.g. "Was the girl helping her father?" or "Was the rabbit in the garden?"). The selected narratives were shortened from the original 20-second duration to 18-second segments to accommodate shorter attention spans, while maintaining the core narrative structure. Each block lasted 18 seconds, with 6-second fixation blocks between blocks and additional fixation blocks at the beginning and end of the run. Each run included one language condition block plus one degraded speech condition block. There are four total runs. As in experiment 1, participants were told that they would listen to some fun audio clips and some clips that were distorted in a way that makes it impossible to understand what the speaker is saying. They were instructed to listen attentively. Prior to the experiment, it was ensured that the volume level was sufficiently loud yet comfortable.

In the MD localizer task, participants completed a Go/no-go task. A training session before the experiment was conducted to ensure task comprehension. The training included practice trials for both "go" (simple response) and "go/no-go" (response inhibition)

conditions with performance feedback, continuing until participants demonstrated reliable response patterns. The formal experiment consisted of four runs, each containing alternating "go" and "go/no-go" blocks separated by 10-second fixation periods. Each block began with a 3-second instruction screen followed by 12 trials lasting 12 seconds total. In "go" blocks, participants pressed a key with their right index finger in response to both cat and dog images. In "go/no-go" blocks, participants pressed the key for chicken images (go) but withheld responses for duck images (no-go). A study personnel monitored participant performance during scanning.

Data acquisition. fNIRS measurements were collected with a continuous wave system NirSmart (Danyang Huichuang Medical Equipment Co., Ltd., China) using wavelengths of 730nm, 808 nm and 850 nm with a sampling rate of 11 Hz. 26 sources and 27 probes constituted 81 measurement channels of 3 cm (see figure 3). The optodes were stabilized using a plastic holder and then affixed to participants' heads over the frontal, temporal, occipital and parietal lobes in the left and right hemisphere using custom headgear. When wearing the optode cap, it was ensured that the Cz point of the electrode cap coincided with the Cz point of the scalp surface measurement.

Data preprocessing. Data were preprocessed in the same manner as Experiment 1, with the exception of the partial pathlength factor (ppf) in the modified Beer-Lambert law calculation. Given the different optical properties of toddler brain tissue compared to adults, we used a ppf value of [2.0 2.0 2.0], which better accounts for the light scattering and absorption characteristics in infant participants (Whiteman et al., 2017).

Data analysis. For each participant and channel, mean HbO2 concentration changes were calculated per trial. The analysis window started 4 seconds after stimulus onset and lasted until 17 seconds post-onset for the language localizer task or 12 seconds post-onset for

the Go/no-go task. This timing accounts for the HRF lag time commonly assumed in children's NIRS research (e.g., Emberson et al., 2015; Lloyd-Fox et al., 2009). Language and MD selective regions were identified and mean HbO responses were extracted using individual fCOI approaches within the same search space (see table 3 for probabilistic mapping of selected fNIRS channels to underlying cortical regions), following Experiment 1's methodology. Inclusion criteria required children to complete at least two runs per experiment, ensuring sufficient trials for the leave-one-run-out procedure. Additional exploratory analyses incorporating age as a fixed effect in the generalized linear mixed models are reported in the supplementary material.

Results

Table 4 provides a summary of the included participants and available runs across participants for different fCOI types based on the criteria for fCOIs rejection we described in experiment 1 (See the distribution of identified channel for each type of fCOI in supplementary material, Figure S1-S4).

Analysis of the language fCOIs in children showed a partially overlapping pattern with adults. The LIFG language fCOI maintained significant selectivity for language processing, showing stronger responses to intact versus degraded speech (β = -5.21e-07, SE = 1.69e-07, t = -3.0781, p = 0.0025). However, unlike adults, the RIFG language fCOI did not show significant differentiation between intact and degraded speech (β = -7.49e-08, SE = 1.90e-07, t = 0.1211, p = 0.693). Consistent with the adult findings, neither language fCOI showed significant modulation by cognitive demand in the Go/no-go task (LIFG: β = -3.22e-08, SE = 1.46e-07, t = -0.21987, p = 0.826; RIFG: β = -8.69e-08, SE = 2.01e-07, t = -0.72473, p = 0.667). This suggests that even in children, the language fCOI we identified maintains specificity for language processing over general cognitive demands (figure 4a & 4b).

The MD fCOI we identified in children showed a more complex pattern than expected. Behavioral performance confirmed the task difficulty manipulation, with participants showing higher accuracy on go trials (M = 81%, SD = 12%) compared to no-go trials (M = 73%, SD = 15%; $t(21) = 2.25$, $p = 0.035$). Only the right MD fCOI displayed higher sensitivity to cognitive demand in the Go/no-go task (significantly stronger responses to the harder versus easier condition; RIFG: $\beta = 4.49e\text{-}07$, SE = 1.48e-07, $t = 3.0185$, $p = 0.00323$). By contrast, the left MD fCOI did not show a significant difference between these conditions (LIFG: $\beta = -8.63e\text{-}08$, SE = 1.25e-07, $t = -0.69016$, $p = 0.4917$). When we tested these fCOI in the language task, an unexpected pattern emerged: although the left MD fCOI was not strongly modulated by cognitive control demands, it nonetheless responded more robustly to degraded than to intact speech ($\beta = 4.2037e\text{-}07$, SE = 1.7142e-07, $t = 2.4523$, $p = 0.015313$). The right MD fCOI showed a similar trend though not reaching statistical significance after correction for multiple comparisons ($\beta = 3.6637e\text{-}07$, SE = 1.8245e-07, $t = 2.0081$, $p = 0.046$). These findings suggest that only the right MD fCOI displays the characteristic MD network profile of responding to cognitive control demands but not to linguistic properties. The left MD fCOI's lack of modulation by task difficulty suggests that an adult-like MD network component may not yet be established in the left IFG in our sample, warranting caution in interpreting its preferential response to degraded speech as we have discussed in the method part (figure 4c & 4d).

Discussion

Our study investigates how the brain supports language processing in early childhood, focusing on whether neural circuits are specialized for language or share with other cognitive domains. By employing fNIRS with an individual functional channel of interest approach, we assessed both adults and toddlers on language and cognitive control tasks to seek evidence for distinct functional profiles in the left and right inferior frontal regions. Our adult findings

validated the fCOI method by replicating well-established dissociations between language-specific and domain-general processor, providing a foundation for investigating the developmental period. Our toddler results suggest that left-hemisphere language selectivity emerges early and remains robust, while right-hemisphere organization shows signs of ongoing maturation.

