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Linking Verbal Working Memory to Reading Development: Insights from the Neurobiology of Early Language Revealed by fNIRS

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Abstract

Memory is a core cognitive function that not only shapes our daily interactions with the environment but also plays a pivotal role in the acquisition of higher-order skills such as language and reading. Among its components, verbal working memory is particularly relevant for early literacy, as it supports the temporary storage and manipulation of phonological information, which is essential for decoding, comprehension, and the gradual automatization of reading. Exploring how verbal short-term memory develops and how it is instantiated in the brain can therefore provide important insights into the neurocognitive foundations of early language learning. This study investigates the relationship between verbal short-term memory and prefrontal cortical activation in 5 to 11 years-old children, a developmental window in which language and reading skills undergo rapid consolidation. Hemodynamic response was measured using functional near-infrared spectroscopy (fNIRS) during a digit-span task in both forward and backward conditions, designed to probe verbal short-term storage and working memory demands. In addition to these neuroimaging measures, participants completed a test on reading fluency. The expected outcomes of this study aim to clarify how prefrontal recruitment during verbal short-term memory tasks relates to the emergence of early reading abilities. Such findings may contribute to a more integrated account of the links between memory and literacy, informing both theoretical models of cognitive development and practical applications in educational and clinical contexts.

Key words: Working memory, reading acquisition, fNIRS.

Introduction

The development of language has placed particular importance on the ability to hold and store verbal information. Humans are frequently required to remember arbitrary sets of numbers or words and to recall them moments later. This capacity, known as verbal short-term memory (VeSTM), is described within the multicomponent model of working memory as an integrated set of systems that support the temporary storage and processing of information (Baddeley & Hitch, 1974).

VeSTM primarily relies on the phonological loop, which comprises two interacting subcomponents: a phonological store that receives information from auditory input, and an articulatory rehearsal process that refreshes information derived from visual input. Both components operate under the control of the central executive, which is responsible for internally oriented attentional control processes (Baddeley, Hitch, & Allen, 2020). Buchsbaum and D'Esposito (2019) proposed a sensorimotor account of the neural functionality of the phonological loop. According to this view, the maintenance of structured verbal information in VeSTM depends on the transformation of auditory input into a regenerable motor–articulatory code. This code enables the reactivation of auditory phonological representations, thereby creating a functional loop between stimulus perception and motor response. The reverberatory process is supported by coordinated activity across three processing nodes: the auditory–phonological region of the superior temporal gyrus (STG), the auditory–motor interface in area Spt (Sylvian parietotemporal region), and motor–articulatory regions in the prefrontal cortex (PFC).

Tasks commonly used to assess phonological rehearsal and manipulation include span tasks, which require the immediate recall of stimulus sequences of varying lengths, such as digits, words, or pseudowords, as well as their manipulation and temporary storage. However, research indicates that both the type of stimuli and the order of recall can influence behavioral performance and neural activation patterns. For example, digit span tasks requiring backward recall are consistently more demanding than forward recall, reflecting a higher executive load on the central executive component (Baddeley, Hitch, & Allen, 2020). Neuroimaging studies show that forward digit recall, primarily supported by phonological rehearsal, is associated with activation in temporofrontal cortices, predominantly in the left hemisphere. In contrast, backward digit span engages additional executive control regions, including the dorsolateral prefrontal cortex (dlPFC), frontal eye fields (FEF), and dorsal anterior cingulate cortex (dACC) (Yang et al., 2015).

There is general consensus that working memory capacity increases from childhood through adolescence (Gathercole, 2004). However, the mechanisms underlying improvements in performance are multifaceted and involve several interacting developmental processes (Cowan, Ricker, Clark, Hinrichs, & Glass, 2014). The development of VeSTM is accelerated by the acquisition of reading and writing skills, with studies reporting an abrupt increase in the number of items that children can recall and manipulate in short-term memory as they enter formal schooling. More specifically, memory for phonemes improves with literacy experience. Despite well-established associations, studies continue to investigate the precise mechanisms and bidirectional relationships among phonological representations, phoneme awareness, and verbal short-term memory in supporting early language and reading development (Cunningham et al., 2021). Structural equation modeling of longitudinal data has shown that performance on phonological memory tasks involving ordered recall predicts reading achievement during the first two years of schooling (from approximately age 4 in English-speaking children), but not at later stages of development (Cunningham et al., 2021). In contrast, among readers aged 6 to 9 years, reading ability is more strongly associated with nonword repetition performance, suggesting a reverse influence whereby already established links between language-based phonological representations and orthographic representations facilitate the encoding of novel words (Cunningham et al., 2021).

