An optical window into brain function in children and adolescents: A systematic review of functional near-infrared spectroscopy studies

Michael K. Yeung [a,b,*]

[a] Department of Neurology and Neurosurgery, Montreal Neurological Institute, McGill University, Canada
[b] Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong, China

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ABSTRACT

Despite decades of research, our understanding of functional brain development throughout childhood and adolescence remains limited due to the challenges posed by certain neuroimaging modalities. Recently, there has been a growing interest in using functional near-infrared spectroscopy (fNIRS) to elucidate the neural basis of cognitive and socioemotional development and identify the factors shaping these types of development. This article, focusing on the fNIRS methods, presents an up-to-date systematic review of fNIRS studies addressing the effects of age and other factors on brain functions in children and adolescents. Literature searches were conducted using PubMed and PsycINFO. A total of 79 fNIRS studies involving healthy individuals aged 3–17 years that were published in peer-reviewed journals in English before July 2020 were included. Six methodological aspects of these studies were evaluated, including the research design, experimental paradigm, fNIRS measurement, data preprocessing, statistical analysis, and result presentation. The risk of bias, such as selective outcome reporting, was assessed throughout the review. A qualitative synthesis of study findings in terms of the factor effects on changes in oxyhemoglobin concentration was also performed. This unregistered review highlights the strengths and limitations of the existing literature and suggests directions for future research to facilitate the improved use of fNIRS in developmental cognitive neuroscience research.

1. Introduction

During the first two decades of life, many aspects of cognitive, social, and emotional functions undergo continual development. For example, executive functions emerge early in life and continue to improve and differentiate throughout childhood, reaching an adult-like level by middle to late adolescence (Best and Miller, 2010; Romine and Reynolds, 2005). Social skills progress from a reliance on one's egocentric perspective to considering the perspectives and understanding the intentions and false beliefs of others, with mentalizing abilities continuing to mature throughout childhood and into young adulthood (Dumontheil et al., 2010; Wellman et al., 2001). The ability to recognize and empathize with the emotions of others while identifying, expressing, and regulating one's own emotions according to various contexts also undergoes gradual improvement from birth to late adolescence or early adulthood (Lawrence et al., 2015; Zeman et al., 2006). While genes exert a major influence on these forms of development, physical and psychosocial environmental factors also play pivotal roles (Tucker-Drob et al., 2013; Wang and Saudino et al., 2013). For instance, prenatal factors (e.g.,

maternal stress and alcohol exposure in pregnancy) and environmental factors (e.g., socioeconomic status (SES) and bilingualism) shape the cognitive and socioemotional development of children (Beauchamp and Anderson, 2010; Mackey et al., 2012).

From birth to early adulthood, cognitive and socioemotional development are paralleled by gradual structural changes in the brain (Webb et al., 2001). Major dendritic growth and synaptogenesis, which progress rapidly during infancy, as well as neuronal and synaptic pruning, which peak during early and middle childhood, begin from birth and continue into early adulthood. Axonal myelination, which also begins from birth and peaks during middle and late childhood, does not reach full maturity until early adulthood. These forms of neurological development follow inferior-to-superior and posterior-to-anterior gradients, with inferior and posterior primary areas maturing earliest in life and superior and frontal association areas maturing later (Colby et al., 2011; Gogtay et al., 2004; Krogsrud et al., 2016). Notably, brain functions also change due to these neurobiological changes. Numerous functional magnetic resonance imaging (fMRI) studies have shown that children recruit similar neural networks to adults during a variety of tasks,

although the extent to which regions within these networks are engaged appears to be age dependent (Houdé et al., 2010; Yaple and Arsalidou, 2018). Notwithstanding these findings, our understanding of functional brain development—especially development pertinent to social interactions and speech production—remains limited. This is because fMRI, which is the most popular neuroimaging modality, is relatively expensive, sensitive to motion artifacts, and uncomfortable for some children.

In the context of these challenges, there has been an emerging interest in using functional near-infrared spectroscopy (fNIRS) to study functional brain development, and this article focuses on the methods involved in this approach. This technique utilizes near-infrared lights—to which living tissues are relatively transparent—to measure hemodynamic changes that occur at the cortical surface (Villringer and Chance, 1997). When near-infrared lights are delivered to the scalp by light-emitting optodes, they transmit through the skin, skull, cerebrospinal fluid, and brain tissue in a banana-shaped trajectory before leaving the scalp and becoming detected by light-receiving optodes (Okada and Delpy, 2003). When neurons are active, neurovascular coupling occurs, which leads to an increase in oxyhemoglobin concentration (HbO) and a decrease in deoxyhemoglobin concentration (HbR). Since the absorptivity of these two chromophores in the near-infrared region varies as a function of wavelength, an fNIRS device utilizes at least two wavelengths of near-infrared light to measure cerebral hemodynamics using algorithms such as the modified Beer–Lambert law (Delpy et al., 1988). Notably, three fNIRS techniques can be used (Ferrari and Quaresima, 2012). Continuous-wave fNIRS can only measure relative—but not absolute—hemoglobin concentration; however, it remains the most commonly used technique due to its cost-effectiveness. Time- and frequency-domain fNIRS can measure absolute hemoglobin concentration but have rarely been applied in research due to their high instrument costs.

Since fNIRS is relatively resilient to motion artifacts and can be used in a natural setting, it has been increasingly used in research on lifespan development. Applications of fNIRS in infancy or early childhood (Lloyd-Fox et al., 2010; Moriguchi and Hiraki, 2013; Vanderwert and Nelson, 2014) and aging Yeung and Chan, 2020 have been reviewed narratively and systematically, respectively. However, much remains unknown regarding its application in childhood and adolescence, during which cognitive and socioemotional functions undergo continual development. Compared to infants and toddlers, children and adolescents have more independence and autonomy that allow them to make their own decisions, explore new places, and encounter new people. These life experiences can have long-term consequences on their cognition and mental well-being, as well as brain health, because childhood and adolescence constitute critical periods for the development of higher-order cognitive and adaptive emotional skills (Khan et al., 2015; Kim et al., 2013; Larsen and Luna, 2018). The first onset of many commonly occurring mental disorders, including impulse-control, anxiety, substance use, and schizophrenic disorders, also usually occurs in childhood or adolescence (Kessler et al., 2007; Meyer and Lee, 2019). Since fNIRS is less expensive than fMRI and more resistant to motion artifacts than fMRI and EEG, which enable widespread use, its application can help speed up our understanding of the neural mechanisms underlying various aspects of child and adolescent development.

In addition, previous developmental reviews have addressed various methodological issues related to applying fNIRS in infants and young children and summarized the findings of some key studies. They also provided some suggestions for improving the fNIRS setup, task design (e.g., jitter block durations), and data interpretation (e.g., reporting both HbO and HbR). Nevertheless, it is not clear whether these suggestions were taken in developmental studies since then. In addition, since these reviews were published, some empirical investigations and methodological reviews have advanced certain aspects of fNIRS data preprocessing and analysis (Brigadoi et al., 2014; Huppert, 2016; Pinti et al., 2019; Scholkmann et al., 2014). Such advanced knowledge and other method-

ological issues, including those pertinent to statistical power, age correction, artifact removal methods, statistical test assumptions, and quality control, have not been incorporated or addressed in previous reviews, although they are important in ensuring high signal quality and accurate data interpretation. Furthermore, currently there exists a large variety of approaches across different labs, and there is a need for more standardization to facilitate reproducibility. Thus, a systematic review and critical evaluation of the methodological aspects of developmental fNIRS studies is timely and useful for ensuring good and standardized research practice in the field.

Thus, this article aimed to bridge the knowledge gaps by providing a systematic review and critical evaluation of the methodological aspects of fNIRS studies with healthy children and adolescents. The research design, experimental paradigm, fNIRS measurement, data preprocessing, statistical analysis, and result presentation, were evaluated. This review highlights the strengths and limitations of the existing literature and suggests directions for future research to facilitate the improved use of fNIRS in developmental cognitive neuroscience research.

2. Methods

2.1. Search strategy and study selection

This review conformed to the standard methodological guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement (Moher et al., 2009) and was not registered in any registry. A literature search was performed using PubMed and PsycINFO on June 21, 2020 to identify fNIRS studies including healthy children and adolescents. The keywords used were "child*" or "adolescen*" or "teen*" and "near-infrared spectroscopy" or "nirs" or "fnirs". No limits were set for the search.

Following the initial search, the titles and abstracts of the articles were screened. A study was included if it applied fNIRS to study brain function, included at least one sample group with a mean age between 3 and 17 years, and examined the effects of age or other factors (i.e., individual differences or interventions) on cerebral oxygenation in children and adolescents. The article had to be written in English and published as original research in a peer-reviewed journal. The gray literature was excluded to ensure that all included studies were of high quality. Also, studies on psychiatric and neurological disorders or any other medical conditions were excluded to ensure that typically developing children and adolescents were included. After the screening, the full texts of the screened articles were retrieved for eligibility assessment based on the same inclusion and exclusion criteria.

These criteria were set to ensure that the review was representative of the fNIRS literature in healthy children and adolescents, who are in critical developmental periods characterized by growing independence and autonomy. Studies with infants or toddlers were not included because many of them had been covered in previous reviews (Lloyd-Fox et al., 2010; Vanderwert and Nelson, 2014), and research practice in infant and toddler studies can be considerably different from that in child and adolescent studies in terms of the fNIRS setup and task design. In addition, studies focusing on atypical development (i.e., neurodevelopmental disorders) were not included because they have been covered in recent reviews on autism spectrum disorder (Liu et al., 2019) and attention-deficit/hyperactivity disorder (Mauri et al., 2018).

2.2. Data extraction

In addition to the first authors' names and publication years, the following information about the research design, experimental paradigm, fNIRS measurement, data preprocessing, statistical analysis, and result presentation was extracted from each identified article: (a) research design: study type, factors, sample characteristics, *a priori* power analysis, and screening test for psychopathology; (b) experimental paradigm:

functional domain and construct, task, task conditions, paradigm design, intertrial interval, and block duration; (c) fNIRS measurement: model, manufacturer, technique, wavelengths, sampling rate, emitter–detector spacing, emitter number, detector number, channel number, brain regions, and presence of channel registration; (d) data preprocessing: toolbox/software, manual and automatic removal, simple frequency filtering, motion/systemic correction, detrending, autocorrelation correction, other artifact removal methods, and age correction of differential pathlength factor; (e) statistical analysis: test for factor effects, normality check for fNIRS signals, channel clustering (for region-of-interest analysis), channel-wise multiple comparison correction, and use of a hemodynamic response function model; (f) result presentation: brain function, fNIRS measures, main effects and contrasts, HbO and HbR results, analysis of both HbO and HbR, significant results found for HbR only, and image reconstruction for factor effects. All attributes and results were synthesized qualitatively rather than quantitatively due to the large variability in fNIRS systems and data analysis across studies. No study authors were contacted for additional information.

These aspects were reviewed in light of the features or limitations of fNIRS: (a) research design: due to the relatively low signal-to-noise ratio of fNIRS compared to fMRI, sufficient statistical power and homogeneous samples are important in fNIRS studies; (b) experimental paradigm: since fNIRS measurement is limited to certain cortical areas, fNIRS may be preferentially applied to study some types of functions. Task parameters, such as trial and block durations, also influence the estimation of the hemodynamic response; (c) fNIRS measurement: the nature of signals measured by an fNIRS device critically depends on its specification (e.g., optode arrangement) and where the optodes are placed on the scalp; (d) data preprocessing: artifacts are common in fNIRS signals, and the adequacy and efficiency of artifact removal/modeling determine the quality of fNIRS measurements; (e) statistical analysis: various data analysis methods exist for fNIRS, each with its assumptions, and a violation of the assumptions may yield inaccurate results; (f) result presentation: fNIRS yields (changes in) HbO and HbR, and the relationship between them informs the quality of signals and the strength of evidence.

2.3. Data coding

Each identified study was coded based on the aforementioned attributes. While some attributes were coded as binary (i.e., yes/no) or continuous, others were coded in categories as follows. For study type, studies examining age effects were classified as cross-sectional or longitudinal, while those examining non-age effects were classified as correlational if individual differences were studied and as experimental or quasi-experimental (e.g., experiments without control) if interventions were studied. Functional domains were categorized into executive function, language, social function, working memory (WM), arithmetic, attention, sensory function, motor function, emotion, or rest. Paradigm designs were coded as blocked if a task involved the repeated or continuous presentation of one task condition and alternation between task conditions, as event-related if a task involved different discrete and transient events presented in a randomized order, and as mixed if a task involved alternation between task conditions, with different events presented in a randomized order during one condition.

Preprocessing for fNIRS data typically involves trial and channel rejection, simple frequency filtering, motion/systemic correction, detrending, and/or temporal autocorrelation correction (Scholkmann et al., 2014), which were coded as follows: (a) whether artifactual data were removed manually, guided by visual inspection or video recording, or using (semi-)automatic algorithms based on amplitude and/or standard deviation (SD) criteria; (b) whether cardiac and respiratory activities, Mayer waves, and slow drifts were attenuated using simple lowpass, highpass, and/or moving-average filtering; (c) whether motion and sys-

temic artifacts were corrected using advanced algorithms, including the movement artifact reduction algorithm (MARA; i.e., spline interpolation), wavelet filtering, correlation-based signal improvement (CBSI), functional–systemic separation, or temporal derivative distribution repair (TDDR); (d) whether detrending was performed using methods other than simple highpass filtering, including discrete cosine transform (DCT)-based highpass filtering, wavelet minimum description length (wavelet-MDL) detrending, or polynomial fitting; (e) whether temporal autocorrelation was corrected using precoloring or prewhitening; (f) whether other methods such as independent component analysis (ICA) and the autoregressive iteratively reweighted least squares (AR-IRLS) algorithm were applied to model and correct for noise.

A test for factor effects refers to statistical tests (e.g., ANOVA) used to assess the effects of certain factors on brain function. Brain function refer to the dimension of fNIRS signals examined, including the level, laterality, latency, connectivity, network organization, and interpersonal synchrony of changes in HbO and/or HbR. fNIRS measures include HbO and/or HbR variables representing different aspects of brain function. Main effects and contrasts indicate the key (pair of) task conditions used to assess the factor effects on fNIRS measures. Where contrasts between two task conditions and between a task condition and a non-task condition were present, the former was chosen. Finally, for HbO and/or HbR results, '+' and '-' indicate significant positive and negative factor effects, respectively, while 'o' indicates no significant factor effect. When multiple comparison corrections were performed, the results after correction were considered.

Overall, there was only one coder, but it is unlikely that any of the review's conclusions would be influenced by inclusion of more coders. This is because this review focused on the methodological aspects of fNIRS studies, and the coding was straightforward and objective for most items. Nevertheless, a second coder was sought to classify the functional domain of tasks, where judgments can be split. Any discrepancy was resolved by consensus.

2.4. Risk of bias assessment

Throughout the review, the risk of bias assessment was conducted similarly to a recent systematic review on the application of fNIRS in aging research (Yeung and Chan, 2020). Underpowered studies are prone to false-negative and false-positive error (Forstmeier et al., 2017), while multichannel fNIRS studies that fail to correct for multiple comparisons at the channel or regional level also have an increased risk of false-positive error. Thus, it was noted whether studies performed *a priori* power analysis and applied multiple comparison correction when testing the factor effects on fNIRS variables in multiple regions. Notably, developmental changes in skull and brain structures lead to differences in the distance of light traveling from source to detector in the head, affecting changes in hemoglobin concentration measured by fNIRS (Duncan et al., 1996). Therefore, it was also noted whether studies controlled for these age-related differences by adjusting the differential pathlength factor for age or by using effect size or other unitless metrics that are independent of the assumed differential pathlength factor.