In line with adult findings and recent work in older children (Hiersche et al., 2024; Ozernov-Palchik et al., 2024), toddlers demonstrated robust language selectivity in the left IFG. The language fCOI within this area showed specific responses to intact versus degraded speech, mirroring the adult pattern, while remaining insensitive to the manipulation of cognitive demands in the Go/No-Go task. This supports the hypothesis of early domain specificity in language processing, as the language selective region within left IFG region exhibited both selectivity and specificity for language (Aslin, 2012; Kanwisher, 2010). Our toddler data align with evidence that even very young children recruit the left frontal cortex for high-level linguistic processing (Dehaene-Lambertz et al., 2006; Minagawa-Kawai et al., 2011; Pena et al., 2003). Moreover, our findings revealed a developmental asymmetry in language processing between hemispheres. While our adult participants showed bilateral IFG fCOIs with selectivity for meaningful speech, toddlers did not exhibit statistically reliable language responses in the RIFG language fCOI. This asymmetry aligns with previous developmental research and recent findings in older children. Hiersche et al. (2024), using a similar speech localizer task comparing sentences to acoustically degraded speech, also found no significant language selectivity in the right IFG. Early in development, infant studies have documented limited right-hemisphere sensitivity to language in speech versus control conditions (Dehaene-Lambertz et al., 2006; Pena et al., 2003). A developmental shift occurs later: children ages 5-11 show right hemisphere engagement, particularly during complex linguistic tasks requiring greater syntactic processing or elevated linguistic demands (Holland

et al., 2007; Szaflarski et al., 2006; Weiss-Croft & Baldeweg, 2015). Our observation of strong LIFG but nonsignificant RIFG selectivity in toddlers (ages 2-4) suggests that RIFG language specialization follows a prolonged developmental trajectory. While LIFG supports core linguistic computations from early development, RIFG may serve complementary functions that become increasingly important as language abilities mature. Studies suggest RIFG involvement in prosodic processing, pragmatic aspects of language, and discourse-level comprehension (Friederici, 2011; Vigneau et al., 2011). The absence of RIFG language selectivity in toddlers suggest that these higher-level linguistic functions develop later, potentially aligning with children's growing ability to process complex narrative (Lynch et al., 2008) and social aspects of language (Airenti, 2017). These findings support a developmental model where left-hemisphere language selectivity emerges early and remains stable, while right-hemisphere language involvement develops gradually throughout childhood (Bunge & Crone, 2009; Szaflarski et al., 2006).

With regard to domain-general processing, our findings revealed a distinct pattern in toddlers from adults: only the right MD fCOI showed selective sensitivity to increased cognitive demands during the Go/No-Go task. These MD fCOIs demonstrated functional profiles that contrasted with language fCOIs - while language regions responded selectively to intact versus degraded speech but showed no sensitivity to cognitive demands, MD fCOIs exhibited the opposite pattern. Importantly, only the right MD fCOI displayed the characteristic MD network profile of responding to cognitive control demands but not to linguistic properties. This toddler-specific pattern diverges from established findings in both adults and older children (approximately 7-12 years). Adults show bilateral MD network responses to escalating task difficulty, and older children demonstrate bilateral prefrontal recruitment during inhibitory control tasks (Bunge et al., 2002; Casey et al., 1997; Crone & Steinbeis, 2017; Rubia et al., 2007). The developmental differences likely reflect the ongoing

structural and functional specialization of the MD network in early childhood. Our findings of right MD responsiveness in toddlers, coupled with previous fNIRS and fMRI studies, suggest that very young children's prefrontal cortex involvement in executive tasks may initially manifests in right hemisphere circuits compared to older groups (Mehnert et al., 2013; Moriguchi & Hiraki, 2011). This aligns with evidence of protracted maturation for left frontal functions (Bunge et al., 2002; Crone & Steinbeis, 2017; Steinbeis et al., 2012). The left MD fCOI's lack of modulation by task difficulty suggests that an adult-like MD network component may not yet be established in the left IFG in our sample. This developmental pattern is further corroborated by recent work from Schettini et al. (2023), who similarly found that the left IFG in children did not show significant selectivity for cognitive demand. While the left MD fCOI exhibited stronger activation to degraded compared to intact speech, this pattern should be interpreted cautiously, as it lacks the hallmark feature of the MD network—sensitivity to cognitive demand—and may reflect immature functional engagement in this region. An alternative possibility is that degraded speech, which is more challenging to understand than intact speech, elicits more effortful processing in children, thereby driving up activity in what would eventually become a domain-general region. In other words, although the left MD fCOI does not show the classic adult-like sensitivity to cognitive demands, it may nonetheless be recruited when children strain to extract meaning from ambiguous input. Together, these findings support previous research indicating ongoing development of prefrontal involvement in domain-general control (Bunge & Crone, 2009; Casey et al., 1997; Schettini et al., 2023), with bilateral integration emerging later in development as children increasingly recruit both hemispheres for executive tasks.

Our use of the fCOI approach addressed several methodological challenges in fNIRS studies. First, it circumvents the limitations of the 'reverse inference' problem which plagues many fNIRS studies that rely on inferring cognitive functions solely from anatomical

correspondence with prior findings. This practice is problematic as the same anatomical location may support different functions across individuals (Poldrack, 2006), particularly in developmental research where variations in head size, brain organization, and probe placement complicate anatomical localization (Kabdebon et al., 2014). Our fCOI approach addresses these limitations by identifying regions based on functional properties rather than assumed anatomical locations, effectively accommodating individual variability in neural functional anatomy across development. Second, it provided enhanced statistical power while controlling for multiple comparisons, which is crucial when working with limited developmental data (Liu et al., 2023). Third, the implementation of the same localizer task used by fMRI studies (Fedorenko et al., 2024; Hiersche et al., 2024; Ozernov-Palchik et al., 2024;) allowed for direct comparison of properties of specific functional regions over developmental stages and imaging modalities. Our successful identification of functionally distinct networks in both adults and toddlers demonstrates the robustness of this approach across developmental stages.

Our experimental design also addressed several methodological challenges. The implementation of a leave-one-run-out cross-validation procedure for fCOI selection avoided the "double dipping" issue in neuroimaging studies (Kriegeskorte et al., 2009), enhancing the reliability of our findings. By employing passive language tasks contrasting meaningful versus degraded speech, we controlled for confounding effects of task difficulty while maintaining prosodic and rhythmic features (Scott et al., 2017). This paradigm, extensively validated in adult studies across different languages, allowed us to specifically probe the processing of high-level linguistic features such as semantics and syntax (Malik-Moraleda et al., 2022). The careful selection of age-appropriate tasks for probing the MD network—spatial working memory for adults and Go/No-go for children—enabled us to examine domain-general processing while accommodating developmental constraints. By comparing

responses to both linguistic and non-linguistic tasks within the same participants, we directly assessed the specificity of these networks to language processing.

