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Examining functional Near-Infrared Spectroscopy as a tool to study brain function in bilinguals

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There is increasing evidence that using more than one languages has significant effects on brain function. These effects have been observed in the developing, adult and aging brain, and have been suggested to have implications for cognitive and brain decline in bilinguals and multilinguals. Aside from extensive investigations with behavioral methods, such effects are now commonly investigated with functional neuroimaging methods, mostly functional Magnetic Resonance Imaging (fMRI) and electroencephalography (EEG). A relatively underused method in the field is functional Near-Infrared Spectroscopy (fNIRS), which carries several advantages over more established methods, including being appropriate for use with infants and children, but also with older and diseased samples. This paper provides an overview of the method and an account of how it has been used in the field of bilingual cognition. It concludes with suggestions of how the method can be best utilized in future research, highlighting it as a method with a strong potential for updating existing theories on the effects of bilingualism on brain function.

KEYWORDS

bilingualism, fNIRS, brain function, brain development, brain decline, executive functions, resting state brain activity, functional neuroimaging

1 Introduction: bilingualism and brain function

Recent advances in our understanding of the effects of bi-/multilingualism on the brain have suggested that the cognitively challenging experience of speaking more than one language brings about significant changes in how the brain functions. This is because it is now well-understood that all languages spoken by a bilingual or a multilingual (henceforth, simply "bilingual") remain active, ready to be produced or comprehended at any time. The consequence of this is that bilingual brains need to efficiently utilize those mental abilities that help allocate attentional resources and control between alternatives, also collectively known as executive functions (Bialystok and Craik, 2022). This finding has led to substantial research on the neural correlates of executive function processes in bilinguals, studied with major functional neuroimaging methods, including fMRI, EEG and, to a lesser extent, Magnetoencephalography (for the available evidence, see Pliatsikas and Luk, 2016; Zhu et al., 2020; Tao et al., 2021; Antoniou, 2023). A full overview of these findings is beyond the scope of the current review; in brief, the emerging patterns from tasks tapping executive functions suggest that bilingualism affects the level of engagement of several frontal and parietal cortical regions and the basal ganglia, as well as the functional connectivity between these regions, while these effects appear to be correlated with the language experiences of the bilingual. Notably, in several of the existing studies, the effects of bilingualism on brain connectivity do not also manifest as behavioral effects (Luk et al., 2010; DeLuca et al., 2020a), highlighting the limitations of relying on either neuroimaging or behavioral experiments alone for understanding brain-behavior correlations. Nevertheless, the findings on the effects of bilingualism on brain function remain mixed and inconsistent (Tao et al., 2021), resembling the inconsistencies reported on its effects on cognition (Valian, 2015), and on brain structure (Pliatsikas, 2020). These discrepancies have been attributed to various factors (Poarch and Krott, 2019; Pliatsikas et al., 2020); one of the most important being the bilingual experiences of the individuals (e.g., quantity and quality of second language use) which may not have been appropriately measured and accounted for in different studies. This has led to recent calls for careful examination of such experience-based factors (DeLuca et al., 2020b).

2 fNIRS: an underused but promising method

A significantly underused method in the field is functional near-Infrared Spectroscopy (fNIRS), a technique with significant benefits which allow researchers to target very specific populations, and therefore with the potential to improve our understanding of brain function in bilinguals. fNIRS measures brain function by using near-Infrared light; specifically, in a typical fNIRS setup, participants wear a head cap with embedded light emitters and detectors. The emitted light travels through different brain types of tissue (skull, cerebrospinal fluid, gray matter) which differentially absorb or reflect it, before being measured by the detectors. Of particular interest in fNIRS is the ratio between oxygenated hemoglobin (HBO) and deoxygenated hemoglobin (HBB) in the blood, which absorb the light differently. Critically, a brain region engaged in a cognitive task is expected to have increased concentration of HBO and decreased concentration of HBB, meaning that differences in detected light can indicate which brain regions are activated by different tasks (Doherty et al., 2023). This makes fNIRS an alternative method to fMRI for the study of Blood Oxygenation Level Dependent (BOLD) response without restricting participants' movements. fNIRS can be used for both whole-brain and region-of-interest (ROI) designs, and its added benefits over fMRI include it being a more economic and portable method, with faster sampling rate, much cheaper to run, much less prone to head movement, and also silent; however, fNIRS has lower spatial resolution and is inevitably limited to measuring surface cortical activity only, as the maximum depth that a usable signal can be measured is 2–3 cm. In comparison to EEG, fNIRS offers much better spatial resolution, tolerance to movement and participant comfort, but worse sampling rate, and it can be substantially more expensive to acquire (Doherty et al., 2023).

The versatility and portability of fNIRS have promoted it as a key neuroimaging method in research that is not always easy to conduct with more commonly used neuroimaging methods such as fMRI. For example, the use of fNIRS allows for field research in the community, including in remote and culturally rich environments (for a review, see Arredondo, 2023); moreover, fNIRS has significant clinical research uses, not only because it allows for testing at patients' home or at clinical settings, but also because it is more comfortable for the patient (e.g., lack of noise) and without the contraindications that fMRI carries (Liampas et al., 2024). As such, it emerges as a promising method to study how brain function is affected by diverse experiences, including bilingualism, at different age ranges, contexts, as well as on healthy and diseased individuals. The remaining sections of this paper will review the available evidence from fNIRS on the study of brain function in bilingualism,[1] followed by a discussion on how it can be utilized in future research in the field.