Artifacts are common in fNIRS signals and may lead to deviant observations that distort parametric tests. Thus, it was examined whether studies performed normality checks for fNIRS signals before statistical analysis. Moreover, it is common for fNIRS studies to analyze only HbO because this index typically has a higher signal-to-noise ratio and exhibits a higher correlation with blood-oxygen-level-dependent (BOLD) signals compared to HbR (Cui et al., 2011; Strangman et al., 2002). However, some researchers may also analyze HbR because only this index can yield significant results. Thus, whether studies reported both fNIRS indices when addressing factor effects and whether they reported significant results for HbR only were examined to determine the potential presence of reporting bias.
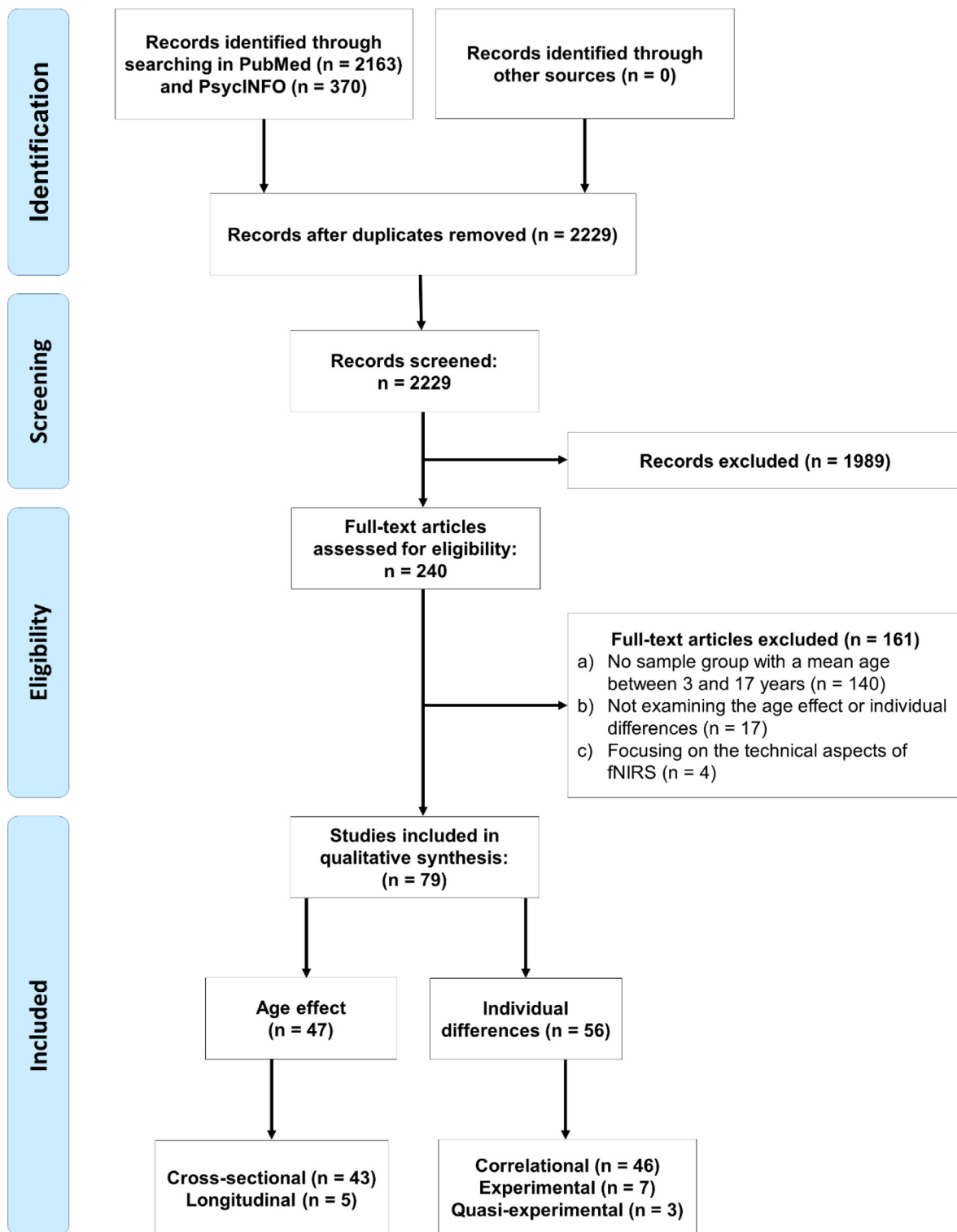
Fig. 1. Flow of the literature search and study selection process.

3. Results

3.1. Flow of the literature search and publication trends

Fig. 1 illustrates the flow of the literature search. Initially, 2163 and 370 articles were identified via PubMed and PsycINFO, respectively. Following screening and eligibility assessment, 79 articles were included in the review. A summary of these studies is provided in Table 1 and the

age range of the study samples is shown in Supplementary Table 1. A total of 45 studies included preschoolers aged 3–5 years, 63 included (primary school) children aged 6–11 years, and 29 included (secondary school) adolescents aged 12–17 years. Fig. 2 presents the annual number of published fNIRS articles about children and adolescents. The first article was published in 2002, and there was no more than one article published each year between 2002 and 2008. After 2008, approximately four articles were published each year until 2018, where the number of

Table 1
Summary of functional near-infrared spectroscopy (fNIRS) studies involving healthy children and adolescents.

Authors	Year	Functional domain (construct)	Factor	Sample (N, mean (SD) [range])	Task	Task conditions	fNIRS system	Brain function (fNIRS measure)	Main effects and contrasts	Oxyhemoglobin concentration (HbO) results
Hoshi and Chen	2002	Emotion (perception)	Age	n = 16, 4.9 (0.8) [4–6]	Video watching	Startle response, anticipation, expectation, unpleasant and pleasant, neutral videos	2 bilateral frontal channels (HEO200; Omron)	Level (mean change)	Emotional > neutral	Age: +
Schroeter et al.	2004	EF (inhibition)	Age	n = 23, 10.4 (1.9) [7–13]; n = 14, 23.9 (3.1) [19–29]	Matching Stroop	Neutral, congruent, incongruent trials	6 bilateral frontal channels (NIRO-300; Hamamatsu)	Level (mean change)	Incongruent > neutral	Age: +
Matsuda and Hiraki	2006	Attention (sustained attention)	Age, task performance	n = 8 for the puzzle game and n = 10 for the fighting game [7–14]	Video game playing	Puzzle, fighting games	24 bilateral frontal channels (OMM-1080S; Shimadzu)	Level (Pearson's r with a boxcar function)	Puzzle, fighting > rest	Age: o, -; Task performance: o, /
Wartenburger et al.	2007	Language (sentence processing)	Sex	n = 51, 4.1 (0.1) [4–4]	Prosody listening	Normal sentences, hummed stimuli, flat stimuli	10 bilateral frontal, temporal channels (Omniat Tissue Oxymeter; ISS)	Level (hrf beta)	Normal sentences, hummed stimuli, flat stimuli	Sex: o, o, o
Dresler et al.	2009	Arithmetic (mental arithmetic)	Age	n = 46 (35 analyzed), 10.0 (0.5); n = 44 (41 analyzed), 13.9 (0.8)	Two-digit addition	Numeric, word problems × calculation, reading	44 bilateral frontal, parietal channels (ETG-4000; Hitachi)	Level (rate of change), laterality (rate of change)	Calculation > reading	Age: o (level), - (laterality)
Moriguchi and Hiraki	2009	EF (shifting)	Age, task performance	n = 15, 3.4 (0.3) [3.1–3.9]; n = 11, 5.7 (0.3) [5.1–6.2]	Dimensional Change Card Sort	Preswitch, postswitch phases	20 bilateral frontal channels (OMM-1080S; Shimadzu)	Level (mean change)	Preswitch, postswitch > rest	Age: o, o; Task performance: +, +
Tsujii, Masuda et al.	2009	Language (verbal fluency)	Intervention (antihistamine)	n = 15, 7.7 [7–8]	Phonemic fluency	Japanese syllables /a/, /ha/, /ra/	44 bilateral frontal channels (ETG-7000; Hitachi)	Level (mean change)	Phonemic fluency > rest	Sedating antihistamine: -; Nonsedating antihistamine: o
Tsujii, Yamamoto et al.	2009	WM (spatial WM maintenance)	Age, task performance	n = 8; Time 1: 5.1 (0.4) [5–6]; Time 2: 7.1 (0.4) [7–8]	Item recognition	8 s of delay	44 bilateral frontal channels (ETG-7000; Hitachi)	Level (mean change), laterality (mean change)	Spatial WM > rest	Age: - (level), + (laterality); Task performance: o (laterality)
Okamoto et al.	2010	Social (social appreciation)	Intervention (writing therapy), task performance	n = 16; 12.1 (0.8)	Positive affective thinking	Imagining, writing × antegrade (from self to others), retrograde (from others to self)	46 bilateral frontal, temporal, parietal channels (ETG-4000; Hitachi)	Level (mean change)	Mental tasks, writing tasks > rest	Writing therapy: + (mental), - (writing); Task performance: ± (writing)
Tsujii et al.	2010	WM (spatial WM maintenance)	Intervention (antihistamine)	n = 15, 5.5 (0.5) [4.5–6.7]	Item recognition	8 s of delay	44 bilateral frontal channels (ETG-7000; Hitachi)	Level (mean change)	Spatial WM > rest	Sedating antihistamine: -; Nonsedating antihistamine: o
Brink et al.	2011	Social (information processing)	Age	n = 24, 5.0 [4.0–6.5]; n = 24, 7.5 [6.5–8.7]	Watching or listening	Affective empathy, cognitive empathy, neutral stories with one or two characters	39 bilateral frontal, temporal, parietal channels (DYNOT; NIRx)	Level (hrf beta)	Affective empathy, cognitive empathy > neutral stories	Age: +, o

Table 1 (*continued*)

Authors	Year	Functional domain (construct)	Factor	Sample (*N*, mean (*SD*) [range])	Task	Task conditions	fNIRS system	Brain function (fNIRS measure)	Main effects and contrasts	Oxyhemoglobin concentration (HbO) results
Kawakubo et al.	2011	Language (verbal fluency)	Age, sex, task performance	*n* = 48, 10.9 (3.4) [5.5–18.6]; *n* = 22, 27.3 (5.5) [21.4–37.4]	Phonemic fluency	Japanese syllable /a/	2 bilateral frontal channels (NIRO-200; Hamamatsu)	Level (mean change)	Phonemic fluency > rest	Age: + (males only); Sex: o; Task performance: o
Moriguchi and Hiraki	2011	EF (shifting)	Age, task performance	*n* = 15 (13 analyzed); Time 1: 3.4 (0.3) [3–3]; Time 2: 4.2 (0.3) [4–4]	Dimensional Change Card Sort	Preswitch, postswitch, control phases	20 bilateral frontal channels (ONM-1080S; Shimadzu)	Level (mean change)	Preswitch, postswitch > control	Age: +, +; Task performance: +, +
Remijn et al.	2011	Sensory (perception)	Age	*n* = 27 (19 analyzed), 4.2 (0.6) [3–4]; *n* = 19 [20–41]	Watching	Static, dynamic videos	37 bilateral frontal channels (FOIRE-3000; Shimadzu)	Level (mean change), latency (time to peak or minimum)	Static and dynamic videos > rest	Age: - (latency); {HbR} Age: o (level)
Sanefuji et al.	2011	WM (visual and verbal WM maintenance)	Age, task performance	*n* = 19, 7.5 (1.6) [5.4–11.0]	WM maintenance	Visual, auditory presentation of familiar items	4 bilateral frontal channels (OMM-2001; Shimadzu)	Level (ratio of the range of change (visual–auditory index))	Visual > auditory WM	Age: o; Task performance: o
Sugiura et al.	2011	Language (word processing)	Age	*n* = 484 (392 analyzed), 8.9 (0.9) [8–10]	Word repetition	1st (Japanese), 2nd (English) language × high-, low-frequency words	44 bilateral frontal, temporal, parietal channels (ETG-4000; Hitachi)	Level (mean change)	high- > low-frequency words	Age: o
Hidaka et al.	2012	Language (sentence processing)	Bilingualism (2nd language exposure)	*n* = 22 [3.9–4.8]; *n* = 13 [5.0–5.9]; *n* = 16 [20–25]	Connected speech listening	1st (Japanese), 2nd (English), rarely exposed (Chinese) languages	24 bilateral frontal, temporal channels (ETG-100; Hitachi)	Level (mean change around peak)	Exposed > rarely exposed speech	2nd language exposure [Bilingualism]: +
Jasinska and Petitto	2013	Language (sentence processing)	Age, bilingualism, age of bilingual exposure	Monolinguals: *n* = 20, 8.9 [7–10]; *n* = 9, 19 [17–24]; Bilinguals: *n* = 20, 8.9 [7–10]; *n* = 10, 19.9 [17–26]	Sentence judgment	Object-subject, subject-object sentences × plausible, implausible	42 bilateral frontal, temporal channels (ETG-4000; Hitachi)	Level (hrf beta)	Age: subject-object > object-subject; Bilingualism, age of bilingual exposure: sentence processing	Age: ±; Bilingualism: +; Age of bilingual exposure (later- > early-exposed): +
Mehnert et al.	2013	EF (inhibition)	Age	*n* = 22, 4.8 (0.6) [4–6]; *n* = 20, 26.3 (4.3) [21–36]	Go/No-go	Go, No-go trials	80 bilateral frontal, temporal, parietal channels (DYNOT 232; NIRx)	Level (hrf beta), connectivity (partial coherence coefficient)	Level: No-go > go; Connectivity: full time course	Age: - (level), - (connectivity)
Yamasaki et al.	2013	Social (information processing)	Age, sex	*n* = 10, 4.1 (0.4) [3–4.5]; *n* = 10, 5.6 (0.4) [4.5–6]	Listening	Mothers' voice, unfamiliar voice, environmental sound	44 bilateral frontal, temporal, parietal channels (ETG-4000; Hitachi)	Level (mean change)	Mother's voice > unfamiliar voice or environmental sound	Age: -; Sex (M>F): + (older group only)
Anderson et al.	2014	EF (inhibition)	Age	*n* = 17, 6.0 (1.0) [4–8]	Go/No-go	Go, Go/No-go blocks	16 bilateral frontal channels (1100; fNIR Devices)	Variability (oxygenation variability based on oxygen saturation)	Full time course	Age: ± (quadratic)
Buss et al.	2014	WM (visual WM maintenance)	Age	*n* = 28 (7–14 analyzed), 3.5 (0.1) [3–3]; *n* = 19 (12–17 analyzed), 4.5 (0.2) [4–4]	WM maintenance	Set sizes of 1, 2, and 3	24 bilateral frontal, parietal channels (CW6; TechEn)	Level (mean change)	Large > medium > small WM set size	{Difference between HbO and HbR} Age: +

Table 1 (*continued*)