Structural MRI studies confirm pronounced developmental changes in the brain during childhood (Botdorf & Riggins, 2018) and indicate that neural restructuring occurs during the critical period of basic education, approximately between ages 4 and 8 years. VeSTM capacity is causally and developmentally linked to language acquisition, particularly vocabulary learning, with cascading effects on phonological, grammatical, and literacy development. Studies examining performance on the digit span task have reported associations with cortical thickness in the superior frontal cortex, middle frontal cortex, superior parietal cortex, and anterior cingulate cortex. Thinner cortical thickness has been associated with better forward digit span performance and age accounted for approximately 32% of the variance in digit span performance. Even when age was included as a covariate, cortical thickness remained a significant predictor in frontal regions (Botdorf & Riggins, 2018) for differing findings, see Bathelt et al. (2017).

Functional near-infrared spectroscopy (fNIRS) is a well-established, non-invasive method for indirectly assessing task-related cortical function by measuring changes in blood oxygenation and deoxygenation. It is particularly suitable for use with pediatric populations, as it is portable, tolerant to head movements, relatively easy to set up, and cost-effective (Chen et al., 2020). The aims of the present study were twofold. First, we examined whether developmental variation in

VeSTM capacity is accompanied by changes in prefrontal cortex (PFC) activation. We hypothesized that digit span performance would increase with age, while PFC activation measured by fNIRS would decrease, reflecting greater neural efficiency. Second, we investigated the relationship between PFC activation and reading skill acquisition. We expected to observe a negative correlation between literacy experience and PFC activation, consistent with previous findings linking literacy to more efficient phonological processing (Ziegler, 2004).

Material and Methods

Participants

A total of 96 children aged 5 to 11 years participated in the study (mean age = 8.26 years, SD=1.47; range=5–11 years). All participants were recruited from a local primary school in Santo André municipal school, São Paulo state. They were classified into two groups based on their reading acquisition development: typical and atypical readers. Group classification was based on teacher reports of children's reading and writing performance. Children classified in the atypical reading development group showed below-expected performance in reading and writing skills and were therefore enrolled in a literacy intervention program (Alfatech) aimed at supporting reading and writing development, which was offered from the end of second grade onward. In contrast, children classified in the typical reading development group demonstrated age-appropriate reading and writing performance and did not participate in any remedial or intervention programs

Children with a confirmed diagnosis of neurodevelopmental disorders, sensory or motor impairments, traumatic brain injury, or a history of behavioral or psychiatric disorders were excluded from the study. Written informed consent was obtained from parents or legal guardians of all participating children. The study protocol was approved by the Institutional Human Research Ethics Committee of Federal University of ABC (UFABC).

All children completed the Digit Span Task during fNIRS data acquisition. However, due to the interruption of data collection caused by the COVID-19 lockdown, only a subset of participants completed the full neuropsychological assessment battery. The distribution of participants across school grades and reading development groups is presented in Table 1.

Table 1: Distribution of participants across school grades. Total number of participants who completed the fNIRS assessment (left) and total number of participants who completed both the fNIRS assessment and the word reading test (right).

Grade	fNIRS			Words Reading Test		
	Typical	Atypical	Total	Typical	Atypical	Total
1	7	---	7	---	---	---
2	16	---	16	---	---	---
3	18	18	36	8	3	11
4	10	6	16	8	5	13
5	14	7	21	9	13	14
Sum	65	31	96	25	13	38

Behavioral Tasks

Digit Span Task (DST)

The Digit Span Task (DST) was used to assess participants' VeSTM capacity. The fNIRS activation paradigm followed a block design and consisted of two runs, each lasting approximately 5 minutes. Each run included seven 20-second epochs of alternating task and rest conditions (Figure 1).

Participants were first tested in the Digit Span Direct Order condition (DO), followed by the Digit Span Inverse Order condition (IO). In the DO condition, participants listened to a prerecorded sequence of digits while a red cross was displayed on the screen. When the cross turned green, participants were instructed to immediately repeat the sequence in the same order. In the IO condition, participants were instructed to repeat the digit sequence in reverse order. Rest epochs were indicated by a white cross on the screen, during which participants were instructed to remain silent.