Despite these methodological strengths, several limitations warrant discussion. First, like most fNIRS experiments, our study faced challenges of limited and non-continuous cortical coverage. While our probe arrangement provided good coverage of bilateral inferior frontal regions, some cortical areas may have fallen into measurement "blind spots" (Lloyd-Fox et al., 2010). Second, we did not have access to short-separation channels in our study. Short-separation channels are efficient in accounting for and removing superficial hemodynamic signals originating from the scalp and skull, thereby isolating the cortical activity of interest (Brigadoi & Cooper, 2015; Gregg et al., 2010). The absence of short-separation channels may have led to contamination of our signals by systemic physiological artifacts. Although we have applied global regression method to filter out systemic physiological artifacts (Zhang et al., 2016), systemic physiological artifacts may still potentially affect the specificity and accuracy of our findings. Third, different cognitive tasks were used for adults and children. While both tasks engage the MD network, the cognitive demands they place on participants differ. However, this adaptation was necessary given the age-appropriate task requirements, and both tasks share the feature of manipulating cognitive control demands. Fourth, while our peak-channel selection approach within predefined anatomical regions of interest was optimized for our specific hypotheses, alternative approaches might be valuable for different research questions. Additionally, we did not examine behavioral metrics of language development, which limits our ability to differentiate between changes in language selectivity due to maturation versus language skill development (Skeide & Friederici, 2016). Finally, our focus was primarily on the inferior frontal cortex, which constrained our ability to fully characterize both the MD network and the language-selective network. While the IFG is a critical hub for domain-general cognitive control

(Duncan, 2010) and language processing (Fedorenko et al., 2013), the broader language network encompasses distributed temporal, parietal, and superior frontal regions. By restricting our measurements to the IFG, we may have overlooked crucial activity in other regions of the language network (e.g., the posterior temporal lobe) that could further elucidate the transition from domain-general to domain-specific processes in language development. Consequently, caution is warranted when generalizing our findings to the broader MD and language networks.

Future research should extend these findings in two main ways. First, longitudinal studies beginning at earlier ages (Dehaene-Lambertz et al., 2006; Karmiloff-Smith, 2015) are needed to clarify whether language networks transition from domain-general to domain-specific functioning over time. Second, studies should examine neural specialization at key language acquisition milestones by collecting brain measures when children reach specific linguistic achievements (e.g., first words, word combinations, complex sentences). This milestone-based approach (Fedorenko et al., 2024; Skeide & Friederici, 2016) would illuminate how maturing brain circuits support children's emerging linguistic abilities.

To conclude, using the methodologically improved fCOI approach with fNIRS, we replicated well-established patterns of bilateral selectivity and specificity in adult participants during linguistic and cognitive control tasks. In toddlers, we found early specialization of the language-selective component within LIFG, while the homologous right hemisphere region had not yet developed language selectivity. On cognitive control tasks, toddlers showed adult-like patterns in the within RIFG only. Notably, the selected MD fCOI in toddler’s LIFG only showed engagement with degraded speech rather than the broader domain-general profile seen in adults, suggesting ongoing maturation of domain-general circuits. These findings advance our understanding of how specialized brain circuits for language emerge

during early childhood and establish the utility of the fCOI approach for studying functional organization in the developing brain.

References

Amunts, K., Schleicher, A., Bürgel, U., Mohlberg, H., Uylings, H. B., & Zilles, K. (1999). Broca's region revisited: cytoarchitecture and intersubject variability. *Journal of Comparative Neurology*, 412(2), 319-341.

Airenti, G. (2017). Pragmatic development. *Research in clinical pragmatics*, 3-28.

Aslin, R.N. (2012). Questioning the questions that have been asked about the infant brain using near-infrared spectroscopy. *Cognitive Neuropsychology*, 29, 7–33.

Blank, I., Kanwisher, N., & Fedorenko, E. (2014). A functional dissociation between language and multiple-demand systems revealed in patterns of BOLD signal fluctuations. *Journal of Neurophysiology*, 112(5), 1105-1118.

Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. (2002). Immature frontal lobe contributions to cognitive control in children: evidence from fMRI. *Neuron*, 33(2), 301-311.

Bunge, S. A., & Crone, E. A. (2009). Neural correlates of the development of cognitive control. *Neuroimaging in developmental clinical neuroscience*, 22-37.

Brigadoi, S., & Cooper, R. J. (2015). How short is short? Optimum source–detector distance for short-separation channels in functional near-infrared spectroscopy. *Neurophotonics*, 2(2), 025005-025005.

Campbell, K. L., & Tyler, L. K. (2018). Language-related domain-specific and domain-general systems in the human brain. *Current Opinion in Behavioral Sciences*, 21, 132-137.

Casey, B. J., Trainor, R. J., Orendi, J. L., Schubert, A. B., Nystrom, L. E., Giedd, J. N., ... & Rapoport, J. L. (1997). A developmental functional MRI study of prefrontal activation

during performance of a go-no-go task. *Journal of cognitive neuroscience*, 9(6), 835-847.

Chater, N., & Christiansen, M. H. (2018). Language as skill: Intertwining comprehension and production. *Current Opinion in Behavioral Sciences*, 21, 205–208.

Chomsky, N. (2005). Three factors in language design. *Linguistic inquiry*, 36(1), 1-22.

Crone, E. A., & Steinbeis, N. (2017). Neural perspectives on cognitive control development during childhood and adolescence. *Trends in cognitive sciences*, 21(3), 205-215.

Dehaene-Lambertz, G., Hertz-Pannier, L., Dubois, J., Mériaux, S., Roche, A., Sigman, M., & Dehaene, S. (2006). Functional organization of perisylvian activation during presentation of sentences in preverbal infants. *Proceedings of the National Academy of Sciences*, 103(38), 14240-14245.

Diachek, E., Blank, I., Siegelman, M., Affourtit, J., & Fedorenko, E. (2020). The domain-general multiple demand (MD) network does not support core aspects of language comprehension: A large-scale fMRI investigation. *Journal of Neuroscience*, 40(23), 4536-4550.

Duncan, J. (2010). The multiple-demand (MD) system of the primate brain: Mental programs for intelligent behaviour. *Trends in Cognitive Sciences*, 14(4), 172-179.

Duncan, J., & Owen, A. M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends in Neurosciences*, 23(10), 475-483.

Edgin, J. O., Spanò, G., Kawa, K., & Nadel, L. (2015). Associations between cognitive and language development in Down syndrome: A combined linguistic and cognitive approach. *Developmental Neuropsychology*, 40(5), 286–304.

Emberson, L.L., Richards, J.E., & Aslin, R.N. (2015). Top-- down modulation in the infant brain: Learning-- induced expectations rapidly affect the sensory cortex at 6 months. Proceedings of the National Academy of Sciences, USA, 112, 9585–9590.

Fedorenko, E., & Blank, I. A. (2020). Broca's area is not a natural kind. *Trends in Cognitive Sciences*, 24(4), 270-284.

Fedorenko, E., Behr, M. K., & Kanwisher, N. (2011). Functional specificity for high-level linguistic processing in the human brain. *Proceedings of the National Academy of Sciences*, 108(39), 16428-16433.

Fedorenko, E., Duncan, J., & Kanwisher, N. (2013). Broad domain generality in focal regions of frontal and parietal cortex. *Proceedings of the National Academy of Sciences*, 110(41), 16616-16621.

Fedorenko, E., Ivanova, A. A., & Regev, T. I. (2024). The language network as a natural kind within the broader landscape of the human brain. *Nature Reviews Neuroscience*, 25, 289–312.

Fedorenko, E., & Shain, C. (2021). Similarity of computations across domains does not imply shared implementation: The case of language comprehension. *Current Directions in Psychological Science*, 30(6), 526-534.

Fedorenko, E., & Varley, R. (2016). Language and thought are not the same thing: Evidence from neuroimaging and neurological patients. *Annals of the New York Academy of Sciences*, 1369(1), 132-153.