Authors	Year	Functional domain (construct)	Factor	Sample (N, mean (SD) [range])	Task	Task conditions	fNIRS system	Brain function (fNIRS measure)	Main effects and contrasts	Oxyhemoglobin concentration (HbO) results
Ding et al.	2014	Social (face recognition)	Age	n = 72, 10.0 (1.8) [7.1–13.5]	Same/old face recognition	Own-race, other-race faces	46 bilateral frontal, occipital channels (ETG-4000; Hitachi)	Level (hrf beta), connectivity (Pearson's r)	Own-race > other-race	Age: + (level), ± (connectivity)
Fekete et al.	2014	Sensory (visual processing)	Temperament (effortful control)	n = 35, 4.5 [3–5]	Movie viewing	Novel, familiar, emotional, neutral stimuli	24 bilateral frontal channels (ETG-4000; Hitachi)	Network organization (characteristic path length, clustering coefficient, small-worldness)	Full time course	Temperamental effortful control: - (path length), + (clustering), + (small-worldness)
Jasińska and Petitto	2014	Language (word processing)	Age, bilingualism	n = 32, 8.6 (0.9) [6–10]; n = 16, 18.8 (0.8)	Word reading (1st language)	Regular, irregular, nonsense words	46 bilateral frontal, temporal, parietal channels (ETG-4000; Hitachi)	Level (hrf beta)	Regular or irregular words > nonsense words	Age: -; Bilingualism: +
Li and Qiu	2014	Rest	Age, sex	n = 12 (11 analyzed), 9.0 (1.5); n = 20, 23.4 (0.9) [22–25]	Sitting with eyes closed	/	44 bilateral frontal, temporal (FOIRE-3000; Shimadzu)	Connectivity (Pearson's r)	Sitting	Age: +; Sex: o
Perlman et al.	2014	Emotion (emotion regulation)	Temperament (frustration tolerance)	n = 22 (17 analyzed), 4.5 [3.0–6.4]	Frustrative Emotion Task for Children	Frustration, winning	12 bilateral frontal channels (CW6; TechEn)	Level (hrf beta)	Frustration > winning	Frustration tolerance [Temperament]: -
Tando et al.	2014	Language (verbal fluency)	Age, task performance	n = 37, 16.6 (9.7) [6–18]; n = 9, 34.8 (4.8)	Phonemic fluency	Japanese syllable /ka/, syllable repetition	22 bilateral frontal channels (ETG-4000; Hitachi)	Level (mean change)	Phonemic fluency > syllable repetition	Age: +; Task performance: o
Goto et al.	2015	Language (word processing)	Age	n = 42, 7.9 (0.6) [7.0–8.8]; n = 35, 9.8 (0.6) [9.0–10.8]; n = 26, 11.8 (0.6) [11.0–12.8]	Word repetition	Repeat, reverse blocks	16 bilateral frontal channels (OEG-16; Spectratech)	Level (mean change), laterality (mean change)	Reverse > repeat	Age: o (level), + (laterality)
Moriguchi et al.	2015	EF (shifting)	Intervention (doll-play-based intervention), imaginary companion	Study 2: n = 15, 5.2 (0.7) [3–5]	Dimensional Change Card Sort	Preswitch, postswitch phases	16 bilateral frontal channels (OEG-16; Spectratech)	Level (mean change)	Preswitch and postswitch > rest	Intervention: +; Imaginary companion: o
Paquette et al.	2015	Language (verbal fluency)	Age	n = 10, 5.0 (1.1) [3–6]; n = 10, 8.6 (1.2) [7–10]; n = 12 (11 analyzed), 14.0 (1.7) [11–16]; n = 11 (9 analyzed), 24.5 (3.4) [19–30]	Semantic fluency	Categories (animals, toys, fruits, etc.)	62 bilateral frontal, temporal channels (Imagent; ISS)	Level (mean change around peak)	Semantic fluency > rest	Age: +
Sugiura et al.	2015	Language (word processing)	Age, sex, bilingualism (2nd language proficiency)	n = 484 (392 analyzed), 8.9 (0.9) [6–10]	Word repetition	1st (Japanese), 2nd (English) language × high-, low-frequency words	44 bilateral frontal, temporal, parietal channels (ETG-4000; Hitachi)	Level (mean change)	2nd language high-frequency words > rest	Age: -; Sex (M>F): +; 2nd language proficiency [Bilingualism]: + (males only)

Table 1 (*continued*)

Authors	Year	Functional domain (construct)	Factor	Sample (*N*, mean (*SD*) [range])	Task	Task conditions	fNIRS system	Brain function (fNIRS measure)	Main effects and contrasts	Oxyhemoglobin concentration (HbO) results
Gallagher et al.	2016	Rest, language (verbal fluency)	Age	*n* = 25, 10.0 (4.1) [3–16]; *n* = 8, 23.8 (4.2) [18–30]	Sitting with eyes open, semantic fluency	/, categories (animals, toys, color, etc.)	68 bilateral frontal, temporal, parietal channels (Imagent; ISS)	Similarity of the spatial distribution (dice similarity coefficient) and laterality of activity (laterality index) between states	Semantic fluency = rest	Age: o (similarity of spatial distribution), o (similarity of laterality)
Lambrick et al.	2016	EF (inhibition)	Intervention (acute exercise), task performance	*n* = 20, 8.8 (0.8) [8–10]	Stroop	Congruent, incongruent trials	3 dominant-side frontal channels (Portalite; Artinis)	Level (mean change)	Stroop > rest	Exercise (intermittent > continuous): o; Task performance: o
Mehta et al.	2016	EF (shifting, inhibition), WM (visual WM maintenance)	Intervention (stand-biased desks)	*n* = 14, 14.1 (0.4)	Wisconsin Card Sorting Test, flanker, memory span, Trail Making, Stroop	Card sort, congruent or incongruent tasks, WM maintenance, numbers/letters only or alternating numbers and letters, color naming or word reading	2 bilateral frontal channels (NIRO-200NX; Hamamatsu)	Level (mean change)	Card sort, flanker, memory span, Trail Making, Stroop > rest	Stand-biased desks: -, o, +, +, o
Perlman et al.	2016	WM (spatial WM maintenance)	Age	*n* = 68, 5.0 (1.2) [3.0–7.8]	WM maintenance	2 s, 6 s delay	12 bilateral frontal channels (CW6; TechEn)	Level (hrf beta)	Short and long WM > rest	Age: +
Vandekerckhove et al.	2016	Motor (cycling)	Sex	*n* = 18, 10.9 (1.0) [9–12]	Maximal incremental exercise test	0–100% peak power output	1 left frontal channel (NIRO-200NX; Hamamatsu)	Level (mean change)	Cycling > rest	Sex (M>F): +
Zhou et al.	2016	Social (face recognition)	Age	*n* = 124, 7.8 (2.8) [3.3–13.5]	Old/new paradigm	Own-race (Chinese), other-race (Caucasian) faces	46 bilateral frontal, occipital channels (ETG-4000; Hitachi)	Connectivity (Granger causality)	Own-race > other-race	Age: ±
Arredondo et al.	2017	EF (inhibition)	Age, task performance, bilingualism, 1st language, proficiency	Monolinguals: *n* = 14, 9.7 (1.7) [7.3–13.6]; Bilinguals: *n* = 13, 10.3 (1.5) [8.6–13.3]	Flanker	Neutral, congruent, incongruent trials	14 bilateral frontal channels (CW6; TechEn)	Level (hrf beta)	Incongruent > congruent	Age: o; Task performance: o; Bilingualism: ±; 1st language proficiency: o
Jasińska et al.	2017	Language (word processing)	Bilingualism	English monolinguals: *n* = 11, 8.1 (0.7); Spanish-English bilinguals: *n* = 7, 8 (1); French-English bilinguals: *n* = 6, 8.3 (1) [7–9]	Overt word reading	Regular, irregular, pseudowords	44 bilateral frontal, temporal, parietal channels (ETG-4000; Hitachi)	Level (hrf beta)	Regular words, irregular words, pseudowords	{HbR} Bilingualism: ±, +, ±

Table 1 (*continued*)

Authors	Year	Functional domain (construct)	Factor	Sample (*N*, mean (*SD*) [range])	Task	Task conditions	fNIRS system	Brain function (fNIRS measure)	Main effects and contrasts	Oxyhemoglobin concentration (HbO) results
Li et al.	2017	EF (inhibition)	Age, temperament (irritability)	n = 46, 4.8 (0.7) [3.2–5.9]	Pet Store Stroop	Congruent, incongruent trials	12 bilateral frontal channels (CW6; TechEn)	Level (hrf beta)	Incongruent > congruent	Age: o; Irritability: + [Temperament: -]
Smith et al.	2017	EF (inhibition), WM (visual WM updating)	Age, task performance	n = 21 for Go/No-go and 15 for n-back, [4.1–10.4]	Go/No-go, shape n-back	Go or Go/No-go blocks, 0- or 1-back blocks	16 bilateral frontal channels (1100; fNIR Devices)	Level (change)	Go/no-go > go; 1-back > 0-back	Age: +, +; Task performance: +, +
Sugiura et al.	2017	Language (word processing)	Age, sex, gene (the catechol-O-methyltransferase gene)	n = 246, 8.9 (0.8) [6–10]	Word repetition	High-, low-frequency words	44 bilateral frontal, temporal, parietal channels (ETG-4000; Hitachi)	Level (mean change)	Word repetition > rest	Age: o; Sex: o; The gene (Met carriers > Val homozygotes): + (older group only)
Artemenko et al.	2018	Arithmetic (mental arithmetic)	Age	n = 19, 12.2 (0.3) [11.8–12.8]	Arithmetic production	Addition, subtraction, multiplication, division × simple, complex problems	44 bilateral frontal, temporal, parietal channels (ETG-4000; Hitachi)	Level (mean change)	Addition, subtraction, multiplication, division > rest	Age: +, -, +, o (± overall)
Cai et al.	2018	Rest	Age	n = 30, 8.1 (0.6) [7.0–8.9]; n = 30, 11.9 (0.6) [11.0–12.9]; n = 30, 23.2 (1.9) [19–27]	Rest with eyes closed	/	46 bilateral frontal, parietal, occipital channels (CW6; TechEn)	Network organization (clustering coefficient, characteristic path length, small-worldness, global efficiency, local efficiency, modularity, nodal degree, nodal efficiency)	Rest	Age: -, +, -, -, o, -, ±, -
Grabell et al.	2018	Emotion (emotion regulation)	Temperament (irritability)	n = 92, 5.2 (1.3) [3–7]	Frustrative Emotion Task for Children	Frustration, winning	12 bilateral frontal channels (CW6; TechEn)	Level (hrf beta)	Frustration	Irritability: ± (inverted U) [Temperament: ±; U-shaped]
Groba et al.	2018	Language (word processing)	Bilingualism	Monolinguals: n = 28 (22 analyzed), 5.0 (0.3) [4.8–5.9]; Bilinguals: n = 32 (12 analyzed), 5.0 (0.5) [4.3–6.0]	German adjective learning with pragmatic cues (1st language)	Property focus, category focus, test trial	26 bilateral frontal, temporal, parietal channels (NIRScout; NIRx)	Level (hrf beta)	Word familiarization (learning)	Bilingualism: +
Li et al.	2018	EF (inhibition)	Intervention (fantastical experience)	Study 2: n = 19, 6.0 (0.8)	Go/No-go	Go, no-go trials	22 bilateral frontal channels (LABNIRS; Shimadzu)	Level (hrf beta)	Go, no-go	Fantastical experience (viewing > playing): +, +
Moriguchi and Shinohara	2018	EF (inhibition)	Age, task performance	n = 99 (43 retested), 5.0 (0.9) [3.5–6.4]	Delay of gratification	Choice between immediate and delayed options	16 bilateral frontal channels (OEG-16; Spectratech)	Level (mean change)	Choice > rest	Age: o; Task performance (high > low delayers): -
Mücke et al.	2018	Language (verbal fluency), arithmetic	Physical (physical activity level)	n = 50, 10.6 (0.3) [10–11]	Semantic fluency, phonemic fluency, backward subtraction	Animals or groceries, "F" or "A", subtractions in steps of 13 starting from "570" or "480"	16 bilateral frontal channels (NIRSport; NIRx)	Level (mean change)	Semantic fluency > rest; Phonemic fluency > rest; Backward subtraction > rest	Physical activity level [Physical]: o, o, o

Table 1 (*continued*)

Authors	Year	Functional domain (construct)	Factor	Sample (N, mean (SD) [range])	Task	Task conditions	fNIRS system	Brain function (fNIRS measure)	Main effects and contrasts	Oxyhemoglobin concentration (HbO) results
Reindl et al.	2018	Social (parent-child dyad)	Age, sex, task performance, temperament (emotion regulation), parental (emotion regulation)	n = 33, 7.5 (0.9) [5–9]	Ball catching	Cooperation, competition × parent, stranger	22 bilateral frontal channels (ETG-4000; Hitachi)	Interpersonal synchrony (proportion of supra-cutoff wavelet coherence values)	Age, sex, task performance: cooperation with parents; Emotion regulation: cooperation with parents > with strangers	Age: o; Sex (M>F): -; Task performance: +; Child emotion regulation [Temperament]: +; Parental emotion regulation [Parental (good > poor)]: +
Sakakibara et al.	2018	Language (verbal fluency)	Age, sex, gene (heritability), SES	Monozygotic pairs: n = 27 (23 analyzed), 11.9 (3.5) [5–17]; Dizygotic pairs: n = 12 (9–10 analyzed), 10 (3.9) [5–17]	Semantic fluency	Fruit	2 bilateral frontal channels (NIRO-200; Hamamatsu)	Age, sex, SES: Level (mean change); Genetics: Similarity of signal waveforms (Pearson's r)	Semantic fluency > rest	Age: +; Sex: o; Heritability (monozygotic > dizygotic twins): +; SES: o
Sugiura et al.	2018	Language (sentence processing)	Bilingualism (2nd language proficiency)	n = 53, 13.9 (0.9) [12–15]	Listening (2nd language)	Correct sentences, incorrect sentences, filler sentences, no sound, pure tone	44 bilateral frontal, temporal, parietal channels (ETG-4000; Hitachi)	Level (hrf beta)	Correct sentences, incorrect sentences	2nd language proficiency [Bilingualism]: + (both sexes), ± (males: -; females: +)
Soltanlou et al.	2018	Arithmetic	Intervention (arithmetic training)	n = 20, 11.1 (0.5)	Multiplication problem-solving	Trained, untrained × simple, complex problems	44 bilateral frontal, temporal, parietal channels (ETG-4000; Hitachi)	Level (hrf beta)	Simple (trained > untrained), complex (trained ≥ untrained)	Training: o, -
Suzuki et al.	2018	WM (spatial WM maintenance)	Age	n = 25, 8.4 (0.4) [7–8]; n = 36, 9.9 (0.6) [9–10]; n = 19, 11.9 (0.4) [11–12]	WM maintenance	Sequential presentation, simultaneous presentation, baseline task	16 bilateral frontal channels (OEG-16; Spectratech)	Laterality (laterality of mean change)	Sequential, simultaneous > baseline	Age: o, +
Witmer et al.	2018	WM (spatial WM manipulation)	IQ	Low-IQ: n = 18, 11.6 (0.6) [11–13]; High-IQ: n = 24, 11.8 (0.6) [11–13]	Backward span	Pseudorandom, systematic presentation	20 left frontal channels (FOIRE-3000; Shimadzu)	Level (hrf beta)	Pseudorandom > systematic	IQ: -
Yabe et al.	2018	Language (story processing)	Intervention (familiarization)	Storytelling-naïve: n = 5, 8.3 (1.6); Picture-book-naïve: n = 4, 8.7 (1.5); Storytelling-familiarized: n = 10, 6.0 (1.5); Picture-book-familiarized: n = 10, 6.4 (1.7) [4–11]	Listening stories read by an unfamiliar person	Storytelling, picture-book reading	22 bilateral frontal channels (ETG-4000; Hitachi)	Level (mean change)	Storytelling, picture-book reading > word recitation	Familiarization: o, -
Arredondo, Hu, Satterfield et al.	2019	Language (word processing)	Bilingualism, IQ, SES (family income), task performance	Monolinguals: n = 22, 8.1 [7.1–9.9]; Bilinguals: n = 21, 8.1 [7.1–9.9]	Lexical selection (1st language)	Phonologically related words, phonologically unrelated words, baseline task	44 bilateral frontal, temporal, parietal channels (CW6; TechEn)	Level (hrf beta)	Overall lexical selection	Bilingualism: -; IQ: +; Family income [SES]: o; Reaction time: + [Task performance: -]

Table 1 (*continued*)