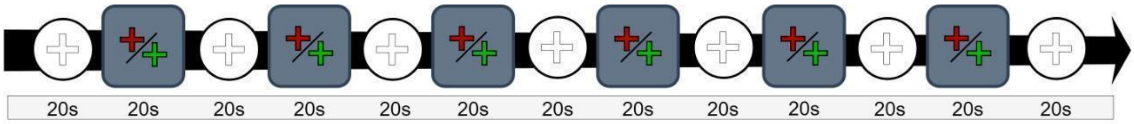

Figure 1: Schematic representation of the block design for the DO and IO conditions. White crosses indicate rest blocks. Gray boxes with red and green crosses indicate task blocks. All blocks lasted 20 s. Participants were required to remember the digit sequence and repeat it in the same order (DO) or in reverse order (IO).

Prior to fNIRS data acquisition, participants completed a pretest in both DO and IO conditions to determine their individual maximum digit span. This pretest was administered using the Digit Span subtest from the Wechsler Intelligence Scale for Children–Fourth Edition (WISC-IV; Wechsler, 2013 – Brazilian adaptation), following standardized procedures. The purpose of the pretest was to equate task difficulty across school grades and to ensure that each participant performed the task at a challenging yet comfortable level during fNIRS recording. Based on pretest performance, the total number of stimuli presented during fNIRS acquisition was adjusted according to span level. Specifically, sequences of two digits were presented in 28 trials, three-digit sequences in 21 trials, and four-digit sequences in 14 trials per run.

Words Reading Test

Reading speed was assessed using an adapted version of a single-word reading task (Salles et al., 2013). The Words Reading Test consisted of 48 words, including 24 regular and 24 irregular words, organized into four sets of 12 words that varied in length (short and long words). Participants were instructed to read the words sequentially and as quickly and accurately as possible. The total number of correctly read words and the total reading time were recorded. Accuracy scores ranged from 0 to 48 correctly read words. Reading time was analyzed only for participants who completed the entire list of 48 words

fNIRS Measurement and Analysis

Functional near-infrared spectroscopy (fNIRS) data were acquired using a NIRSport 1 8×8 system (NIRx Medical Technologies, Glen Head, NY), equipped with eight light sources (760 nm and 850 nm) and seven silicon photodiode detectors. Data were sampled at a rate of 7.81 Hz. The fNIRS probe configuration covered frontal brain regions and comprised 28 measurement channels, including eight short-separation channels, eight emitters, and seven detectors (Figure 2). Inter-optode distances were 3 cm for long-separation channels and 8 mm for short-separation channels.

Optodes were mounted on a head cap positioned according to the international 10–10 EEG system, with the central probe aligned at Fpz as shown in Figure 2 (Jurcak et al., 2007). Participants were seated comfortably at a desk in front of a laptop displaying task instructions. After cap placement, system calibration and signal quality checks were performed for each channel, and optodes were repositioned when necessary to optimize signal quality. The preparation phase lasted approximately

5 minutes, followed by approximately 5 minutes of fNIRS data acquisition during the Digit Span Task.

Both oxygenated (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) signals were analyzed. Mean activation values were computed for predefined regions of interest (ROIs). Dorsolateral prefrontal cortex (DLPFC) activation was averaged across channels corresponding to the F3 location for the left hemisphere (channels 8 and 9) and the F4 location for the right hemisphere (channels 15 and 16). Dorsomedial prefrontal cortex (DMPFC) activation was averaged across channels corresponding to Fpz (channels 1, 2, and 3). These ROIs were selected based on their established involvement in executive functions and VeSTM (Moriguchi & Hiraki, 2013). ROI definitions and channel assignments were determined using the fOLD toolbox (Morais, Balardin, & Sato, 2018).