Fishburn F.A., Ludlum R.S., Vaidya C.J., & Medvedev A.V. (2019). Temporal Derivative Distribution Repair (TDDR): A motion correction method for fNIRS. *NeuroImage*, 184, 171-179.

Friederici, A. D. (2011). The brain basis of language processing: from structure to function. *Physiological reviews*, *91*(4), 1357-1392.

Friederici, A. D., Brauer, J., & Lohmann, G. (2011). Maturation of the language network: from inter-to intrahemispheric connectivities. *PLoS one*, 6(6), e20726.

Gervain, J., Mehler, J., Werker, J.F., Nelson, C.A., Csibra, G., Lloyd-Fox, S., … Aslin, R.N. (2011). Near-¬infrared spectroscopy: A report from the McDonnell infant methodology consortium. *Developmental Cognitive Neuroscience*, 1, 22–46.

Gregg, N. M., White, B. R., Zeff, B. W., Berger, A. J., & Culver, J. P. (2010). Brain specificity of diffuse optical imaging: improvements from superficial signal regression and tomography. *Frontiers in Neuroenergetics*, 2, 14.

Gweon, H., Dodell-Feder, D., Bedny, M. and Saxe, R. (2012). Theory of Mind Performance in Children Correlates With Functional Specialization of a Brain Region for Thinking About Thoughts. *Child Development*, 83: 1853-1868.

Hagoort, P. (2014). Nodes and networks in the neural architecture for language: Broca's region and beyond. *Current Opinion in Neurobiology*, 28, 136-141.

Hasson, U., Egidi, G., Marelli, M., & Willems, R. M. (2018). Grounding the neurobiology of language in first principles: The necessity of non-language-centric explanations for language comprehension. *Cognition*, 180, 135-157.

Hiersche, K. J., Schettini, E., Li, J., & Saygin, Z. M. (2024). Functional dissociation of the language network and other cognition in early childhood. *Human Brain Mapping*, 45(9), e26757.

Holland, S. K., Vannest, J., Mecoli, M., Jacola, L. M., Tillema, J.-M., Karunanayaka, P. R., Schmithorst, V. J., Yuan, W., Plante, E., & Byars, A. W. (2007). Functional MRI of

language lateralization during development in children. *International Journal of Audiology*, 46(9), 533–551.

Hoshi, Y. (2003). Functional near□infrared optical imaging: Utility and limitations in human brain mapping. *psychophysiology*, *40*(4), 511-520.

Hyde, D. C., Simon, C. E., Ting, F., & Nikolaeva, J. I. (2018). Functional organization of the temporal–parietal junction for theory of mind in preverbal infants: a near-infrared spectroscopy study. *Journal of Neuroscience*, 38(18), 4264-4274.

Johnson, M. H. (2011). Interactive specialization: a domain-general framework for human functional brain development?. *Developmental Cognitive Neuroscience*, 1(1), 7-21.

Kanwisher, N. (2010). Functional specificity in the human brain: a window into the functional architecture of the mind. *Proceedings of the national academy of sciences*, 107(25), 11163-11170.

Kabdebon, C., Leroy, F., Simmonet, H., Perrot, M., Dubois, J., & Dehaene-Lambertz, G. (2014). Anatomical correlations of the international 10–20 sensor placement system in infants. *NeuroImage*, 99, 342-356.

Karmiloff-Smith, A. (2015). An alternative to domain-general or domain-specific frameworks for theorizing about human evolution and onto-genesis. *AIMS Neuroscience*, 2(2), 91–104.

Kocsis, L., Herman, P., & Eke, A. (2006). The modified Beer–Lambert law revisited. *Physics in Medicine & Biology*, *51*(5), N91.

Kriegeskorte, N., Simmons, W. K., Bellgowan, P. S., & Baker, C. I. (2009). Circular analysis in systems neuroscience: the dangers of double dipping. *Nature Neuroscience*, 12(5), 535-540.

Liu, Y., Hernández, F. S., Ting, F., & Hyde, D. C. (2022). Comparing fixed-array and functionally-defined channel of interest approaches to infant functional near-infrared spectroscopy data. *NeuroImage*, 261, 119520.

Lloyd-Fox, S., Blasi, A., & Elwell, C. E. (2010). Illuminating the developing brain: The past, present and future of functional near infrared spectroscopy. *Neuroscience & Biobehavioral Reviews*, 34(3), 269-284.

Lloyd-Fox, S., Blasi, A., Volein, A., Everdell, N., Elwell, C.E., & Johnson, M.H. (2009). Social perception in infancy: A near infrared spectroscopy study. Child Development, 80, 986–999.

Luke, R., Larson, E., Shader, M. J., Innes-Brown, H., Van Yper, L., Lee, A. K., ... & McAlpine, D. (2021). Analysis methods for measuring passive auditory fNIRS responses generated by a block-design paradigm. *Neurophotonics*, 8(2), 025008-025008.

Luke, R., Shader, M. J., Gramfort, A., Larson, E., Lee, A. K., & McAlpine, D. (2021). Oxygenated hemoglobin signal provides greater predictive performance of experimental condition than de-oxygenated. *BioRxiv*, 2021-11.

Lynch, J. S., Van Den Broek, P., Kremer, K. E., Kendeou, P., White, M. J., & Lorch, E. P. (2008). The development of narrative comprehension and its relation to other early reading skills. *Reading Psychology*, *29*(4), 327-365.

MacGregor, L. J., Diachek, E., Wagner, M., van Gaal, S., & Fedorenko, E. (2022). Causal contributions of the domain-general (multiple demand) and the language-selective brain networks to perceptual and semantic challenges in speech comprehension. *Neurobiology of Language*, 3(4), 665-698.

Malik-Moraleda, S., Ayyash, D., Gallée, J., Affourtit, J., Hoffmann, M., Mineroff, Z., ... & Fedorenko, E. (2022). An investigation across 45 languages and 12 language families reveals a universal language network. *Nature Neuroscience*, 25(8), 1014-1019.

May, L., Gervain, J., Carreiras, M., & Werker, J. F. (2018). The specificity of the neural response to speech at birth. *Developmental Science*, 21(3), e12564.

Mehnert, J., Akhrif, A., Telkemeyer, S., Rossi, S., Schmitz, C. H., Steinbrink, J., ... & Neufang, S. (2013). Developmental changes in brain activation and functional connectivity during response inhibition in the early childhood brain. *Brain and Development*, 35(10), 894-904.

McMullen, E., & Saffran, J. R. (2004). Music and language: A developmental comparison. *Music Perception*, 21(3), 289-311.

McCauley, S. M., & Christiansen, M. H. (2019). Language learning as language use: A cross-linguistic model of child language development. *Psychological Review*, 126(1), 1–51.

Minagawa-Kawai, Y., Van Der Lely, H., Ramus, F., Sato, Y., Mazuka, R., & Dupoux, E. (2011). Optical brain imaging reveals general auditory and language-specific processing in early infant development. *Cerebral Cortex*, 21(2), 254-261.