Authors	Year	Functional domain (construct)	Factor	Sample (*N*, mean (*SD*) [range])	Task	Task conditions	fNIRS system	Brain function (fNIRS measure)	Main effects and contrasts	Oxyhemoglobin concentration (HbO) results
Arredondo, Hu, Seifert et al.	2019	Language (sentence processing)	Bilingualism	Monolinguals: *n* = 18, 9.6 (1.8) [6.6–13.6]; Bilinguals: *n* = 15, 10.7 (1.3) [6.9–12.4]	Auditory grammaticality judgment (1st language)	Corrects, errors for early-acquired morphemes, errors for later-acquired morphemes	16 bilateral frontal channels (CW6; TechEn)	Level (hrf beta)	Errors on late-acquired morphemes > errors on early-acquired morphemes, corrects	Bilingualism: ±, ±
Cai et al.	2019	Rest	Age	*n* = 30, 8.1 (0.6) [7.0–8.9]; *n* = 30, 23.2 (1.9) [19–27]	Rest with eyes closed	/	46 bilateral frontal, parietal, occipital channels (CW6; TechEn)	Connectivity (Pearson's *r*), laterality of network organization (global efficiency asymmetry, local efficiency asymmetry, nodal efficiency asymmetry)	Rest	{HbR} Age: +, o, +, ±
Chevalier et al.	2019	EF (inhibition, shifting)	Age, task performance	*n* = 30, 5.9 (0.6) [5.1–6.9]; *n* = 30, 8.8 (0.6) [8.1–10.0]	Modified Real Animal Size Test	Congruent, incongruent trials × feedback in a neutral, cooperative, or competitive context	20 bilateral frontal channels (NTS; Gowerlabs)	Level (mean change)	Age: Switching > inhibition or control; Task performance: executive function > rest	Age: +; Task performance: - (older group only)
Dumont et al.	2019	EF (inhibition), emotion (facial emotion recognition)	Sex, SES (adversity)	High-risk: *n* = 20, 5.9 (0.6) [5–6]; Low-risk: *n* = 18, 5.7 (0.6) [5–6]	Animal Stroop, emotion labeling	Congruent or incongruent trials, happy or angry faces	32 bilateral frontal channels (unknown model and manufacturer)	Level (mean change)	Stroop: incongruent > congruent; Emotion: angry > happy faces	Sex: o, o; Adversity: -, o [SES: +, o]
Fishburn et al.	2019	EF (inhibition)	Temperament, task performance	*n* = 118, 4.9 (0.6) [4–5]	Go/No-go	Go, Go/No-go blocks	10 bilateral frontal channels (NIRScout; NIRx)	Level (hrf beta)	Go/No-go > Go	Temperament: -; Task performance: -
Grabell et al.	2019	Emotion (emotion regulation)	Intervention (deliberate emotion regulation interpersonal scaffolding), temperament (emotion regulation)	*n* = 60 (scaffolding or control), 4.9 (0.9) [4–6]	Incredible Cake Kids (frustration)	Positive, negative feedback	10 bilateral frontal channels (CW6; TechEn)	Level (hrf beta)	Positive feedback, negative feedback after frustration	Interpersonal scaffolding: +, o; Temperament: o, o
Groba et al.	2019	Language (word learning)	Bilingualism	Monolinguals: *n* = 28 (21 analyzed), 5.0 (0.3) [4.8–5.9]; Bilinguals: *n* = 32 (13 analyzed), 5.0 (0.5) [4.3–6.0]	Novel property term learning (German; 1st language)	Property focus, category focus, test trial	26 bilateral frontal, temporal, parietal (NIRScout; NIRx)	Level (hrf beta)	Word familiarization (learning)	Bilingualism: -
Huang et al.	2019	EF (inhibition)	Age, sex, task performance, physical (body mass index)	*n* = 38, 16.1 (4.8) [9–25]	Modified Stroop	Congruent, incongruent trials	20 bilateral frontal channels (unknown model; NIRx)	Level (change)	Incongruent > congruent	Age: o; Sex: o; Task performance: o; Body mass index [Physical]: o

Table 1 (*continued*)

Authors	Year	Functional domain (construct)	Factor	Sample (*N*, mean (*SD*) [range])	Task	Task conditions	fNIRS system	Brain function (fNIRS measure)	Main effects and contrasts	Oxyhemoglobin concentration (HbO) results
Li et al.	2019	EF (monitoring)	Age, task performance	n = 16, 6.5 (0.6); n = 19, 21.5 (2.4)	Reality judgment	Fantastical, real characters × fantastical, real events	22 bilateral frontal channels (LABNIRS; Shimadzu)	Level (mean change)	Video watching, reality judging	Age: -, -; Task performance: o, o
Miller et al.	2019	Social (mother-child dyad)	Age, sex, temperament (child attachment), social reciprocity (cooperation performance)	n = 28, 11.2 (1.3) [8.1–12.9]	Incentivized reaction time	Cooperation, independent task	15 right frontal, temporal, parietal channels (ETG-4000; Hitachi)	Interpersonal synchrony (wavelet coherence)	Cooperation > independent task	Age: o; Sex (M>F): +; Child attachment [Temperament]: o; Cooperation performance [Social reciprocity]: o
Moriguchi and Shinohara	2019	EF (shifting)	Age, SES (poverty), parental (parenting style), task performance	n = 93, 5.0 (0.9) [3.5–6.4]	Dimensional Change Card Sort	Preswitch, postswitch, mix phases	16 bilateral frontal channels (OEG-16; Spectratech)	Level (mean change)	Card sort > rest	Age: o; Poverty: - [SES: +]; Parenting style: o; Task performance: o
Perdue et al.	2019	Social (information processing)	Parental (maternal stress, family care), SES (poverty), physical (height, head circumference, inflammation)	n = 130 (121 analyzed), 3.0 (0.0) [3–3]	Video watching and listening	Social, nonsocial videos × visual, auditory presentation	38 bilateral frontal, temporal, occipital channels (NTS; Gowerlabs)	Level (mean change)	Visual social, auditory social > visual nonsocial	Maternal stress: +, -; Family care: o, + [Parental (good > poor): -, +]; Poverty [SES]: o, o; Height, head circumference, inflammation [Physical]: o, o
Quiñones-Camacho, Fishburn, Camacho, Hlutkowsky et al.	2019	Social (mother-child dyad)	Social reciprocity (behavioral synchrony), temperament (irritability), parental (maternal irritability)	n = 117, 4.9 (0.6) [4–5]	Disruptive Behavior Diagnostic Observation Schedule: Biological Synchrony	Frustration, recovery phases	10 bilateral frontal channels (NIRScout; NIRx)	Interpersonal synchrony (Pearson's r (z-transformed))	Frustration, recovery	Behavioral synchrony [social reciprocity]: +, o; Child irritability: o, - [Temperament: o, +]; Maternal irritability [Parental]: o, o
Quiñones-Camacho, Fishburn, Camacho, Wakschlag et al.	2019	EF (inhibition)	Age, temperament (effortful control), task performance	n = 151 (123 analyzed), 4.8 (0.6) [3.8–5.9]	Pet Store Stroop	Congruent, incongruent trials	10 bilateral frontal channels (NIRScout; NIRx)	Level (hrf beta)	Incongruent > congruent	Age: o; Temperamental effortful control: -; Task performance: o
Saggar et al.	2019	EF (creative thinking)	Age, task performance	n = 56 (26 analyzed), 9.2 (0.6)	Torrance test of Creative Thinking–Figural	Creative drawing, control drawing	52 bilateral frontal channels (ETG-4000; Hitachi)	Network organization (between-community interaction score (integration level))	Creative drawing, control drawing, rest	Age: o, o (both inversely related to creativity changes), o; Task performance: -, /, /

Table 1 (*continued*)

Authors	Year	Functional domain (construct)	Factor	Sample (*N*, mean (*SD*) [range])	Task	Task conditions	fNIRS system	Brain function (fNIRS measure)	Main effects and contrasts	Oxyhemoglobin concentration (HbO) results
Sagiv et al.	2019	EF (shifting, inhibition), WM (verbal WM maintenance, spatial WM updating), language (word processing), social (gesture recognition)	Prenatal (organophosphate pesticide exposure)	*n* = 95, 15.4 (0.5) [15–17]	Wisconsin Card Sorting Test, Go/No-Go, Sternberg WM, spatial *n*-back, Pyramids and Palm Trees, Dynamic Social Gestures	Card sort or control, Go or No-go trials, 7- or 8-letter strings, 0- or 1- or 2-back blocks, semantic meaning or control, social or nonsocial gestures	28 bilateral frontal, temporal, parietal channels (NIRScout; NIRx)	Level (hrf beta)	Card sort > control; no-go > go; encoding > recall; 2-back > 1-back > 0-back; semantic meaning > control; social > nonsocial	Prenatal exposure: o, o, o, o, o, o
Kerr-German and Buss	2020	EF (shifting), attention (selective attention)	Task performance	*n* = 15, 3.6 [3–5]; *n* = 16, 4.4 [3–5]	Dimensional Change Card Sort, triad classification	Pre-switch or post-switch or mixed phases, holistic or identity objects	48 bilateral frontal, parietal channels (CW6; TechEn)	Level (mean change)	Postswitch > preswitch; triad classification > trial onset	Task performance: +, +
Moriguchi and Sakata	2020	EF (shifting)	Age	*n* = 25, 4.1 [3.5–4.5]; *n* = 20, 5.0 [4.7–6.5]	Dimensional Change Card Sort	Observation, execution of card sorting	16 bilateral frontal channels (OEG-16; Spectratech)	Level (mean change)	<u>Observation</u>, execution > rest	Age: +, o
Nguyen et al.	2020	Social (mother-child dyad)	Social reciprocity (behavioral reciprocity), task performance, parental (maternal stress), child agency, temperament	*n* = 42, 5.7 (0.3) [5.0–6.1]	Problem solving	Work alone, work together	16 bilateral frontal, temporal, parietal channels (NIRScout; NIRx)	Level (hrf beta), interpersonal synchrony (wavelet coherence)	<u>Work together</u>, work alone, rest	Behavioral reciprocity [Social reciprocity]: o, o, o (level), +, o, o (synchrony); Task performance: +, o, o (level, synchrony); Maternal stress: -, o, o [parental (good > poor): +, o, o] (synchrony); Child agency: o, o, o (level, synchrony); Temperament: o, o, o (synchrony)
Su et al.	2020	Social (action imitation)	Age, social reciprocity (interpersonal synchrony)	*n* = 17, 10.8 (2.8); *n* = 15, 22.6 (2.7)	Action observation and execution using the right hand	Do with the tester, do alone, watch the tester	24 bilateral frontal, temporal, parietal channels (ETG-4000; Hitachi)	Level (hrf beta)	<u>Do together</u>, do alone, watch	Age: +, +, -; Interpersonal synchrony [Social reciprocity]: ±, ±, +
Yeung et al.	2020	EF (inhibition)	Age	*n* = 28, 11.8 (3.0) [7–16]	Stroop, flanker	Neutral or incongruent trials, congruent or incongruent trials	16 bilateral frontal channels (OEG-SpO2; Spectratech)	Level (mean change)	Stroop: incongruent > neutral; Flanker: incongruent > congruent	Age: +, +

Note. EF = executive function; HbR = deoxyhemoglobin concentration; hrf = hemodynamic response function; IQ = intelligence quotient; SES = socioeconomic status; WM = working memory. When more than one main effect and contrast existed, the underlined main effect and contrast was chosen for the qualitative synthesis of evidence. The symbols "+", "-", and "±" represent significant positive, negative, and mixed effects (after multiple comparison correction), respectively, whereas the symbol "o" represents a nonsignificant effect. A mixed effect means that significant positive and negative effects are both present, and the directionality depends on the region/channel. The order of symbols follows the order of main effects and contrast.
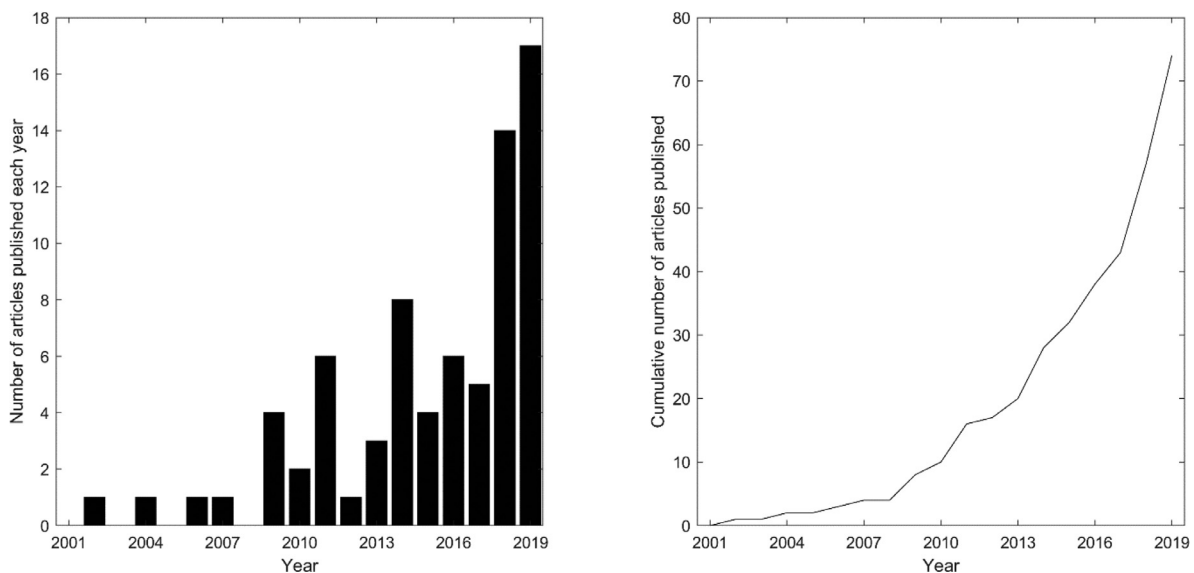
Fig. 2. (a) The annual and (b) cumulative numbers of functional near-infrared spectroscopy articles involving healthy children and adolescents that were published in peer-reviewed journals in English before 2020. Five articles were published between January 1 and June 21, 2020 (not shown).

published articles increased to 14. A total of 16 articles were published in 2019 and five were published between January 1 and June 21, 2020.

3.2. Research design

Supplementary Table 2 details the research designs used in the included studies. The effect of age was examined in 48 (61%) of the studies, of which 43 were cross-sectional, 4 were longitudinal, and 1 combined both approaches. All longitudinal studies spanned 1–2 years. Also, non-age factors were examined in 57 (72%) of the studies, of which 47 were correlational, 6 were experimental, and 4 were quasi-experimental. Correlational and experimental studies examined individual difference factors, including task performance ($n = 23$), sex ($n = 12$), bilingualism ($n = 11$), temperament ($n = 10$), parental conditions ($n = 5$), SES ($n = 5$), social reciprocity ($n = 4$), physical states ($n = 3$), genetics ($n = 2$), intelligence ($n = 2$), first language proficiency ($n = 1$), age of bilingual exposure ($n = 1$), child agency ($n = 1$), prenatal insecticide exposure ($n = 1$), and presence of imaginary companion ($n = 1$). Also, (quasi-)experimental studies focused on behavioral ($n = 8$) and pharmaceutical ($n = 2$) interventions.

The total sample size of each study ranged from 8 to 392, with a median of 38. When considering only individuals aged below 18 years, the median sample size was 33. Only three (4%) of the studies provided *a priori* power analysis or a rationale to justify their sample sizes. Also, only five (6%) of the studies administered standardized tests to screen for childhood psychopathology. These tests include the Child Behavior Checklist, Kiddle Schedule for Affective Disorders and Schizophrenia (Present and Lifetime version), Mini-International Neuropsychiatric Interview, Strengths and Difficulties Questionnaire, and Symptom Checklist-90 ($n = 1$ each).

3.3. Experimental paradigm

Supplementary Table 3 details the experimental paradigm employed in each study. Overall, 25 (32%) of the studies were concerned with executive functions: 17 studies assessed inhibition using the Stroop ($n = 8$), Go/No-go ($n = 6$), flanker ($n = 3$), delay of gratification ($n = 1$), and/or modified Real Animal Size ($n = 1$) tests. Nine studies examined shifting using the Dimensional Card Sorting ($n = 6$), Wisconsin Card Sorting ($n = 2$), or modified Real Animal Size ($n = 1$) tests. One study assessed monitoring and creative thinking using a reality judgment task, while

one other study used the Torrance Test of Creative Thinking–Figural Test. Additionally, 23 (29%) of the studies evaluated language functions: 10 examined word processing using a repetition or reading task ($n = 6$), a learning task ($n = 2$), a lexical selection task ($n = 1$), or a comprehension task (i.e. the Pyramids and Palm Trees Test) ($n = 1$). Seven studies examined verbal fluency using the phonemic fluency test ($n = 4$) and/or the semantic fluency task ($n = 4$). Five studies examined sentence processing using a listening task ($n = 3$) or a judgment task ($n = 2$). Moreover, one study examined story processing using a listening task.

Notably, 12 (15%) of the studies examined social functions: three studies examined social information processing using a watching or listening task, four studies examined parent-child or interpersonal dyads using a cooperation task ($n = 3$) or the Disruptive Behavior Diagnostic Observation Schedule ($n = 1$), two studies assessed face recognition using an old/new paradigm, and one study each examined action imitation, gesture recognition, and social appreciation, respectively. Additionally, 10 (13%) of the studies assessed WM using tasks that emphasized the maintenance of spatial ($n = 4$), visual ($n = 2$), or visual and verbal ($n = 1$) WM, the manipulation of spatial WM ($n = 1$), and/or the updating of visual ($n = 1$) or spatial ($n = 1$) WM. Furthermore, five (6%) of the studies assessed emotional function using a frustration-based emotion regulation task ($n = 3$), a facial emotion recognition task ($n = 1$), or a perception task ($n = 1$). Also, four (5%) of the studies examined mental arithmetic skills with a task involving all four arithmetic operations ($n = 1$) or only addition ($n = 1$), subtraction ($n = 1$), or multiplication ($n = 1$) problems. Another four (5%) of the studies focused on rest with closed ($n = 3$) or open ($n = 1$) eyes. Additionally, two (3%) of the studies assessed attention, including sustained ($n = 1$; video game playing) and selective attention ($n = 1$; triad classification). Finally, two (3%) of the studies examined sensory functions using movie-viewing tasks, while one (1%) of the studies examined motor functions involving cycling.