3 fNIRS and brain function in bilingualism: insights from tasks tapping executive functions

fNIRS has been extensively used to study brain activity relating to executive functions in children and adults (Moriguchi and Hiraki, 2013; Ferreri et al., 2014). In the field of bilingualism, the few available studies have focused on children only, following up on suggestions that bilingualism may affect cognition during development (for a review, see Gunnerud et al., 2020). For example, in Arredondo et al. (2017), Spanish-English bilingual ($n = 13$) and English monolingual ($n = 14$) children aged 7–13 performed the child-friendly version of the flanker Attention Network Test (ANT), a task tapping attention and executive functions. This task required children to look at either a single fish in the middle of the screen (Neutral condition) or rows of five fish that either all face the same direction (Congruent condition) or the middle one faces the opposite direction to the others (Incongruent condition). The children had to press a button to indicate the direction that the middle fish was facing, with the Incongruent condition considered the most challenging because of the conflicting directions between the target and the flanking fish. Children's brain activity was concurrently measured with fNIRS, focusing on the right and left inferior, middle and superior frontal gyri, key regions for attention and executive function processes which have been shown to alter their functionality as an effect of bilingual experiences (Abutalebi and Green, 2016). The two groups did not differ in their task performance; however, the fNIRS analysis revealed that bilinguals showed greater activity in the left hemisphere for Incongruent vs. Congruent trials, while monolinguals showed the opposite pattern. Moreover, when the two groups were directly compared, bilinguals showed greater left hemisphere activation than monolinguals for Incongruent vs. Congruent, whereas monolinguals again showed the opposite pattern. The authors treated these findings as evidence that bilingualism affects functional organization of the developing brain, at least as long as attentional control is concerned, by being a driving force promoting neural specialization for selective attention [see also Li et al., 2019, for similar findings from 6-year old Mandarin-English bilinguals ($n = 25$) compared to Mandarin monolinguals ($n = 36$)]. Subsequently, Arredondo et al. (2022b)

1 fNIRS has also been used to study language processing in bilinguals. For a full review of these findings, see Leung et al. (2024).

used the same task on a group of 7–9 year old children (26 Spanish-English bilinguals and 26 English monolinguals), and they first performed a between-groups analysis, which revealed that the task engaged bilateral frontal and parietal regions, with greater left-hemisphere activity for bilinguals vs. monolinguals. They then adopted a data-driven approach where their participants would be classified into bilingual and monolingual subgroups based on functional connectivity patterns. Specifically, they used their between-groups results to identify ROIs that comprise the executive attention network. After estimating connectivity patterns per individual within these ROIs, they used them to detect two subgroups based on shared connectivity patterns. Notably, their classification matched very closely the reported language background of the children, largely separating bilinguals from monolinguals.

Subsequent fNIRS investigations have so far failed to provide a consistent account of the effects of bilingualism on brain function. For example, Moriguchi and Lertladaluck (2020) used fNIRS to record brain activity from the bilateral prefrontal cortex in 24 4-year-old Japanese-English bilingual children completing a Dimensional Change Card Sort (DCCS) task. A typical DCCS task includes presenting stimuli which have two dimensions (usually shape and color), and the participants are asked to decide whether pairs of stimuli match on one of these dimensions, which could either remain the same (e.g., always shape) or change in consecutive trials (*Switch* trials). This task is thought to tap shifting abilities, and the prediction is that Switch trials will take longer to respond because attention needs to be shifted to a different dimension. These shifting abilities may be affected by bilingualism: indeed, Okanda et al. (2010) showed that 4-year-old Japanese-French bilingual children ($n = 18$) face smaller delays for Switch trials in the DCCS task compared to an age-matched Japanese monolingual group ($n = 18$) with matched verbal age [measured with the Peabody Picture Vocabulary Test (Dunn and Dunn, 2007)], but not compared to different monolingual group ($n = 18$) with matched verbal age. Moriguchi and Lertladaluck reported positive correlations between bilingual children's performance and both their second language (L2) proficiency and duration of language education. However, no commensurate effects were observed in activity of the targeted regions, with authors suggesting that perhaps different regions should have been targeted for this particular task. The same task was used by subsequent investigations: Xie et al. (2021) tested 49 5-year-old Chinese-English bilingual children and reported a positive correlation between children's L2 proficiency (as rated by an instructor) and prefrontal cortex activity (recorded from a single channel). Subsequently, Li et al. (2023) tested preschoolers on the same paradigm, and, despite working with small groups ($n = 6$ each), they reported that, compared to monolingual children, bilingual children activated more their right inferior cortex while performing the DCCS task, and this activity engaged fewer channels. The two groups did not differ behaviorally. The authors interpreted the observed pattern of higher but more circumscribed activity for bilinguals in the absence of behavioral differences as evidence for more efficient cognitive shifting; however, they did not specify the assumed underlying mechanism that drives this proposed efficiency.