Mineroff, Z., Blank, I. A., Mahowald, K., & Fedorenko, E. (2018). A robust dissociation among the language, multiple demand, and default mode networks: Evidence from inter-region correlations in effect size. *Neuropsychologia*, 119, 501-511.

Moriguchi, Y., & Hiraki, K. (2011). Longitudinal development of prefrontal function during early childhood. *Developmental Cognitive Neuroscience*, 1(2), 153-162

Noah, J. A., Zhang, X., Dravida, S., DiCocco, C., Suzuki, T., Aslin, R. N., ... & Hirsch, J. (2021). Comparison of short-channel separation and spatial domain filtering for

removal of non-neural components in functional near-infrared spectroscopy signals. *Neurophotonics*, *8*(1), 015004-015004.

Novick, J. M., Trueswell, J. C., & Thompson-Schill, S. L. (2005). Cognitive control and parsing: Reexamining the role of Broca's area in sentence comprehension. *Cognitive, Affective, & Behavioral Neuroscience*, 5(3), 263-281.

Ozernov-Palchik, O., O'Brien, A. M., Lee, E. J., Richardson, H., Romeo, R., Lipkin, B., ... & Fedorenko, E. (2024). Precision fMRI reveals that the language network exhibits adult-like left-hemispheric lateralization by 4 years of age. *bioRxiv*, 2024-05.

Pailian, H., Libertus, M. E., Feigenson, L., & Halberda, J. (2016). Visual working memory capacity increases between ages 3 and 8 years, controlling for gains in attention, perception, and executive control. *Attention, Perception, & Psychophysics*, 78, 1556-1573.

Paunov, A. M., Blank, I. A., & Fedorenko, E. (2019). Functionally distinct language and Theory of Mind networks are synchronized at rest and during language comprehension. *Journal of Neurophysiology*, 121(4), 1244-1265.

Pena, M., Maki, A., Kovac□ić, D., Dehaene-Lambertz, G., Koizumi, H., Bouquet, F., & Mehler, J. (2003). Sounds and silence: an optical topography study of language recognition at birth. *Proceedings of the National Academy of Sciences*, 100(20), 11702-11705.

Pinti, P., Scholkmann, F., Hamilton, A., Burgess, P., & Tachtsidis, I. (2019). Current status and issues regarding pre-processing of fNIRS neuroimaging data: an investigation of diverse signal filtering methods within a general linear model framework. *Frontiers in Human Neuroscience*, 12, 505.

Poldrack, R. A. (2006). Can cognitive processes be inferred from neuroimaging data?. *Trends in cognitive sciences*, 10(2), 59-63.

Powell, L. J., Deen, B., & Saxe, R. (2018). Using individual functional channels of interest to study cortical development with fNIRS. *Developmental Science*, 21(4), e12595.

Quillen, I. A., Yen, M., & Wilson, S. M. (2021). Distinct neural correlates of linguistic and non-linguistic demand. *Neurobiology of Language*, 2(2), 202-225.

Rakison, D. H., & Yermolayeva, Y. (2011). How to identify a domain-general learning mechanism when you see one. *Journal of Cognition and Development*, 12(2), 134-153.

Richardson, H., Taylor, J., Kane-Grade, F., Powell, L., Enlow, M. B., & Nelson, C. A. (2021). Preferential responses to faces in superior temporal and medial prefrontal cortex in three-year-old children. *Developmental Cognitive Neuroscience*, 50, 100984.

Rubia, K., Smith, A. B., Taylor, E., & Brammer, M. (2007). Linear age‐correlated functional development of right inferior fronto‐striato‐cerebellar networks during response inhibition and anterior cingulate during error‐related processes. *Human brain mapping*, 28(11), 1163-1177.

Sato, H., Hirabayashi, Y., Tsubokura, H., Kanai, M., Ashida, T., Konishi, I., ... & Maki, A. (2012). Cerebral hemodynamics in newborn infants exposed to speech sounds: A whole‐head optical topography study. *Human Brain Mapping*, 33(9), 2092-2103.

Schettini, E., Hiersche, K. J., & Saygin, Z. M. (2023). Individual variability in performance reflects selectivity of the multiple demand network among children and adults. *Journal of Neuroscience*, 43(11), 1940-1951.

Scott, T. L., Gallée, J., & Fedorenko, E. (2017). A new fun and robust version of an fMRI localizer for the frontotemporal language system. *Cognitive Neuroscience*, 8(3), 167-176.

Shain, C., Blank, I. A., van Schijndel, M., Schuler, W., & Fedorenko, E. (2020). fMRI reveals language-specific predictive coding during naturalistic sentence comprehension. *Neuropsychologia*, 138, 107307.

Sharp, H. M., & Hillenbrand, K. (2008). Speech and language development and disorders in children. *Pediatric Clinics of North America*, 55(5), 1159-1173.

Simpson, A., & Riggs, K. J. (2006). Conditions under which children experience inhibitory difficulty with a "button-press" go/no-go task. *Journal of Experimental Child Psychology*, 94(1), 18-26.

Skeide, M. A., & Friederici, A. D. (2016). The ontogeny of the cortical language network. *Nature Reviews Neuroscience*, 17(5), 323-332.

Spelke, E. S., & Kinzler, K. D. (2007). Core knowledge. *Developmental science*, 10(1), 89-96.

Steinbeis, N., Bernhardt, B. C., & Singer, T. (2012). Impulse control and underlying functions of the left DLPFC mediate age-related and age-independent individual differences in strategic social behavior. *Neuron*, 73(5), 1040-1051.

Szaflarski, J. P., Schmithorst, V. J., Altaye, M., Byars, A. W., Ret, J., Plante, E., & Holland, S. K. (2006). A longitudinal functional magnetic resonance imaging study of language development in children 5 to 11 years old. *Annals of Neurology*, 59(5), 796-807.

Thiessen, E. D., & Saffran, J. R. (2007). Learning to learn: Infants' acquisition of stress-based strategies for word segmentation. *Language learning and development*, 3(1), 73-100.

Vigneau, M., Beaucousin, V., Hervé, P. Y., Duffau, H., Crivello, F., Houdé, O., Mazoyer, B., & Tzourio-Mazoyer, N. (2006). Meta-analyzing left hemisphere language areas: Phonology, semantics, and sentence processing. *NeuroImage*, 30(4), 1414–1432.

Vigneau, M., Beaucousin, V., Hervé, P. Y., Jobard, G., Petit, L., Crivello, F., ... & Tzourio-Mazoyer, N. (2011). What is right-hemisphere contribution to phonological, lexico-semantic, and sentence processing?: Insights from a meta-analysis. *Neuroimage*, *54*(1), 577-593.

Wang, L., Mruczek, R. E., Arcaro, M. J., & Kastner, S. (2015). Probabilistic maps of visual topography in human cortex. *Cerebral cortex*, 25(10), 3911-3931.

Wehbe, L., Blank, I. A., Shain, C., Futrell, R., Levy, R., von der Malsburg, T., ... & Fedorenko, E. (2021). Incremental language comprehension difficulty predicts activity in the language network but not the multiple demand network. *Cerebral Cortex*, 31(9), 4006-4023.