Overall, 58 (73%) of the studies employed the blocked design exclusively. Among these studies, active task blocks and rest or non-task blocks were of variable duration in 13 and 18 studies, respectively. Also, 17 (22%) of the studies employed the event-related design exclusively, with the rapid design (i.e., average intertrial intervals < 6 seconds) and jittering interstimulus intervals being used in three and six studies, respectively. Two (3%) of the studies employed both the blocked and event-related designs (depending on the task), while two (3%) of the studies employed a mixed design. Additionally, after excluding three

studies that focused on rest only, 69 (91%) of the studies employed one task, while seven (9%) studies employed at least two tasks. A pool of 85 tasks was employed across studies, each of which included 1 to 10 task conditions, with a median of two conditions. Among these 85 tasks, 73 (86%) included more than one task condition, whereas the remainder included only one task condition.

3.4. fNIRS Measurement

Supplementary Table 4 details the fNIRS system employed in each study. Apart from one study not specifying the system used and three studies utilizing a frequency-domain system manufactured by the ISS, all studies used a continuous-wave system. Hitachi systems ($n = 25$)—specifically the ETG-4000 ($n = 21$), ETG-7000 ($n = 3$), and ETG-100 ($n = 1$) models—were most commonly used. The TechEn CW6 device ($n = 12$) and NIRx systems ($n = 11$; one unknown)—specifically the NIRScout ($n = 7$), DYNOT ($n = 2$), and NIRSport ($n = 1$) models—were also frequently utilized. Moreover, Shimadzu systems ($n = 9$)—specifically the ONM-1080S ($n = 3$), FOIRE-3000 ($n = 3$), LAB-NIRS ($n = 2$), and ONM-2001 ($n = 1$) models—were often employed. Additionally, Spectratech systems ($n = 7$)—specifically the OEG-16 ($n = 6$) and OEG-SpO2 ($n = 1$) models were also sometimes used. Furthermore, Hamamatsu systems ($n = 5$)—specifically the NIRO-200 ($n = 2$), NIRO-200NX ($n = 2$), and NIRO-300 ($n = 1$) models—have also been occasionally employed. Finally, fNIRS Devices ($n = 2$), Gowerlabs NTS ($n = 2$), Omron HEO-200 ($n = 1$), and Artinis Portalite ($n = 1$) systems were rarely used. Except for the Hamamatsu and Shimadzu systems, which utilized four and three wavelengths, respectively, all devices utilized two wavelengths (one above and one below the isosbestic point).

The sampling rate of data acquisition was unknown in four studies. For the remaining studies, the sampling rate ranged from 0.8 to 50 Hz, with a median of 10 Hz. Source–detector spacing was unknown in three studies. For the remaining studies, this value ranged from 20 to 50 mm, with a median of 30 mm. Notably, 71 (90%) of the studies employed a fixed source-detector separation. Probe distances varied in eight studies, which was largely due to caps adjustable to head sizes being used and the probes being placed according to the international 10–20 system. For all studies, the number of sources used ranged from 1 to 20, with a median of 8. The number of detectors used ranged from 1 to 32, with a median of 20. The number of available measurement channels ranged from 1 to 80, with a median of 22. Furthermore, measurements over the frontal, temporal, parietal, and occipital lobes were performed in all (100%), 23 (29%), 21 (27%), and five (6%) of the studies, respectively. All but four (95%) of the studies measured brain activity in both hemispheres. Moreover, 53 (67%) of the studies performed spatial registration of the channels, which was aided by 3D digitizers in 13 (25%) studies.

3.5. Data preprocessing

Supplementary Table 5 presents the preprocessing procedure undertaken in each study. Only 39 (49%) of the studies reported the use of a specific toolbox or software, including the HomER or HomER2 ($n = 13$), NIRS-SPM ($n = 7$), NIRS Brain AnalyzIR ($n = 4$), POTATo ($n = 4$), FastICA ($n = 3$), OEG-16 software ($n = 3$), FC-NIRS ($n = 2$), fNIRSOFT ($n = 2$), NIRS Toolbox ($n = 2$), SPM-NIRS ($n = 2$), EasyNIRS ($n = 1$), NAP ($n = 1$), NILAB ($n = 1$), nirsLAB ($n = 1$), and NIRS ($n = 1$) to preprocess fNIRS data. Overall, the more frequently used toolboxes were open-source functions implemented in Matlab, while the commercial software accompanying fNIRS systems were used less frequently.

The removal of artifactual data was performed manually in 24 (30%) of the studies, 20 of which relied on a visual inspection, while the remainder relied on video recording. This removal was also performed using (semi-)automatic algorithms in 24 (30%) of the studies, 13 of which were based on SD only, 9 on amplitude only, and 2 on both criteria. Additionally, simple frequency filtering was performed in 48 (61%) of

the studies. Specifically, the included studies applied lowpass filtering ($n = 36$; range: 0.05–1 Hz, median: 0.3 Hz), highpass filtering ($n = 28$; range: 0.007–0.05 Hz, median: 0.01 Hz), and/or moving-average filtering ($n = 11$; three with a 5 s window, three with unknown parameters, two with a Savitzky–Golay filter, two with five data points, and one with three-point triangular smoothing). Notably, 26 studies applied both lowpass and highpass filtering (i.e., bandpass filtering), while one study applied both highpass and moving-average filtering.

Twenty-nine (37%) of the studies applied more advanced motion and/or systemic correction methods, including wavelet filtering ($n = 8$), the MARA ($n = 5$), functional–systemic separation ($n = 4$), CBSI (n = 3), ICA ($n = 3$), TDDR ($n = 3$), a semi-automated procedure with linear interpolation ($n = 2$), or sliding-window motion artifact removal ($n = 1$). Moreover, 26 (33%) of the studies applied detrending techniques beyond simple highpass filtering, including linear fitting ($n = 14$), wavelet-MDL ($n = 5$), DCT-based highpass filtering ($n = 4$), quadratic fitting plus ICA ($n = 1$), third-order Legendre polynomial fitting ($n = 1$), or an unknown method ($n = 1$). Combined with studies using simple highpass filtering, 49 (62%) of the studies applied detrending correction. Additionally, 12 (15%) of the studies corrected for temporal autocorrelation using Gaussian smoothing ($n = 4$), hemodynamic response function precoloring ($n = 4$), or prewhitening ($n = 4$). Finally, six (8%) of the studies applied AR-IRLS to model noise structure, two (3%) interpolated missing or rejected channels, and one (1%) performed short-channel regression.

Regarding the age-dependent differential pathlength factor used to estimate changes in hemoglobin concentration, 47 studies did not require age correction because these studies analyzed the effect size or other unitless metrics, including beta estimates ($n = 26$), Z-scores ($n = 9$), Pearson's r (i.e., connectivity) and other network measures ($n = 7$), and ratios between conditions or chromophores ($n = 5$). For the remaining 32 studies, only five (15%) corrected the differential pathlength factor for age using an equation.

3.6. Statistical analysis

Supplementary Table 6 summarizes the statistical analyses conducted in each study. To determine the relationship between different factors and fNIRS variables, 76 (96%) of the studies used at least one parametric test, including t-test, ANOVA, ANCOVA, Pearson's correlation, partial correlation, multiple regression, and/or a linear mixed model. In contrast, only six (9%) studies used a non-parametric test, including the Spearman's correlation or Mann–Whitney U test. Moreover, seven (9%) of the studies tested for the normality of fNIRS variables. Normality was achieved in five studies, with four proceeding with parametric tests. Normality was violated in two studies, and one study proceeded with parametric tests.

After excluding one study using a single-channel fNIRS system, 37 (47%) studies clustered channels and performed a region of interest analysis to determine factor effects. Also, after excluding 29 studies involving factor effects on brain functions across regions or broadly in the two hemispheres, 22 (44%) studies applied multiple comparison correction at the channel or regional level. These correction methods included false discovery rate correction ($n = 13$), Bonferroni correction ($n = 5$), Dubey/Armitage-Parmar adjustment (which considers the spatial correlation among channels) ($n = 2$), Sun's tube formula correction ($n = 2$), and an arbitrary adjustment of the p-value threshold ($n = 1$).

3.7. Result presentation

Supplementary Table 7 presents the fNIRS results and how these were presented in each study. Sixty-four (81%) of the studies examined the level of changes in brain activity in terms of mean change over a task period ($n = 34$), beta value or Pearson's r ($n = 27$), mean change around the peak ($n = 2$), an unspecified change ($n = 2$), rate of change ($n = 1$), or ratio of the range of change ($n = 1$). Three of these and one other

study examined the laterality of changes in fNIRS signals by investigating the ratio ($n = 3$) or difference in the rate of change ($n = 1$) of brain activity between the two hemispheres. Among these 65 studies on the level and/or laterality of brain activity, 27 (42%) relied on modeling the hemodynamic response. Also, five (6%) of the studies examined connectivity in terms of the Pearson's r ($n = 3$), partial coherence ($n = 1$), or Granger causality ($n = 1$) between two regions. Furthermore, four (5%) of the studies examined interpersonal synchrony in terms of the wavelet coherence ($n = 3$) or Pearson's r ($n = 1$) between the brain activity of two individuals, while one (1%) of the studies examined the similarity of changes in brain activity between twins. Four studies examined functional network organization ($n = 3$) and its laterality ($n = 1$) using graph measures. Finally, one study each examined the latency of brain activation, the variability of brain activity, and the similarity of brain activity between the resting and task states, respectively.

Regarding the task conditions that formed the basis of factor effects, some studies did not require contrasting conditions. Three studies examined the effect of different factors on the resting-state connectivity or brain network configuration. Moreover, three studies examined connectivity throughout a task, while one study compared the similarity of brain activity between the resting and task states. For the remaining 72 studies, only 37 (51%) contrasted one task condition with other task conditions, while the remainder only contrasted a task condition with the rest or non-task period.

Notably, 77 (97%) of the studies analyzed HbO, while two studies analyzed HbR only. After excluding seven studies that combined HbO and HbR as a result of data preprocessing or analysis, 26 (36%) of the 72 studies analyzed both indices when determining the factor effects on brain function. Interestingly, among these 26 studies, no studies reported significant results for HbR only, whereas 10 (38%) studies reported significant results for HbO only. Also, 11 (42%) of these 26 studies noted significant factor effects supported by opposite or consistent changes in HbO and HbR. Finally, among all the 79 studies included in the present review, image reconstruction was used to illustrate the factor effects on brain function in 35 (44%) of the studies, while 20 (57%) involved interpolation between channels.

In light of the high heterogeneity of studies and the limited number of studies in each functional domain and age group, the study findings are not commented (but see Table 1 for individual study findings and Supplementary Table 8 for a qualitative synthesis of evidence). Readers interested in a narrative presentation of the key findings of developmental fNIRS studies are referred to the reviews by Moriguchi and Hiraki (2013) and Vanderwert and Nelson (2014).

4. Discussion

Recently, there has been growing interest in the use of fNIRS to study brain function in the context of lifespan development, which is largely due to the increasing recognition that this technique is cost-effective, resistant to motion artifacts, and can be used in natural settings. Applications of fNIRS in infants or young children (Lloyd-Fox et al., 2010; Moriguchi and Hiraki, 2013; Vanderwert and Nelson, 2014) and older adults (Yeung and Chan, 2020) have been reviewed narratively and systematically, respectively. However, fNIRS application in healthy children and adolescents, who exhibit increasing independence and autonomy and undergo continual cognitive and socioemotional development, remains largely unknown. This article systematically reviews 79 studies that addressed the effects of age and other factors (e.g., individual differences) on brain function in healthy children and adolescents. This discussion will introduce key points from the existing fNIRS literature, highlight its limitations, and provide recommendations and directions for future developmental fNIRS research. After analyzing the various methodological aspects of these studies, it is suggested that future studies make fuller use of fNIRS without falling into the potential pitfalls of this technique. Table 2 lists the methodological issues of previous studies and the recommendations for the field; the suggestions emerged out

of the literature on addressing these issues (i.e., methodological studies and reviews) and of the author's research experience.

4.1. Considerations for the design of an fNIRS study

Most fNIRS studies involving children and adolescents to date have generated cross-sectional and correlational evidence. Notably, relatively few longitudinal and experimental studies have sought to identify the causal roles for age and other factors in children's and adolescents' brain function. Notwithstanding these contributions, few studies have considered age-related differences in skull and brain structures or brain-scalp distance (Beauchamp et al., 2011). Failure to control for these differences can lead to the underestimation of brain activity in older individuals (due to larger brain-scalp distances) and increase between-subject variability. Thus, it is essential to make corrections for these confounding factors either by using effect sizes (Schroeter et al., 2003) or by correcting the differential pathlength factor for age using the general equation (Scholkmann and Wolf, 2013), or the generalized model (which additionally corrects for sex and head circumference) if the study involves 5- to 11-year-olds only (Whiteman et al., 2017). Although general linear modeling with the canonical hemodynamic response function yields beta estimates that are independent of the assumed differential pathlength factor, age may affect the shape of the hemodynamic response function (Kamran et al., 2018). Thus, future work would benefit from characterizing the relationship between age and hemodynamic response function to improve the accuracy of the model-based analytic approach.

The median total sample size of the reviewed studies is 38. Considering a power of 0.80 and an alpha level of 0.05, this sample size is just enough to detect a medium-to-large correlation ($r = 0.39$) or a large difference ($d = 0.83$) between two equal-sized groups, if any. Notably, this argument assumes that all statistical tests are driven by *a priori* hypotheses, or that only one test is performed to compare two groups or evaluate a bivariate relationship. The sample size will not be enough to detect effects of these effect size values if some statistical tests are exploratory and require multiple comparison correction (such as when comparing more than two groups and channels/regions), or when performing multiple regression or multivariate analysis. Accordingly, it is speculated that many fNIRS studies might have been underpowered. It is well known that underpowered studies are prone to committing false-positive and false-negative errors (Forstmeier et al., 2017). Therefore, it is suggested that future studies conduct and report *a priori* power analyses to justify their sample sizes based on studies that shared similar task and sample characteristics and/or factors of interest (i.e., look up Table 1). Notably, due to random measurement error and variation in task and sample characteristics across studies, the estimated required sample size based on a single study, especially one that is underpowered, is unlikely to be highly accurate. Thus, researchers who are planning a new study should estimate the required sample size based on the weighted mean effect size derived from most, if not all, of the studies that share similar features.

According to the present review, very few studies screened for childhood psychopathology in their samples using standardized tests. A wealth of evidence suggests that many mental disorders first emerge in childhood and adolescence (Kessler et al., 2007; Meyer and Lee, 2019), and that neurodevelopmental disorders are becoming more commonly diagnosed (Boyle et al., 2011). Thus, future studies would benefit from administering standardized inventories, such as the Strengths and Difficulties Questionnaire (Goodman, 1997), to screen for common childhood psychopathology and improve the characterization and homogeneity of their study samples.

Most fNIRS studies involving children and adolescents have examined executive, language, and social functions separately, using one task at a time. Accumulated evidence suggests that executive function differentiates into distinct constructs throughout childhood (Brydges et al., 2014; Xu et al., 2013) and that executive, language, and socioemotional development are interrelated (Kuhn et al., 2014; Riggs et al., 2006).

Table 2

Suggestions to enhance research practice in developmental functional near-infrared spectroscopy (fNIRS) studies in light of the methodological issues identified in this review.