The versatile and non-invasive nature of fNIRS makes it possible to study younger populations than those reviewed so far, such as infants. However, very limited evidence exists from this age group. For example, Arredondo et al. (2022a) tested suggestions that bilingual environments can have an effect on the very young developing brain (Ayneto and Sebastian-Galles, 2017) by examining infants raised as bilinguals or monolinguals in two age groups, 6-months old (24 bilingual and 25 monolingual) and 10-months old (20 bilingual and 24 monolingual) on a spatial cueing attention task while collecting fNIRS data. The infants saw a series of trials featuring a cue stimulus followed by a target stimulus on different screens, while their eye gaze was monitored. The stimuli appeared in two conditions: the Valid trials, where both the cue and the target appeared on the same side of the screen, and the Invalid trials, where they appeared on opposite sides of the screen, which were therefore considered more challenging, as they require shifting attention to a different side of the screen. Similar to earlier studies, while the two language groups did not differ behaviorally in either age group, they showed significant differences in brain function during the task. Specifically, both 6-month old groups showed increased frontal activity for the Valid vs. Invalid trials, either in the left hemisphere (bilinguals) or the right one (monolinguals). Conversely, 10-month old bilinguals showed greater activity in bilateral frontal regions for the Invalid trials, compared to the Valid ones, whereas monolinguals only showed increased left frontal activity for the opposite comparison. The authors treated this pattern, which is reminiscent of findings in older children (Arredondo et al., 2017), as further evidence that bilingualism affects developmental trajectories, in that being immersed in a dual-language environment affects the function of frontal regions relating to executive control and attention orienting.

4 fNIRS and the bilingual brain at rest

A handful of studies have looked at resting state functional connectivity in bilingualism, following on the footsteps of similar research conducted with fMRI (Tao et al., 2021). Specifically, Blanco et al. (2021) compared fNIRS data collected from 36 Spanish-English bilingual, 30 Spanish monolingual and 33 Basque monolingual infants (mean age: 123 days) during a 9-min sleep. The authors did not report any between-group differences in either spontaneous hemodynamic activity or functional connectivity patterns. This lack of effects was attributed to the limited exposure to bilingual environments (∼4 months) that the infants had received, which may have not been sufficient to affect intrinsic functional connectivity at rest, at least not in ways detectable by fNIRS. Nevertheless, this study introduced a useful methodological and analytical resting-state protocol that can further be utilized in future studies on older children and/or adults. Following up, Gao et al. (2022) reanalyzed the same dataset but focused on functional connectivity in the frontal lobes only, and used a different analytical approach. After performing a graph theory analysis, the authors reported more pronounced left frontal lateralization in bilingual infants; a subsequent effective connectivity analysis showed a left-to-right information flow in frontal lobes in bilingual infants, and the opposite pattern in monolingual ones. These examples help highlight fNIRS as a valid tool for testing resting-state functional connectivity, but also showcase the types of methodological and analytical considerations that are relevant.

5 Looking forward: fNIRS as a method to understand the developing, aging, and diseased bilingual brain

Research using fNIRS on bilinguals has so far revealed patterns that are largely compatible to those reported in studies with other functional neuroimaging methods (e.g., experience-dependent frontal engagement for executive functions tasks, changes in resting state connectivity, a mismatch between behavior and brain function), albeit in samples that are difficult or impossible to study with those methods, especially younger children and, to a much lesser extent, infants. This is an important new direction of the field that should be encouraged, as it provides crucial evidence from a very important demographic, and it can help collecting data from communities where fMRI facilities may not be readily available, including in developing countries and those with non-WEIRD populations (Henrich et al., 2010). The other demographic that could be better studied with fNIRS is older bilinguals, following up on extensive fNIRS research which however has not accounted for bilingualism yet, including on healthy older participants (Yeung and Chan, 2021) and patients diagnosed with progressive neurodegenerative diseases (e.g., Alzheimer's, Parkinson's, Huntington's, Multiple Sclerosis) (Liampas et al., 2024). This is crucial, because the challenging, life-long experience of bilingualism has been suggested to enhance functional connectivity in older age in ways that result in a cognitive reserve, i.e., better preserved cognition on the face of brain decline (Gallo and Abutalebi, 2024). This has been suggested for both healthy older adults and those suffering from progressive neurodegenerative diseases, and can be attributed to more efficient brain connectivity, among other mechanisms (Voits et al., 2020). However, these suggestions have stemmed from a limited number of, largely behavioral, studies, on samples that may be challenging to test with fMRI, due to issues such as incompatibilities (e.g., the presence of peacemakers or mental implants) or reduced mobility. None of these shortcomings apply to fNIRS, and given its suitability for testing functional connectivity, the use of fNIRS for studying cognitive reserves in bilingualism is strongly recommended. This, combined with the study of the developing brain, will help us study the effects of bilingualism on brain function across the entire age spectrum, making fNIRS a key method that will help us refine and improve our current theories on bilingualism and the brain.

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