Whiteman, A. C., Santosa, H., Chen, D. F., Perlman, S., & Huppert, T. (2018). Investigation of the sensitivity of functional near-infrared spectroscopy brain imaging to anatomical variations in 5-to 11-year-old children. *Neurophotonics*, 5(1), 011009-011009.

Wolff, P. (1963). Observations on the early development of smiling. *Determinants of infant behavior*, 2, 113-138.

Woolgar, A., Duncan, J., Manes, F., & Fedorenko, E. (2018). Fluid intelligence is supported by the multiple-demand system not the language system. *Nature Human Behaviour*, 2(3), 200-204.

Yücel, M. A., Lühmann, A. V., Scholkmann, F., Gervain, J., Dan, I., Ayaz, H., ... & Wolf, M. (2021). Best practices for fNIRS publications. *Neurophotonics*, 8(1), 012101.

Zhang, X., Noah, J. A., Dravida, S., & Hirsch, J. (2017). Signal processing of functional NIRS data acquired during overt speaking. *Neurophotonics*, *4*(4), 041409-041409.

Zhang, X., Noah, J. A., & Hirsch, J. (2016). Separation of the global and local components in functional near-infrared spectroscopy signals using principal component spatial filtering. *Neurophotonics*, 3(1), 015004-015004.

Endnote

[1] The task was originally designed with three distinct language conditions (mental, social, and physical) to serve a dual purpose: localizing language processing and theory of mind networks. However, pilot testing revealed that children could not sustain this lengthy protocol, leading us to simplify the design to a single language condition for child participants. For adult participants, we maintained all three language conditions but combined them into a single intact speech condition for analysis, contrasting it with the degraded speech condition. This resulted in an uneven distribution of stimuli between conditions (24 intact vs. 8 degraded clips).

FIGURE 1 : (a) Schematic representation of the fNIRS optode placement. Red circles indicate sources, blue circles indicate detectors, and yellow lines represent measurement channels. (b) Spatial registration result of the probe array. Red dots with number indicate channel positions on the MNI standard brain template .

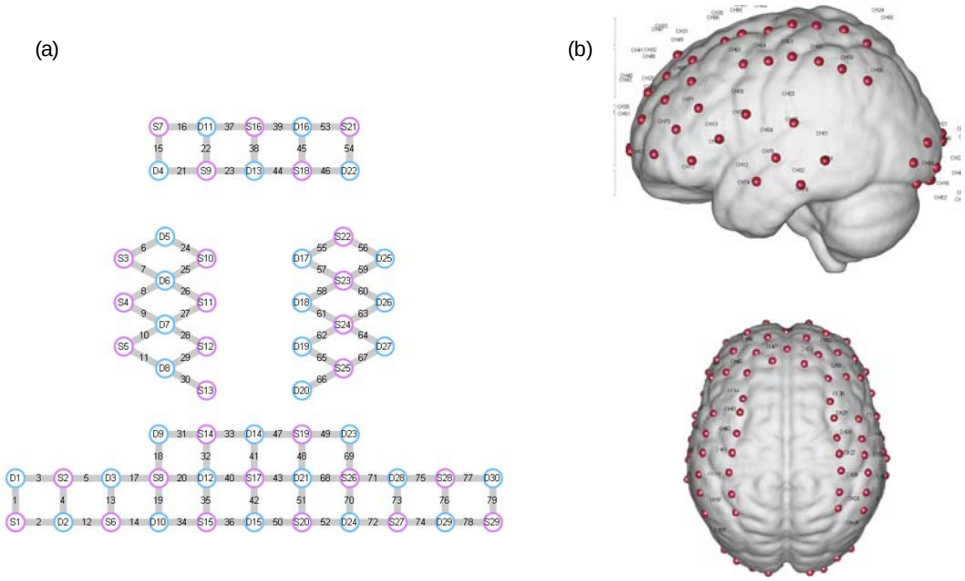

FIGURE 2 Results from Experiment 1: Mean HbO2 responses in the selected fCOIs (a) Left hemisphere language fCOI responses showing significant selectivity for intact versus degraded speech (p = 0.0036) and no significant modulation by cognitive demand (p = 0.381). (b) Right hemisphere language fCOI responses showing significant selectivity for intact versus degraded speech (p = 0.00049) and no significant modulation by cognitive demand (p = 0.661). (c) Left hemisphere MD fCOI responses showing significant sensitivity to cognitive demand (p = 0.0095) and no significant difference between speech conditions (p = 0.988). (d) Right hemisphere MD fCOI responses showing significant sensitivity to cognitive demand (p

= 0.0011) and no significant difference between speech conditions (p = 0.756). Error bars represent standard error of the mean.