Methodological issue	Suggestion	Rationale
1) Little consideration of age-related differences in head structures	Use effect sizes (Schroeter et al., 2003) or correct the differential pathlength factor for age using the general equation (Scholkmann and Wolf, 2013), or the generalized model (which additionally corrects for sex and head circumference) if the study involves 5- to 11-year-olds only (Whiteman et al., 2017)	To reduce between-subject variability and ensure that age-related differences in fNIRS variables reflect age-related differences in brain functions
2) Inadequate sample size or statistical power	Perform and report *a priori* power analysis based on studies that shared similar sample and task characteristics and/or factors of interest (i.e., look up Table 1)	To minimize the risks of committing false-positive and false-negative errors
3) Insufficient sample characterization	Administer standardized inventories to screen for common child and adolescent psychopathology	To reduce between-subject variability
4) Use or reporting of only one task at a time	Use at least two tasks to contrast different functions, preferably in a within-subject manner	To inform the relationships between the developmental trajectories across functional domains
5) Tasks designed in ways that may hinder an accurate estimation of brain activity	Jitter interblock and interstimulus intervals when using the blocked design, or adopt the (rapid) event-related design if possible	To avoid habituation and anticipation effects and allow a separation of neural responses to different trials
6) Lack of regional comparisons	Compare regions using effect sizes (Schroeter et al., 2003), or after correcting the differential pathlength factor for region and other factors if the study involves 5- to 11-year-olds only (Whiteman et al., 2017)	To inform the spatial patterns of functional brain development
7) Variable preprocessing pipelines	Apply a standardized preprocessing pipeline (see Pinti et al., 2019)	To improve the reproducibility of results
8) Insufficient artifact removal	Apply wavelet filtering (and spline interpolation) to correct for motion artifacts (Brigadoi et al., 2014; Di Lorenzo et al., 2019) and a customized bandpass filter (Pinti et al., 2019) to correct for high-frequency noise and slow drifts; alternatively, model noise structures using the autoregressive iteratively reweighted least squares algorithm (Barker et al., 2013)	To enable an accurate estimation of the hemodynamic response due to neuronal activity
9) Contrast between task and rest periods only	Contrast at least two conditions that differ in the psychological process of interest only	To clarify the conceptual meaning of fNIRS variables
10) Little consideration of parametric test assumptions	Check normality using Shapiro–Wilk tests, and remove outliers by conducting Grubbs' tests (Grubbs, 1969) and/or calculating Cook's distance (Cook, 1977)	To enhance the accuracy of parametric test results
11) No multiple comparison correction	When testing multiple regions or channels, apply false discovery rate correction (Singh and Dan, 2006) and report both the corrected and uncorrected results	To avoid inflated Type I error rates
12) Incomplete reporting of fNIRS indices	Analyze and report both the HbO and HbR data	To inform signal quality and provide a complete picture of the hemodynamic response
13) Little consideration of the possible confound between age and channel signal quality	Examine if age correlates with the correlation between (changes in) HbO and HbR (Cui et al., 2010; Yeung and Chan, 2020), the coefficient of variation of raw light intensity values (Piper et al., 2014), or the amount of data removed	To ensure that age-related differences in fNIRS variables reflect age-related differences in brain functions

Note. HbO = oxyhemoglobin concentration; HbR = deoxyhemoglobin concentration

Thus, future fNIRS studies comparing developmental changes in brain function among different tasks are required to enhance our holistic understanding of cognitive and socioemotional development throughout childhood. Whenever possible, such investigations should be performed within individuals to minimize between-subject variance and strengthen the evidence.

The blocked design has likely served as the primary experimental design for fNIRS because it offers higher detection power than the event-related design. However, the blocked design does not separate neural responses to different trials and is prone to rapid habituation and anticipation, which affects the magnitude and onset of hemodynamic responses. To overcome these challenges, researchers interested in neural responses to different trial types (e.g., correct and incorrect trials) and who want to prevent habituation and anticipation effects may consider adopting the event-related design. However, this design often involves longer experiments and increased boredom among participants when stimuli are presented slowly. To harness the advantages of this design and increase time efficiency, rapid event-related fNIRS with brain activity modeled using a canonical hemodynamic response function and its temporal derivative can be employed (Heilbronner and Münte, 2013; Plichta et al., 2007). Also, the present review reveals that most previous studies used fixed durations for task and/or non-task periods. Additionally, jittering interblock and interstimulus intervals should be beneficial in minimizing anticipatory effects.

Most of the reviewed studies measured activity in multiple brain regions, with measurements often being confined to the frontal lobes since the forehead region offers better optode–scalp contact—and thus better signal quality—compared to posterior regions. While approximately 40% of the measurements covered frontal and non-frontal regions, only a few studies made regional comparisons. Moreover, while some evidence suggests that structural brain development follows inferior-to-superior and posterior-to-anterior gradients (Colby et al., 2011; Gogtay et al., 2004; Krogsrud et al., 2016), the question of whether functional brain development follows similar patterns remains unresolved. Since executive, language, and socioemotional functions engage the frontal, parietal and/or temporal lobes as well as their interactions (Houdé et al., 2010; McKenna et al., 2017; Pelphery and Carter, 2008), it would be interesting to determine whether there is a parallel between structural and functional brain development. While a comparison between regions is difficult for fNIRS due to differences in brain-scalp distance across regions (Beauchamp et al., 2011), such a comparison could be possible if the differential pathlength factor is corrected for the region. Currently, such correction is only available for 5- to 11-year-olds (Whiteman et al., 2017) and adults (Zhao et al., 2002) using limited wavelengths; therefore, future work would benefit from determining the differential pathlength factor for different scalp regions across childhood and adolescence. Alternatively, effect size metrics can be employed, but whether the hemo-

dynamic response function differs among brain regions remains to be determined.

4.2. Considerations for the preprocessing, analysis, and presentation of fNIRS data

The preprocessing for fNIRS varied greatly across studies, while many studies did not report their preprocessing pipelines. Most studies relied on custom scripts, with a few reporting the use of open-source Matlab toolboxes. Recently, Pinti et al. (2019) proposed the standardized procedure of fNIRS experimental design, data acquisition, data preprocessing, and statistical inference. To enhance reproducibility of methods and results, fNIRS researchers are recommended to follow this procedure.

Cardiac and respiratory activities, Mayer waves, and other physiological noise and motion are common sources of artifacts in fNIRS. If insufficiently treated, these artifacts reduce detection power and can lead to erroneous conclusions. While most studies have relied on trial and channel rejection as well as simple frequency filtering to attenuate artifacts, only a few have utilized more advanced algorithms to effectively remove or account for noise. Recent years have seen empirical comparisons among different motion correction and other artifact removal methods (Brigadoi et al., 2014; Di Lorenzo et al., 2019; Fishburn et al., 2019; Hu et al., 2015; Huppert, 2016; Pinti et al., 2019). Based on the recent literature, the combination of wavelet filtering (and spline interpolation) and bandpass filtering with a higher-order finite impulse response filter and cutoffs determined by inspecting the frequency spectrum of fNIRS signals (Pinti et al., 2019) constitutes an effective preprocessing pipeline under most circumstances. Notably, these algorithms have been implemented by some open-source toolboxes, including HomER2. Alternatively, fNIRS data can be unfiltered, while the AR-IRLS method, which involves the application of autoregressive-based prewhitening and robust regression concepts to model noise structures in a general linear model (Barker et al., 2013) and is implemented in the AnalyzIR toolbox (Santosa et al., 2018), can be used.

While most fNIRS studies have used a task with multiple task conditions, only half of them addressed the effect of their factors of interest on brain function by contrasting one task condition with another. For the remaining half, investigations were based on the contrast between one task condition and a rest or non-task period. Furthermore, non-significant results might have prevented researchers from using the contrast between task conditions. Nonetheless, task conditions and the resting state differ in numerous unspecific ways (e.g., attention and motivation). To isolate the factor effects on brain activity related to a specific psychological process, future studies should contrast at least two task conditions differing only in the psychological process of interest. A parametric design that involves the manipulation of task difficulty and has been adopted by some recent studies (Chevalier et al., 2019; Sagiv et al., 2019) is highly encouraged. For example, studies on verbal fluency development may contrast between a low set size condition (i.e., high demand), a high set size condition (i.e., low demand), and a repetition condition (i.e., no demand) to elucidate the functional brain development of word retrieval.

While most studies used parametric tests for statistical analysis, few have verified the normality of fNIRS variables. Since artifacts are common in fNIRS signals, deviant observations that distort the results of parametric tests may be present. Thus, future work would benefit from checking and reporting the normality of fNIRS variables. When normality is violated, data transformation, objective outlier removal (e.g., Grubbs' test and Cook's distance), or non-parametric tests can improve normality or account for any non-normal data. Also, some multichannel fNIRS studies applied multiple comparison correction when addressing the factor effects on activity in multiple brain regions. While a region of interest analysis does not warrant multiple comparison correction because *a priori* hypotheses are tested, such correction provides information regarding the strength of evidence—results that survive correc-

tion constitute stronger evidence than those that do not. Future studies are encouraged to apply multiple testing correction, preferably false-discovery-rate correction (Singh and Dan, 2006). Results that do not survive correction can also be reported since they may warrant further investigation.

One-third of the reviewed studies analyzed both HbO and HbR, whereas most of the remaining studies analyzed HbO only. Studies involving young adults noted that HbO seemingly has a higher signal-to-noise ratio and correlates better with BOLD signals when compared to HbR (Cui et al., 2011; Strangman et al., 2002), yet contradictory evidence exists (Huppert et al., 2006). In line with these observations, the present review highlights that fNIRS studies with children and adolescents are generally more likely to yield significant results for HbO than for HbR and that the analysis and reporting of HbR do not appear to reflect reporting bias. Importantly, some studies have reported significant opposite effects for these two indices, which provides strong evidence for links between different factors and brain function. Since the relationship between changes in HbO and HbR provides invaluable insights into the origin of these changes—with negative relationships indicating neuronal activity and positive relationships reflecting systemic or artifactual activities (Cui et al., 2010)—the analysis of both HbO and HbR constitutes an important quality control step for fNIRS. Future work would benefit from clarifying whether the correlation between changes in HbO and HbR in response to events is moderated by age and other factors.

Due to developmental differences in attention span (Lin et al., 1999), younger children can concentrate on the task for shorter durations compared to older children. Thus, when testing younger children with fNIRS, it is important to keep each run of the task paradigm short and include longer breaks, or the results can be confounded by a lack of task engagement. In addition, younger children are less capable of sitting still for long periods of time compared to older children. Accordingly, younger children may exhibit more prominent motion artifacts, which hinder the estimation of brain activity. Unfortunately, few studies have attempted to look at the potential confound between age and channel signal quality, but there are several ways that could be used to check whether channel signal quality differs across age groups. First, the relationship between age and the correlation between changes in HbO and HbR can be examined (Cui et al., 2010; Yeung and Chan, 2020). However, it relies on the assumption that the coupling of changes in HbO and HbR is age-invariant, which is not necessarily true (Fabiani et al., 2014). Alternatively, the relationship between age and the coefficient of variation, calculated by dividing the standard deviation of raw light intensity values by the mean value (during rest), can be examined (Piper et al., 2014). The relationship between age and the amount of data removed can also be examined.

4.3. Where fNIRS stands in developmental neuroscience

The cost-effective, user-friendly, and motion-insensitive properties of fNIRS have made it a suitable tool to study brain dynamics in large groups of young children interacting with each other. Specifically, the present review reveals that 64 (81%) of the included studies involved children between 3 and 7 years of age and contributed to our understanding of brain functions in these children. These findings extend the pertinent fMRI work, which usually investigates older populations (aged at least 8 years) (Houdé et al., 2010; McKenna et al., 2017). Additionally, numerous fNIRS studies have demonstrated how different environmental and personality factors affected brain functions in groups of children with sample sizes of over 100 (Fishburn et al., 2019; Quiñones-Camacho et al., 2019; Sugiura et al., 2015). Notably, the median sample size for individuals between 3–17 years in these studies is 33, which contrasts with the typical sample size of less than 30 in fMRI studies (McKenna et al., 2017). Furthermore, some fNIRS hyperscanning studies have generated evidence that sheds light on the neural basis of interpersonal interactions in children (particularly parent-child

dyads) in ways that are infeasible with other neuroimaging modalities (Quiñones-Camacho et al., 2019; Nguyen et al., 2020). In summary, fNIRS studies have opened new lines of investigation into how brain functions develop early in life and the factors that influence brain development.

Like fNIRS, electroencephalography (EEG) is of low cost and suitable for a wide developmental range. Since EEG has better temporal resolution but poorer spatial resolution than fNIRS, the choice of tool depends on whether the research emphasizes the temporal dynamics or spatial localization of brain activity. Depending on the type of EEG/fNIRS systems and the number of electrodes/channels, the setup time can vary greatly. During EEG or fNIRS setup, it is necessary for the experimenters to maintain interest in younger children by talking to them. It can be difficult to get some children to wear the EEG or fNIRS cap. For these children, the experimenters should try to get them familiar with the equipment, such as by asking them to touch it or imagine wearing a swim cap. In EEG research, both EEG power and coherence (level and functional coupling of electrical activity) can be obtained during a prolonged period of rest or cognitive events on the order of minutes. In fNIRS research, however, a task block is often limited to 20–30 and up to 60 s. When blocks are too long, the hemodynamic response may become nonlinear (i.e., diminished after long stimulation periods; Wagner et al., 2005); slow drift (< 0.01 Hz) and stimulation frequencies may also overlap, which poses difficulty in removing the slow drifts without attenuating task-related signal changes. Also, longer trials are typically needed for fNIRS studies due to the sluggish hemodynamic response. Furthermore, fNIRS investigations into the resting state are often restricted to the study of functional connectivity or other network properties; while fNIRS measures vascular functional connectivity, EEG measures neuronal functional connectivity (Wolf et al., 2011).

In conclusion, fNIRS has some limitations that developmental researchers must consider. This technique cannot measure hemodynamic changes in deep brain structures, does not provide neuroanatomical information, and has a lower signal-to-noise ratio and spatial resolution when compared to fMRI. Since both fNIRS and fMRI are based on the hemodynamic response, most fMRI paradigms are readily applicable for use with fNIRS. However, due to a higher noise level, more trials are needed for fNIRS studies under most circumstances. Also, evidence supporting the reliability and validity of fNIRS stems from studies of young adults, and the reliability and validity of this technique remain to be explicitly determined for children and adolescents. Furthermore, fNIRS has potential pitfalls related to data interpretation, and erroneous conclusions may be drawn when study and task designs as well as data preprocessing and analysis are inadequate. Notwithstanding these limitations and potential pitfalls, the unique properties of fNIRS make it a promising tool for understanding the neural basis of cognitive and socioemotional development throughout childhood and adolescence as well as identifying the individual differences and factors that shape these forms of development.

Declaration of Competing Interest

The author has no conflict of interest to disclose.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2020.117672.

References

Anderson, A.A., Smith, E., Chernomordik, V., Ardeshirpour, Y., Chowdhry, F., Thurm, A., ..., Gandjbakhche, A.H., 2014. Prefrontal cortex hemodynamics and age: a pilot study using functional near infrared spectroscopy in children. Front. Neurosci. 8, 393.

Arredondo, M.M., Hu, X.S., Satterfield, T., Kovelman, I., 2017. Bilingualism alters children's frontal lobe functioning for attentional control. Dev. Sci. 20 (3), e12377.

Arredondo, M.M., Hu, X.S., Satterfield, T., Riobóo, A.T., Gelman, S.A., Kovelman, I., 2019. Bilingual effects on lexical selection: a neurodevelopmental perspective. Brain Lang. 195, 104640.

Arredondo, M.M., Hu, X.S., Seifert, E., Satterfield, T., Kovelman, I., 2019. Bilingual exposure enhances left IFG specialization for language in children. Bilingualism 22 (4), 783–801.

Artemenko, C., Soltanlou, M., Ehlis, A.C., Nuerk, H.C., Dresler, T., 2018. The neural correlates of mental arithmetic in adolescents: a longitudinal fNIRS study. Behav. Brain Funct. 14 (1), 1–13.

Barker, J.W., Aarabi, A., Huppert, T.J., 2013. Autoregressive model based algorithm for correcting motion and serially correlated errors in fNIRS. Biomed. Opt. Express 4 (8), 1366–1379.

Beauchamp, M.H., Anderson, V., 2010. SOCIAL: an integrative framework for the development of social skills. Psychol. Bull. 136 (1), 39–64.

Beauchamp, M.S., Beurlot, M.R., Fava, E., Nath, A.R., Parikh, N.A., Saad, Z.S., ..., Oghalai, J.S., 2011. The developmental trajectory of brain-scalp distance from birth through childhood: implications for functional neuroimaging. PLoS One 6 (9), e24981.