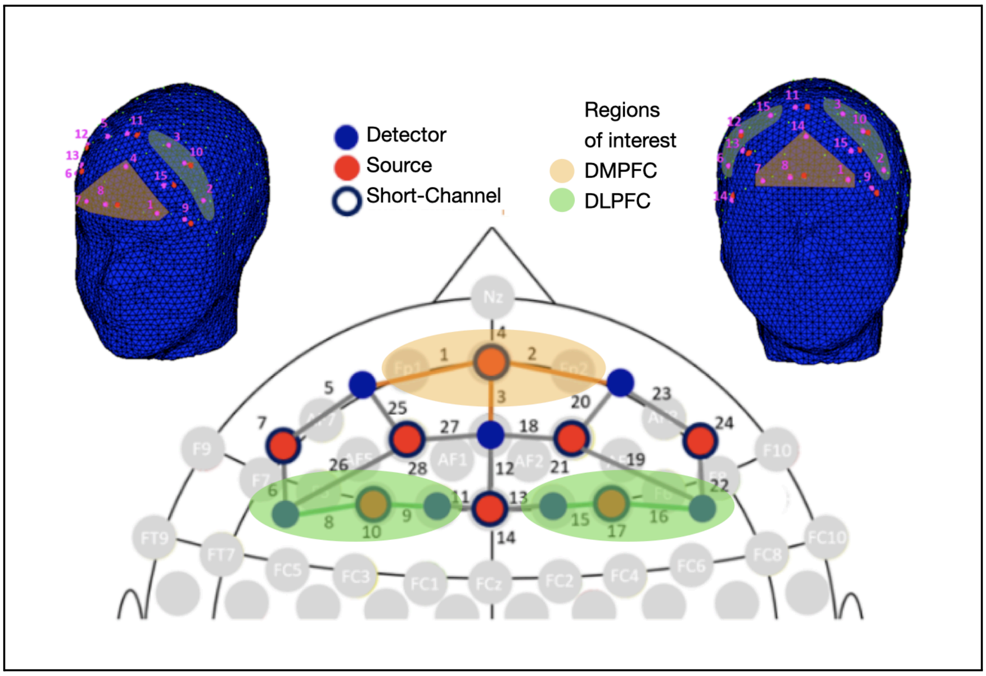

Figure 2: Location of source and detector probes for fNIRS recording. The sources are represented by red dots and detectors by blue dots. Regions of interest marked orange in the Dorsolateral prefrontal cortex (DLPFC) contain channels 8 and 9 in the left hemisphere and channels 15 and 16 in the right hemisphere. The dorsomedial prefrontal cortex (DMPFC) marked orange includes channels 1, 2, and 3.

Statistical Analysis

Participant performance was defined as the percentage of correct responses, calculated as the number of correct trials divided by the total number of repetitions. A response was considered correct only if the participant accurately recalled the entire digit sequence in either the direct order (DO) or inverse order (IO) condition. Accuracy was calculated separately for DO and IO conditions and analyzed using non-parametric Kruskal–Wallis tests to compare performance across school grades and reading development groups. In addition to accuracy, digit span in DO and IO conditions was analyzed using the same statistical approach.

fNIRS data collected during the working memory task were processed using NIRSLab software, version 2019 (NIRx Medical Technologies, USA; Xu, Graber, & Barbour, 2014). As no interruption occurred between the two task blocks during acquisition, the fNIRS signal was truncated 20s prior to the onset of the first trial and 5s after the final trial for both DO and IO conditions. Signal quality was assessed using a coefficient of variation threshold of 7.5. Participants with more than 40% of bad frames were excluded from the final sample reported in Table 1 (total collected sample: N = 127; excluded: 23.6%).

General linear model (GLM) analyses were performed using pre-whitening with an autoregressive model (AR[n]) and a canonical hemodynamic response function (HRF) as the basis function as suggested by (Santosa 2020). Contrast vectors were specified for the DO condition, the IO condition, and the subtraction contrast (IO − DO).

Beta coefficients derived from the GLM were used as indices of cortical activation and compared across conditions using Kruskal–Wallis tests. Analyses focused on regions of interest (ROIs) in the dorsolateral prefrontal cortex (DLPFC) and dorsomedial prefrontal cortex (DMPFC). Hemispheric differences in DLPFC activation were assessed using lateralization indices (LI), calculated as (Right DLPFC − Left DLPFC) for the subtractive index and (Right DLPFC − Left DLPFC) / (Right DLPFC + Left DLPFC) for the relative index.

To investigate the relationship between frontal activation and reading performance, linear regression analyses were conducted using word reading accuracy (hits) and reading time as predictors of digit span behavioral performance and fNIRS activation measures. Only participants who completed both the fNIRS recording and the word reading test were included in these analyses (N=38; see Table 1). All statistical analyses were performed in R, with the significance level set at $p < 0.05$.

Results

Behavioral performance

Performance on the Digit Span Task revealed no significant differences between atypical and typical readers in forward digit span (DO span; Kruskal–Wallis, χ^2=1.629, p=0.202; Figure 3).