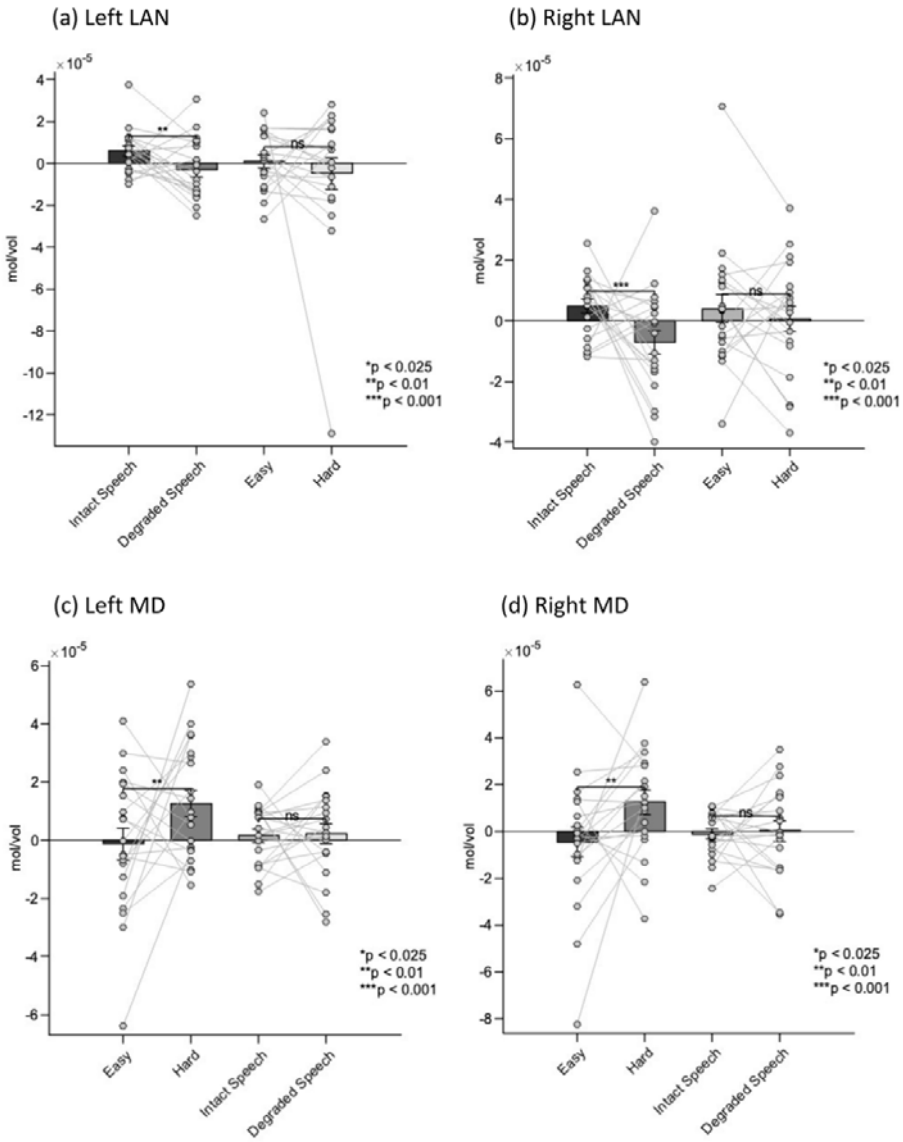

FIGURE 3 : (a) Schematic representation of the fNIRS optode placement. Red circles indicate sources, blue circles indicate detectors, and yellow lines represent measurement channels. (b) Spatial registration result of the probe array. Red dots with number indicate channel positions on the MNI standard brain template .

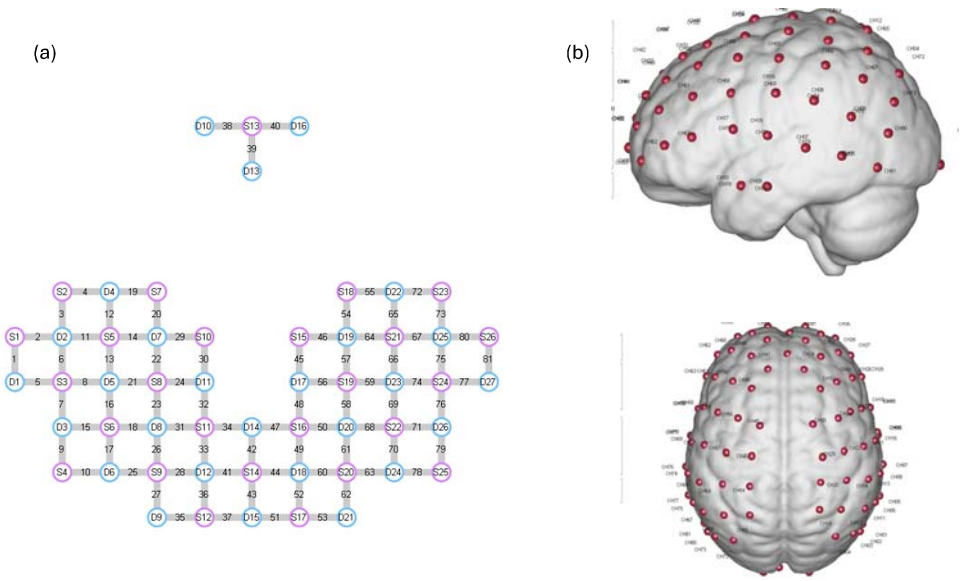

FIGURE 4 Results from Experiment 2: Mean HbO2 responses in the selected fCOIs (a) Left hemisphere language fCOI responses showing significant selectivity for intact versus degraded speech (p = 0.0025) and no significant modulation by cognitive demand (p = 0.826). (b) Right hemisphere language fCOI responses showing no significant selectivity for speech conditions (p = 0.693) and no significant modulation by cognitive demand (p = 0.667). (c) Left hemisphere MD fCOI responses showing no significant sensitivity to cognitive demand (p = 0.4917) but significant preference for degraded speech (p = 0.015). (d) Right hemisphere MD fCOI responses showing significant sensitivity to cognitive demand (p = 0.00323) and marginal preference for degraded speech (p = 0.046). Error bars represent standard error of the mean.

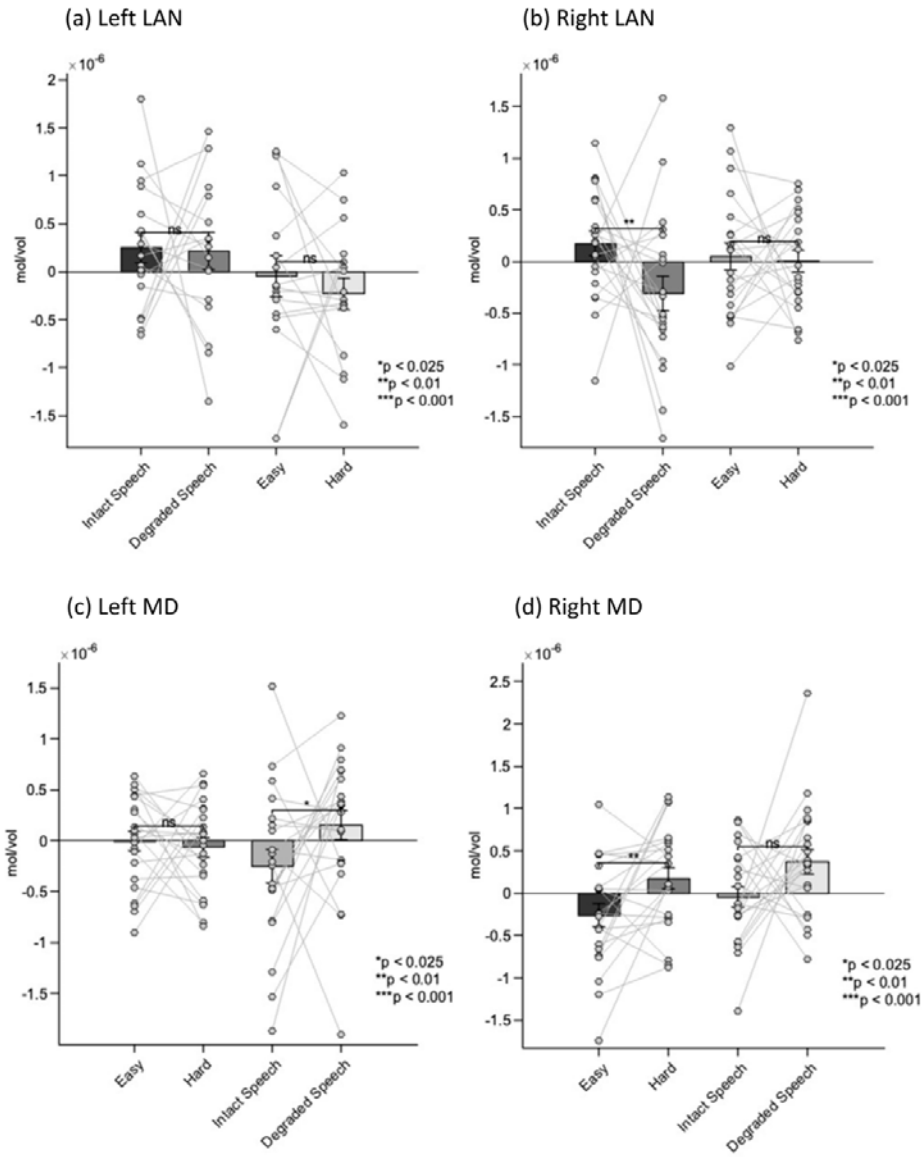

TABLE 1 Probabilistic mapping of fNIRS channels to underlying cortical regions showing Brodmann areas (based on MRIcro atlas) and corresponding MNI coordinates for each source-detector pair. Percentages indicate the probability of channel placement over the specified anatomical regions.