Best, J.R., Miller, P.H., 2010. A developmental perspective on executive function. Child Dev. 81 (6), 1641–1660.

Boyle, C.A., Boulet, S., Schieve, L.A., Cohen, R.A., Blumberg, S.J., Yeargin-Allsopp, M., ..., Kogan, M.D., 2011. Trends in the prevalence of developmental disabilities in US children, 1997–2008. Pediatrics 127 (6), 1034–1042.

Brigadoi, S., Ceccherini, L., Cutini, S., Scarpa, F., Scatturin, P., Selb, J., ..., Cooper, R.J., 2014. Motion artifacts in functional near-infrared spectroscopy: a comparison of motion correction techniques applied to real cognitive data. Neuroimage 85, 181–191.

Brink, T.T., Urton, K., Held, D., Kirilina, E., Hofmann, M., Klann-Delius, G., ..., Kuchinke, L., 2011. The role of orbitofrontal cortex in processing empathy stories in 4-to 8-year-old children. Front. Psychol. 2, 80.

Brydges, C.R., Fox, A.M., Reid, C.L., Anderson, M., 2014. The differentiation of executive functions in middle and late childhood: a longitudinal latent-variable analysis. Intelligence 47, 34–43.

Buss, A.T., Fox, N., Boas, D.A., Spencer, J.P., 2014. Probing the early development of visual working memory capacity with functional near-infrared spectroscopy. Neuroimage 85, 314–325.

Cai, L., Dong, Q., Niu, H., 2018. The development of functional network organization in early childhood and early adolescence: a resting-state fNIRS study. Dev. Cognit. Neurosci. 30, 223–235.

Cai, L., Dong, Q., Wang, M., Niu, H., 2019. Functional near-infrared spectroscopy evidence for the development of topological asymmetry between hemispheric brain networks from childhood to adulthood. Neurophotonics 6 (2), 025005.

Chevalier, N., Jackson, J., Roux, A.R., Moriguchi, Y., Auyeung, B., 2019. Differentiation in prefrontal cortex recruitment during childhood: evidence from cognitive control demands and social contexts. Dev. Cognit. Neurosci. 36, 100629.

Colby, J.B., Van Horn, J.D., Sowell, E.R., 2011. Quantitative in vivo evidence for broad regional gradients in the timing of white matter maturation during adolescence. Neuroimage 54 (1), 25–31.

Cui, X., Bray, S., Reiss, A.L., 2010. Functional near infrared spectroscopy (NIRS) signal improvement based on negative correlation between oxygenated and deoxygenated hemoglobin dynamics. Neuroimage 49 (4), 3039–3046.

Cui, X., Bray, S., Bryant, D.M., Glover, G.H., Reiss, A.L., 2011. A quantitative comparison of NIRS and fMRI across multiple cognitive tasks. Neuroimage 54 (4), 2808–2821.

Delpy, D.T., Cope, M., van der Zee, P., Arridge, S., Wray, S., Wyatt, J.S., 1988. Estimation of optical pathlength through tissue from direct time of flight measurement. Phys. Med. Biol. 33 (12), 1433.

Di Lorenzo, R., Pirazzoli, L., Blasi, A., Bulgarelli, C., Hakuno, Y., Minagawa, Y., Brigadoi, S., 2019. Recommendations for motion correction of infant fNIRS data applicable to multiple data sets and acquisition systems. Neuroimage 200, 511–527.

Ding, X.P., Fu, G., Lee, K., 2014. Neural correlates of own-and other-race face recognition in children: a functional near-infrared spectroscopy study. Neuroimage 85, 335–344.

Dresler, T., Obersteiner, A., Schecklmann, M., Vogel, A.C.M., Ehlis, A.C., Richter, M.M., ..., Fallgatter, A.J, 2009. Arithmetic tasks in different formats and their influence on behavior and brain oxygenation as assessed with near-infrared spectroscopy (NIRS): a study involving primary and secondary school children. J. Neural Transm. 116 (12), 1689.

Dumont, F.M., Tarabulsy, G.M., Sylvestre, A., Voisin, J., 2019. Children's emotional self-regulation in the context of adversity and the association with academic functioning. Child Psychiatry Hum. Dev. 50 (5), 856–867.

Dumontheil, I., Apperly, I.A., Blakemore, S.J., 2010. Online usage of theory of mind continues to develop in late adolescence. Dev. Sci. 13 (2), 331–338.

Duncan, A., Meek, J.H., Clemence, M., Elwell, C.E., Fallon, P., Tyszczuk, L., ..., Delpy, D.T., 1996. Measurement of cranial optical path length as a function of age using phase resolved near infrared spectroscopy. Pediatr. Res. 39 (5), 889–894.

Fekete, T., Beacher, F.D., Cha, J., Rubin, D., Mujica-Parodi, L.R., 2014. Small-world network properties in prefrontal cortex correlate with predictors of psychopathology risk in young children: a NIRS study. Neuroimage 85, 345–353.

Ferrari, M., Quaresima, V., 2012. A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. Neuroimage 63 (2), 921–935.

Fishburn, F.A., Hlutkowsky, C.O., Bemis, L.M., Huppert, T.J., Wakschlag, L.S., Perlman, S.B., 2019. Irritability uniquely predicts prefrontal cortex activation during preschool inhibitory control among all temperament domains: a LASSO approach. Neuroimage 184, 68–77.

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.

Forstmeier, W., Wagenmakers, E.J., Parker, T.H., 2017. Detecting and avoiding likely false-positive findings–a practical guide. Biol. Rev. 92 (4), 1941–1968.

Gallagher, A., Tremblay, J., Vannasing, P., 2016. Language mapping in children using resting-state functional connectivity: comparison with a task-based approach. J. Biomed. Opt. 21 (12), 125006.

Gogtay, N., Giedd, J.N., Lusk, L., Hayashi, K.M., Greenstein, D., Vaituzis, A.C., ..., Rapoport, J.L., 2004. Dynamic mapping of human cortical development during childhood through early adulthood. Proc. Natl. Acad. Sci. 101 (21), 8174–8179.

Goodman, R., 1997. The strengths and difficulties questionnaire: a research note. J. Child Psychol. Psychiatry 38 (5), 581–586.

Goto, T., Kita, Y., Suzuki, K., Koike, T., Inagaki, M., 2015. Lateralized frontal activity for Japanese phonological processing during child development. Front. Hum. Neurosci. 9, 417.

Grabell, A.S., Huppert, T.J., Fishburn, F.A., Li, Y., Hlutkowsky, C.O., Jones, H.M., ..., Perlman, S.B., 2019. Neural correlates of early deliberate emotion regulation: young children's responses to interpersonal scaffolding. Dev. Cognit. Neurosci. 40, 100708.

Grabell, A.S., Li, Y., Barker, J.W., Wakschlag, L.S., Huppert, T.J., Perlman, S.B., 2018. Evidence of non-linear associations between frustration-related prefrontal cortex activation and the normal: abnormal spectrum of irritability in young children. J. Abnorm. Child Psychol. 46 (1), 137–147.

Groba, A., De Houwer, A., Mehnert, J., Rossi, S., Obrig, H., 2018. Bilingual and monolingual children process pragmatic cues differently when learning novel adjectives. Bilingualism 21 (2), 384–402.

Groba, A., De Houwer, A., Obrig, H., Rossi, S., 2019. Bilingual and monolingual first language acquisition experience differentially shapes children's property term learning: evidence from behavioral and neurophysiological measures. Brain Sci. 9 (2), 40.

Heilbronner, U., Münte, T.F., 2013. Rapid event-related near-infrared spectroscopy detects age-related qualitative changes in the neural correlates of response inhibition. Neuroimage 65, 408–415.

Hidaka, S., Shibata, H., Kurihara, M., Tanaka, A., Konno, A., Maruyama, S., ..., Koizumi, M., 2012. Effect of second language exposure on brain activity for language processing among preschoolers. Neurosci. Res. 73 (1), 73–79.

Hoshi, Y., Chen, S.J., 2002. Regional cerebral blood flow changes associated with emotions in children. Pediatr. Neurol. 27 (4), 275–281.

Houdé, O., Rossi, S., Lubin, A., Joliot, M., 2010. Mapping numerical processing, reading, and executive functions in the developing brain: an fMRI meta-analysis of 52 studies including 842 children. Dev. Sci. 13 (6), 876–885.

Hu, X.S., Arredondo, M.M., Gomba, M., Confer, N., DaSilva, A.F., Johnson, T.D., ..., Kovelman, I., 2015. Comparison of motion correction techniques applied to functional near-infrared spectroscopy data from children. J. Biomed. Opt. 20 (12), 126003.

Huppert, T.J., Hoge, R.D., Diamond, S.G., Franceschini, M.A., Boas, D.A., 2006. A temporal comparison of BOLD, ASL, and NIRS hemodynamic responses to motor stimuli in adult humans. Neuroimage 29 (2), 368–382.

Huang, J., Xiong, M., Xiao, X., Xu, X., Hong, X., 2019. fNIRS correlates of the development of inhibitory control in young obese subjects. J. Integr. Neurosci. 18 (3), 253–259.

Huppert, T.J., 2016. Commentary on the statistical properties of noise and its implication on general linear models in functional near-infrared spectroscopy. Neurophotonics 3 (1), 010401.

Jasinska, K.K., Petitto, L.A., 2013. How age of bilingual exposure can change the neural systems for language in the developing brain: a functional near infrared spectroscopy investigation of syntactic processing in monolingual and bilingual children. Dev. Cognit. Neurosci. 6, 87–101.

Jasińska, K.K., Petitto, L.A., 2014. Development of neural systems for reading in the monolingual and bilingual brain: new insights from functional near infrared spectroscopy neuroimaging. Dev. Neuropsychol. 39 (6), 421–439.

Jasińska, K.K., Berens, M.S., Kovelman, I., Petitto, L.A., 2017. Bilingualism yields language-specific plasticity in left hemisphere's circuitry for learning to read in young children. Neuropsychologia 98, 34–45.

Kamran, M.A., Mannann, M., Jeong, M.Y., 2018. Differential path-length factor's effect on the characterization of brain's hemodynamic response function: a functional near-infrared study. Front. Neuroinform. 12, 37.

Kawakubo, Y., Kono, T., Takizawa, R., Kuwabara, H., Ishii-Takahashi, A., Kasai, K., 2011. Developmental changes of prefrontal activation in humans: a near-infrared spectroscopy study of preschool children and adults. PLoS One 6 (10), e25944.

Kerr-German, A.N., Buss, A.T., 2020. Exploring the neural basis of selective and flexible dimensional attention: an fNIRS study. J. Cognit. Dev. 21 (3), 313–325.

Kessler, R.C., Amminger, G.P., Aguilar-Gaxiola, S., Alonso, J., Lee, S., Ustun, T.B., 2007. Age of onset of mental disorders: a review of recent literature. Curr. Opin. Psychiatry 20 (4), 359.

Khan, A., McCormack, H.C., Bolger, E.A., McGreenery, C.E., Vitaliano, G., Polcari, A., Teicher, M.H., 2015. Childhood maltreatment, depression, and suicidal ideation: critical importance of parental and peer emotional abuse during developmental sensitive periods in males and females. Front. Psychiatry 6, 42.

Kim, P., Evans, G.W., Angstadt, M., Ho, S.S., Sripada, C.S., Swain, J.E., ..., Phan, K.L., 2013. Effects of childhood poverty and chronic stress on emotion regulatory brain function in adulthood. Proc. Natl. Acad. Sci. 110 (46), 18442–18447.

Krogsrud, S.K., Fjell, A.M., Tamnes, C.K., Grydeland, H., Mork, L., Due-Tønnessen, P., ..., Walhovd, K.B., 2016. Changes in white matter microstructure in the developing brain—a longitudinal diffusion tensor imaging study of children from 4 to 11 years of age. Neuroimage 124, 473–486.

Kuhn, L.J., Willoughby, M.T., Wilbourn, M.P., Vernon-Feagans, L., Blair, C.B., Family Life Project Key Investigators, 2014. Early communicative gestures prospectively predict language development and executive function in early childhood. Child Dev. 85 (5), 1898–1914.

Lambrick, D., Stoner, L., Grigg, R., Faulkner, J., 2016. Effects of continuous and intermittent exercise on executive function in children aged 8–10 years. Psychophysiology 53 (9), 1335–1342.

Larsen, B., Luna, B., 2018. Adolescence as a neurobiological critical period for the development of higher-order cognition. Neurosci. Biobehav. Rev. 94, 179–195.

Lawrence, K., Campbell, R., Skuse, D., 2015. Age, gender, and puberty influence the development of facial emotion recognition. Front. Psychol. 6, 761.

Li, H., Liu, T., Woolley, J., Zhang, P., 2019. Reality status judgments of real and fantastical events in children's prefrontal cortex: an fNIRS study. Front. Hum. Neurosci. 13, 444.

Li, H., Subrahmanyam, K., Bai, X., Xie, X., Liu, T., 2018. Viewing fantastical events versus touching fantastical events: short-term effects on children's inhibitory control. Child Dev. 89 (1), 48–57.

Li, J., Qiu, L., 2014. Temporal correlation of spontaneous hemodynamic activity in language areas measured with functional near-infrared spectroscopy. Biomed. Opt. Express 5 (2), 587–595.

Li, Y., Grabell, A.S., Wakschlag, L.S., Huppert, T.J., Perlman, S.B., 2017. The neural substrates of cognitive flexibility are related to individual differences in preschool irritability: a fNIRS investigation. Dev. Cognit. Neurosci. 25, 138–144.

Lin, C.C., Hsiao, C.K., Chen, W.J., 1999. Development of sustained attention assessed using the continuous performance test among children 6–15 years of age. J. Abnorm. Child Psychol. 27 (5), 403–412.

Liu, T., Liu, X., Yi, L., Zhu, C., Markey, P.S., Pelowski, M., 2019. Assessing autism at its social and developmental roots: a review of Autism Spectrum Disorder studies using functional near-infrared spectroscopy. Neuroimage 185, 955–967.

Lloyd-Fox, S., Blasi, A., Elwell, C.E., 2010. Illuminating the developing brain: the past, present and future of functional near infrared spectroscopy. Neurosci. Biobehav. Rev. 34 (3), 269–284.

Mackey, A.P., Raizada, R.D., Bunge, S.A., 2012. Environmental influences on prefrontal development. In: Stuss, D.T., Knight, R.T. (Eds.), Principles of Frontal Lobe Function. Oxford University Press, pp. 146–163.

Matsuda, G., Hiraki, K., 2006. Sustained decrease in oxygenated hemoglobin during video games in the dorsal prefrontal cortex: a NIRS study of children. Neuroimage 29 (3), 706–711.

Mauri, M., Nobile, M., Bellina, M., Crippa, A., Brambilla, P., 2018. Light up ADHD: I. Cortical hemodynamic responses measured by functional Near Infrared Spectroscopy (fNIRS): Special Section on "Translational and Neuroscience Studies in Affective Disorders" Section Editor, Maria Nobile MD, PhD. This Section of JAD focuses on the relevance of translational and neuroscience studies in providing a better understanding of the neural basis of affective disorders. The main aim is to briefly summarise relevant research findings in clinical neuroscience with particular regards ..... J. Affect. Disord. 234, 358–364.

McKenna, R., Rushe, T., Woodcock, K.A., 2017. Informing the structure of executive function in children: a meta-analysis of functional neuroimaging data. Front. Hum. Neurosci. 11, 154.

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 Dev. 35 (10), 894–904.

Mehta, R.K., Shortz, A.E., Benden, M.E., 2016. Standing up for learning: a pilot investigation on the neurocognitive benefits of stand-biased school desks. Int. J. Environ. Res. Public Health 13 (1), 59.

Meyer, H.C., Lee, F.S., 2019. Translating developmental neuroscience to understand risk for psychiatric disorders. Am. J. Psychiatry 176 (3), 179–185.

Miller, J.G., Vrtička, P., Cui, X., Shrestha, S., Hosseini, S.H., Baker, J.M., Reiss, A.L., 2019. Inter-brain synchrony in mother-child dyads during cooperation: an fNIRS hyperscanning study. Neuropsychologia 124, 117–124.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., Group, P., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 6 (7), e1000097.

Moriguchi, Y., Hiraki, K., 2009. Neural origin of cognitive shifting in young children. Proc. Natl. Acad. Sci. 106 (14), 6017–6021.

Moriguchi, Y., Hiraki, K., 2011. Longitudinal development of prefrontal function during early childhood. Dev. Cognit. Neurosci. 1 (2), 153–162.

Moriguchi, Y., Hiraki, K., 2013. Prefrontal cortex and executive function in young children: a review of NIRS studies. Front. Hum. Neurosci. 7, 867.

Moriguchi, Y., Sakata, C., 2020. Development of cognitive shifting from others' behavior in young children: a near-infrared spectroscopy study. Dev. Neuropsychol. 45 (1), 39–47.

Moriguchi, Y., Shinohara, I., 2018. Effect of the COMT Val158Met genotype on lateral prefrontal activations in young children. Dev. Sci. 21 (5), e12649.

Moriguchi, Y., Shinohara, I., 2019. Socioeconomic disparity in prefrontal development during early childhood. Sci. Rep. 9 (1), 1–8.

Moriguchi, Y., Sakata, Y., Ishibashi, M., Ishikawa, Y., 2015. Teaching others rule-use improves executive function and prefrontal activations in young children. Front. Psychol. 6, 894.

Mücke, M., Andrä, C., Gerber, M., Pühse, U., Ludyga, S., 2018. Moderate-to-vigorous physical activity, executive functions and prefrontal brain oxygenation in children: a functional near-infrared spectroscopy study. J. Sports Sci. 36 (6), 630–636.

Nguyen, T., Schleihauf, H., Kayhan, E., Matthes, D., Vrtička, P., Hoehl, S., 2020. The effects of interaction quality on neural synchrony during mother-child problem solving. cortex 124, 235–249.

Okada, E., Delpy, D.T., 2003. Near-infrared light propagation in an adult head model. II. Effect of superficial tissue thickness on the sensitivity of the near-infrared spectroscopy signal. Appl. Opt. 42 (16), 2915–2921.

Okamoto, Y., Morita, K., Yamamoto, A., Ishii, Y., Haruguchi, N., Uchimura, N., 2010. Changes in task-associated cerebral blood induced by role lettering: measurement by multichannel near-infrared spectroscopy. Kurume Med. J. 57 (3), 51–58.

Paquette, N., Lassonde, M., Vannasing, P., Tremblay, J., González-Frankenberger, B., Florea, O., ..., Gallagher, A., 2015. Developmental patterns of expressive language hemispheric lateralization in children, adolescents and adults using functional near-infrared spectroscopy. Neuropsychologia 68, 117–125.

Pelphrey, K.A., Carter, E.J., 2008. Brain mechanisms for social perception: lessons from autism and typical development. Ann. N. Y. Acad. Sci. 1145, 283–299.

Perdue, K.L., Jensen, S.K., Kumar, S., Richards, J.E., Kakon, S.H., Haque, R., ..., Nelson, C.A., 2019. Using functional near-infrared spectroscopy to assess social information processing in poor urban Bangladeshi infants and toddlers. Dev. Sci. 22 (5), e12839.

Perlman, S.B., Huppert, T.J., Luna, B., 2016. Functional near-infrared spectroscopy evidence for development of prefrontal engagement in working memory in early through middle childhood. Cereb. Cortex 26 (6), 2790–2799.

Perlman, S.B., Luna, B., Hein, T.C., Huppert, T.J., 2014. fNIRS evidence of prefrontal regulation of frustration in early childhood. Neuroimage 85, 326–334.

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. Front. Hum. Neurosci. 12, 505.

Piper, S.K., Krueger, A., Koch, S.P., Mehnert, J., Habermehl, C., Steinbrink, J., ..., Schmitz, C.H., 2014. A wearable multi-channel fNIRS system for brain imaging in freely moving subjects. Neuroimage 85, 64–71.

Plichta, M.M., Heinzel, S., Ehlis, A.C., Pauli, P., Fallgatter, A.J., 2007. Model-based analysis of rapid event-related functional near-infrared spectroscopy (NIRS) data: a parametric validation study. Neuroimage 35 (2), 625–634.

Quiñones-Camacho, L.E., Fishburn, F.A., Camacho, M.C., Hlutkowsky, C.O., Huppert, T.J., Wakschlag, L.S., Perlman, S.B., 2019. Parent–child neural synchrony: a novel approach to elucidating dyadic correlates of preschool irritability. J. Child Psychol. Psychiatry doi:10.1111/jcpp.13165, Advance online publication.

Quiñones-Camacho, L.E., Fishburn, F.A., Camacho, M.C., Wakschlag, L.S., Perlman, S.B., 2019. Cognitive flexibility-related prefrontal activation in preschoolers: a biological approach to temperamental effortful control. Dev. Cognit. Neurosci. 38, 100651.

Reindl, V., Gerloff, C., Scharke, W., Konrad, K., 2018. Brain-to-brain synchrony in parent-child dyads and the relationship with emotion regulation revealed by fNIRS-based hyperscanning. Neuroimage 178, 493–502.

Remijn, G.B., Kikuchi, M., Yoshimura, Y., Shitamichi, K., Ueno, S., Nagao, K., ..., Minabe, Y., 2011. Hemodynamic responses to visual stimuli in cortex of adults and 3-to 4-year-old children. Brain Res. 1383, 242–251.

Riggs, N.R., Jahromi, L.B., Razza, R.P., Dillworth-Bart, J.E., Mueller, U., 2006. Executive function and the promotion of social–emotional competence. J. Appl. Dev. Psychol. 27 (4), 300–309.

Romine, C.B., Reynolds, C.R., 2005. A model of the development of frontal lobe functioning: findings from a meta-analysis. Appl. Neuropsychol. 12 (4), 190–201.

Saggar, M., Xie, H., Beaty, R.E., Stankov, A.D., Schreier, M., Reiss, A.L., 2019. Creativity slumps and bumps: examining the neurobehavioral basis of creativity development during middle childhood. Neuroimage 196, 94–101.

Sagiv, S.K., Bruno, J.L., Baker, J.M., Palzes, V., Kogut, K., Rauch, S., ..., Eskenazi, B., 2019. Prenatal exposure to organophosphate pesticides and functional neuroimaging in adolescents living in proximity to pesticide application. Proc. Natl. Acad. Sci. 116 (37), 18347–18356.

Sakakibara, E., Takizawa, R., Kawakubo, Y., Kuwabara, H., Kono, T., Hamada, K., ..., Kasai, K., 2018. Genetic influences on prefrontal activation during a verbal fluency task in children: a twin study using near-infrared spectroscopy. Brain Behav. 8 (6), e00980.

Sanefuji, M., Takada, Y., Kimura, N., Torisu, H., Kira, R., Ishizaki, Y., Hara, T., 2011. Strategy in short-term memory for pictures in childhood: a near-infrared spectroscopy study. Neuroimage 54 (3), 2394–2400.

Santosa, H., Zhai, X., Fishburn, F., Huppert, T., 2018. The NIRS brain AnalyzIR toolbox. Algorithms 11 (5), 73.

Scholkmann, F., Wolf, M., 2013. General equation for the differential pathlength factor of the frontal human head depending on wavelength and age. J. Biomed. Opt. 18 (10), 105004.

Scholkmann, F., Kleiser, S., Metz, A.J., Zimmermann, R., Pavia, J.M., Wolf, U., Wolf, M., 2014. A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology. Neuroimage 85, 6–27.

Schroeter, M.L., Zysset, S., Kruggel, F., Von Cramon, D.Y., 2003. Age dependency of the hemodynamic response as measured by functional near-infrared spectroscopy. Neuroimage 19 (3), 555–564.

Schroeter, M.L., Zysset, S., Wahl, M., von Cramon, D.Y., 2004. Prefrontal activation due to Stroop interference increases during development—an event-related fNIRS study. Neuroimage 23 (4), 1317–1325.

Singh, A.K., Dan, I., 2006. Exploring the false discovery rate in multichannel NIRS. Neuroimage 33 (2), 542–549.

Smith, E., Anderson, A., Thurm, A., Shaw, P., Maeda, M., Chowdhry, F., ..., Gandjbakhche, A., 2017. Prefrontal activation during executive tasks emerges over early childhood: evidence from functional near infrared spectroscopy. Dev. Neuropsychol. 42 (4), 253–264.

Soltanlou, M., Sitnikova, M.A., Nuerk, H.C., Dresler, T., 2018. Applications of functional near-infrared spectroscopy (fNIRS) in studying cognitive development: the case of mathematics and language. Front. Psychol. 9, 277.

Strangman, G., Culver, J.P., Thompson, J.H., Boas, D.A., 2002. A quantitative comparison of simultaneous BOLD fMRI and NIRS recordings during functional brain activation. Neuroimage 17 (2), 719–731.

Su, W.C., Culotta, M.L., Hoffman, M.D., Trost, S.L., Pelphrey, K.A., Tsuzuki, D., Bhat, A.N., 2020. Developmental differences in cortical activation during action observation, action execution and interpersonal synchrony: an fNIRS study. Front. Hum. Neurosci. 14, 57.

Sugiura, L., Hata, M., Matsuba-Kurita, H., Uga, M., Tsuzuki, D., Dan, I., ..., Homae, F., 2018. Explicit performance in girls and implicit processing in boys: a simultaneous fNIRS–ERP study on second language syntactic learning in young adolescents. Front. Hum. Neurosci. 12, 62.

Sugiura, L., Ojima, S., Matsuba-Kurita, H., Dan, I., Tsuzuki, D., Katura, T., Hagiwara, H., 2011. Sound to language: different cortical processing for first and second languages in elementary school children as revealed by a large-scale study using fNIRS. Cereb. Cortex 21 (10), 2374–2393.

Sugiura, L., Ojima, S., Matsuba-Kurita, H., Dan, I., Tsuzuki, D., Katura, T., Hagiwara, H., 2015. Effects of sex and proficiency in second language processing as revealed by a large-scale fNIRS study of school-aged children. Hum. Brain Mapp. 36 (10), 3890–3911.

Sugiura, L., Toyota, T., Matsuba-Kurita, H., Iwayama, Y., Mazuka, R., Yoshikawa, T., Hagiwara, H., 2017. Age-dependent effects of Catechol-O-Methyltransferase (COMT) gene Val158Met polymorphism on language function in developing children. Cereb. Cortex 27 (1), 104–116.

Suzuki, K., Kita, Y., Oi, Y., Okumura, Y., Okuzumi, H., Inagaki, M., 2018. Right prefrontal cortex specialization for visuospatial working memory and developmental alterations in prefrontal cortex recruitment in school-age children. Clin. Neurophysiol. 129 (4), 759–765.

Tando, T., Kaga, Y., Ishii, S., Aoyagi, K., Sano, F., Kanemura, H., ..., Aihara, M., 2014. Developmental changes in frontal lobe function during a verbal fluency task: a multi-channel near-infrared spectroscopy study. Brain Dev. 36 (10), 844–852.

Tsujii, T., Masuda, S., Yamamoto, E., Ohira, T., Akiyama, T., Takahashi, T., Watanabe, S., 2009. Effects of sedative and nonsedative antihistamines on prefrontal activity during verbal fluency task in young children: a near-infrared spectroscopy (NIRS) study. Psychopharmacology 207 (1), 127.

Tsujii, T., Yamamoto, E., Masuda, S., Watanabe, S., 2009. Longitudinal study of spatial working memory development in young children. Neuroreport 20 (8), 759–763.

Tsujii, T., Yamamoto, E., Ohira, T., Takahashi, T., Watanabe, S., 2010. Antihistamine effects on prefrontal cortex activity during working memory process in preschool children: a near-infrared spectroscopy (NIRS) study. Neurosci. Res. 67 (1), 80–85.

Tucker-Drob, E.M., Briley, D.A., Harden, K.P., 2013. Genetic and environmental influences on cognition across development and context. Curr. Dir. Psychol. Sci. 22 (5), 349–355.

Vandekerckhove, K., Coomans, I., Moerman, A., De Wolf, D., Boone, J., 2016. Characterizing cerebral and locomotor muscle oxygenation to incremental ramp exercise in healthy children: relationship with pulmonary gas exchange. Eur. J. Appl. Physiol. 116 (11–12), 2345–2355.

Vanderwert, R.E., Nelson, C.A., 2014. The use of near-infrared spectroscopy in the study of typical and atypical development. Neuroimage 85, 264–271.

Villringer, A., Chance, B., 1997. Non-invasive optical spectroscopy and imaging of human brain function. Trends Neurosci. 20 (10), 435–442.

Wager, T.D., Vazquez, A., Hernandez, L., Noll, D.C., 2005. Accounting for nonlinear BOLD effects in fMRI: parameter estimates and a model for prediction in rapid event-related studies. Neuroimage 25 (1), 206–218.

Wang, M., Saudino, K.J., 2013. Genetic and environmental influences on individual differences in emotion regulation and its relation to working memory in toddlerhood. Emotion 13 (6), 1055–1067.

Wartenburger, I., Steinbrink, J., Telkemeyer, S., Friedrich, M., Friederici, A.D., Obrig, H., 2007. The processing of prosody: evidence of interhemispheric specialization at the age of four. Neuroimage 34 (1), 416–425.

Webb, S.J., Monk, C.S., Nelson, C.A., 2001. Mechanisms of postnatal neurobiological development: implications for human development. Dev. Neuropsychol. 19 (2), 147–171.

Wellman, H.M., Cross, D., Watson, J., 2001. Meta-analysis of theory-of-mind development: the truth about false belief. Child Dev. 72 (3), 655–684.

Whiteman, A.C., Santosa, H., Chen, D.F., Perlman, S.B., Huppert, T., 2017. 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.

Witmer, J.S., Aeschlimann, E.A., Metz, A.J., Troche, S.J., Rammsayer, T.H., 2018. Functional near-infrared spectroscopy recordings of visuospatial working memory processes. Part II: a replication study in children on sensitivity and mental-ability-induced differences in functional activation. Brain Sci. 8 (8), 152.

Wolf, U., Toronov, V., Choi, J.H., Gupta, R., Michalos, A., Gratton, E., Wolf, M., 2011. Correlation of functional and resting state connectivity of cerebral oxy-, deoxy-, and total hemoglobin concentration changes measured by near-infrared spectrophotometry. J. Biomed. Opt. 16 (8), 087013.

Xu, F., Han, Y., Sabbagh, M.A., Wang, T., Ren, X., Li, C., 2013. Developmental differences in the structure of executive function in middle childhood and adolescence. PLoS One 8 (10), e77770.

Yabe, M., Oshima, S., Eifuku, S., Taira, M., Kobayashi, K., Yabe, H., Niwa, S.I., 2018. Effects of storytelling on the childhood brain: near-infrared spectroscopic comparison with the effects of picture-book reading. Fukushima J. Med. Sci. 64 (3), 125–132.

Yamasaki, T., Ogata, K., Maekawa, T., Ijichi, I., Katagiri, M., Mitsudo, T., ..., Tobimatsu, S., 2013. Rapid maturation of voice and linguistic processing systems in preschool children: a near-infrared spectroscopic study. Exp. Neurol. 250, 313–320.

Yaple, Z., Arsalidou, M., 2018. N-back working memory task: meta-analysis of normative fMRI studies with children. Child Dev. 89 (6), 2010–2022.

Yeung, M.K., Chan, A.S., 2020. A systematic review of the application of functional near-infrared spectroscopy to the study of cerebral hemodynamics in healthy aging. Neuropsychol. Rev. Advanced Online Publication.. https://doi.org/10.1007/s11065-020-09455-3.

Yeung, M.K., Lee, T.L., Chan, A.S., 2020. Neurocognitive development of flanker and Stroop interference control: a near-infrared spectroscopy study. Brain Cognit. 143, 105585.

Zeman, J., Cassano, M., Perry-Parrish, C., Stegall, S., 2006. Emotion regulation in children and adolescents. J. Dev. Behav. Pediatr. 27 (2), 155–168.

Zhao, H., Tanikawa, Y., Gao, F., Onodera, Y., Sassaroli, A., Tanaka, K., Yamada, Y., 2002. Maps of optical differential pathlength factor of human adult forehead, somatosensory motor and occipital regions at multi-wavelengths in NIR. Phys. Med. Biol. 47 (12), 2075.

Zhou, G., Liu, J., Ding, X.P., Fu, G., Lee, K., 2016. Development of effective connectivity during own-and other-race face processing: a granger causality analysis. Front. Hum. Neurosci. 10, 474.