Channel	**MNI coordinates**	**Anatomic label**	**Percentage**	**Search Space**

5	64.9643, 5.7288, 27.8566	4 - Primary Motor Cortex, 6 - Pre-Motor and Supplementary Motor Cortex, 43 - Subcentral area, 44 - pars opercularis	6.35%, 59.53%, 27.42%, 6.69%	RIFG
13	61.2752, 22.4516, 12.4687	6 - Pre-Motor and Supplementary Motor Cortex, 44 - pars opercularis, 45 - pars triangularis, 48 - Retrosubicular area	5.75%, 31.95%, 51.12%, 11.18%	RIFG
14	57.049, 37.9202, -2.4401	38 - Temporopolar area, 45 - pars triangularis, 46 - Dorsolateral prefrontal cortex, 47 - Inferior prefrontal gyrus	3.34%, 66.22%, 21.40%, 9.03%	RIFG
17	53.2021, 33.3479, 29.3424	44 - pars opercularis, 45 - pars triangularis, 46 - Dorsolateral prefrontal cortex	6.69%, 92.57%, 0.74%	RIFG
19	49.1243, 47.253, 15.4105	45 - pars triangularis, 46 - Dorsolateral prefrontal cortex	48.70%, 51.30%	RIFG
20	36.6861, 51.5968, 29.9235	9 - Dorsolateral prefrontal cortex, 45 - pars triangularis, 46 - Dorsolateral prefrontal cortex	4.17%, 3.70%, 92.13%	RIFG
68	-38.2423, 52.8662, 27.4047	45 - pars triangularis, 46 - Dorsolateral prefrontal cortex	12.45%, 87.55%	LIFG
69	-43.5347,	9 - Dorsolateral prefrontal cortex,	25.45%, 4.55%,	LIFG

	37.7257, 38.1227	44 - pars opercularis, 45 - pars triangularis, 46 - Dorsolateral prefrontal cortex	39.09%, 30.91%	
70	-50.5051, 46.6936, 10.4438	45 - pars triangularis, 46 - Dorsolateral prefrontal cortex	53.45%, 46.55%	LIFG
71	-54.2983, 33.6329, 22.7694	45 - pars triangularis	100%	LIFG
72	-56.3003, 37.7076, -7.1488	38 - Temporopolar area, 45 - pars triangularis, 46 - Dorsolateral prefrontal cortex, 47 - Inferior prefrontal gyrus	8.14%, 48.06%, 19.77%, 24.03%	LIFG
73	-59.7137, 21.7772, 5.0031	6 - Pre-Motor and Supplementary Motor Cortex, 38 - Temporopolar area, 44 - pars opercularis, 45 - pars triangularis, 48 - Retrosubicular area	4.03%, 15.44%, 14.09%, 36.24%, 30.20%	LIFG
75	-66.014, 6.3358, 19.328	6 - Pre-Motor and Supplementary Motor Cortex, 43 - Subcentral area, 44 - pars opercularis, 48 - Retrosubicular area	59.79%, 31.12%, 4.90%, 4.20%	LIFG

TABLE 2 Summary of the available runs across participants for different fCOI types

fCOI	**Total LAN Subjects**	**Mean LAN Runs**	**Total MD**	**Mean MD**

Type	Included	(SDs)	Subjects Included	Runs (SDs)
LAN LIFG	20	6.95(0.683)	20	3.85(0.489)
LAN RIFG	20	7.15(0.3663)	20	3.85(0.489)
MD LIFG	20	7.10(0.4472)	20	3.90(0.4472)
MD RIFG	20	7.15(0.3663)	20	3.90(0.4472)

TABLE 3 Probabilistic mapping of fNIRS channels to underlying cortical regions showing Brodmann areas (based on MRIcro atlas) and corresponding MNI coordinates for each source-detector pair. Percentages indicate the probability of channel placement over the specified anatomical regions.

Channel	MNI coordinates	Anatomic label	Percentage	Search Space
17	77.67, 19.00, 17.33	6 - Pre-Motor and Supplementary Motor Cortex, 43 - Subcentral area, 44 - pars opercularis, 45 - pars triangularis Broca's area, 48 - Retrosubicular area	51.44%, 0.32%, 42.49%, 4.79%, 0.96%	RIFG
18	69.67, 20.33, 44.67	6 - Pre-Motor and Supplementary Motor Cortex, 9 - Dorsolateral prefrontal cortex, 44 - pars	36.02%, 9.20%, 54.79%	RIFG

		opercularis		
25	69.33, 42.67, 13.33	45 - pars triangularis Broca's area, 46 - Dorsolateral prefrontal cortex	99.32%, 0.68%	RIFG
26	60.33, 42.67, 40.33	9 - Dorsolateral prefrontal cortex, 44 - pars opercularis, 45 - pars triangularis Broca's area, 46 - Dorsolateral prefrontal cortex	0.81%, 6.07%, 75.30%, 17.81%	RIFG
27	59.67, 60.33, 5.67	10 - Frontopolar area, 45 - pars triangularis Broca's area, 46 - Dorsolateral prefrontal cortex	4.14%, 7.52%, 88.35%	RIFG
56	46.00, 42.33, 59.67	10 - Frontopolar area, 45 - pars triangularis Broca's area, 46 - Dorsolateral prefrontal cortex	0.85%, 4.68%, 94.47%	LIFG
57	33.00, 36.00, 73.00	44 - pars opercularis, 45 - pars triangularis Broca's area, 46 - Dorsolateral prefrontal cortex	1.23%, 90.95%, 7.82%	LIFG
59	33.67, 62.67, 50.67	45 - pars triangularis Broca's area, 46 - Dorsolateral prefrontal cortex	99.65%, 0.35%	LIFG
64	-57.67, -46.33, 79.33	6 - Pre-Motor and Supplementary Motor Cortex, 44 - pars opercularis	33.45%, 66.55%	LIFG
66	-70.33, 18.33, 39.00	6 - Pre-Motor and Supplementary Motor Cortex, 44 - pars opercularis, 45 - pars triangularis Broca's area, 48 - Retrosubicular	49.49%, 31.99%, 0.67%, 17.85%	LIFG

	area			

TABLE 4 Summary of the available runs across participants for different fCOI types

fCOI Type	**Total LAN Subjects Included**	**Mean LAN Runs (SDs)**	**Total MD Subjects Included**	**Mean MD Runs (SDs)**
LAN LIFG	22	3.54(0.510)	21	2.24(0.436)
LAN RIFG	22	3.50(0.597)	17	2.23(0.437)
MD RIFG	22	3.50(0.597)	22	2.27(0.457)
MD LIFG	21	3.38(0.74)	21	2.24(0.539)