However, children with atypical reading development showed higher accuracy in the DO condition compared to typical readers (Kruskal–Wallis, $\chi^2=8.250$, $p < 0.05$; Figure 4). In the inverse order (IO) condition, no significant differences were observed between developmental groups for either span ($\chi^2 = 0.312$, $p = 0.576$; Figure 5) or accuracy ($\chi^2 = 1.164$, $p = 0.281$; Figure 6). These findings indicate that both groups performed similarly on the digit span task, suggesting a ceiling effect in the task accuracy. Therefore, observed differences in brain activation cannot be attributed to differences in task performance.

With respect to maturational changes in VeSTM, a significant main effect of school grade was observed for DO span ($\chi^2=23.199$, $p < 0.001$), DO accuracy ($\chi^2=20.537$, $p<0.001$), IO span ($\chi^2=42.418$, $p<0.001$), and IO accuracy ($\chi^2=18.407$, $p<0.001$). Bonferroni-corrected post hoc analyses revealed that, for DO span, first-grade children showed significantly lower span than children in grades 3, 4, and 5 (all $p < 0.05$). A similar pattern was observed for DO accuracy, with first-grade children performing worse than those in grades 3, 4, and 5 (all $p < 0.05$).

For IO span, first-grade children performed worse than children in grades 3, 4, and 5 (all $p < 0.05$). Additionally, second-grade children showed lower IO span than fifth-grade children ($p < 0.05$), and third-grade children showed lower IO span than fifth-grade children ($p <0.05$). In contrast, for IO accuracy, first-grade children showed lower accuracy only when compared to children in grades 3 and 4 (both $p < 0.05$).

Regarding reading fluency, Kruskal–Wallis tests revealed significant differences between developmental groups for both reading accuracy (hits; $\chi^2=7.925$, $p<0.01$) and reading time ($\chi^2=6.291$, $p<0.05$) on the word reading test, with children in the atypical development group showing poorer performance (see the behavioral and fNIRS data by group in Supplementary Table 1).

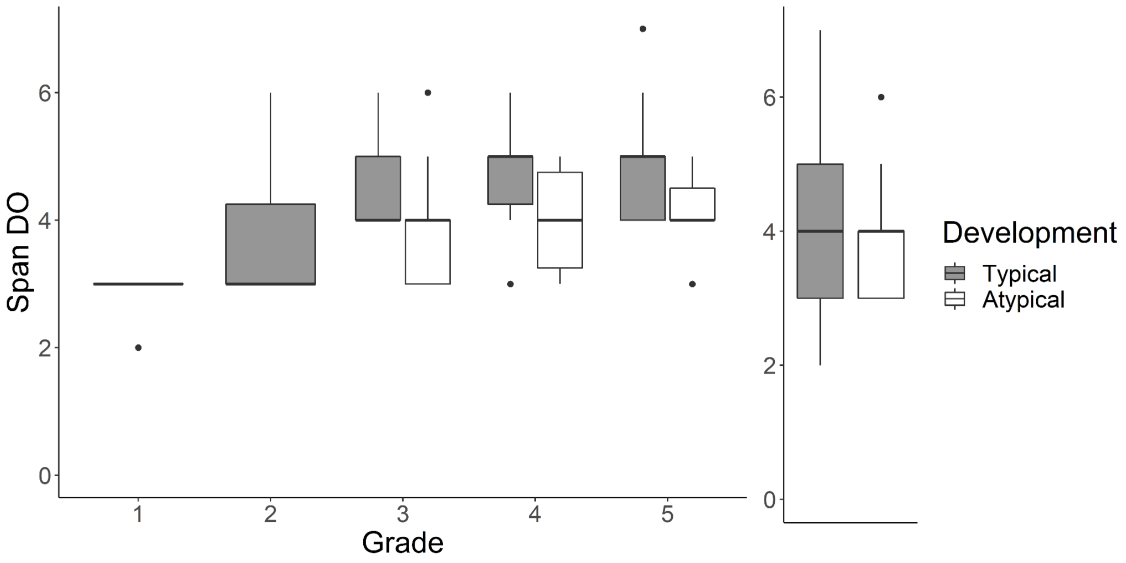

Figure 3: Forward digit span (DO) as a function of school grade and developmental group. DO span differed significantly across grades but not between developmental groups. First-grade children showed lower span than children in grades 3, 4, and 5 (post hoc comparisons not shown).

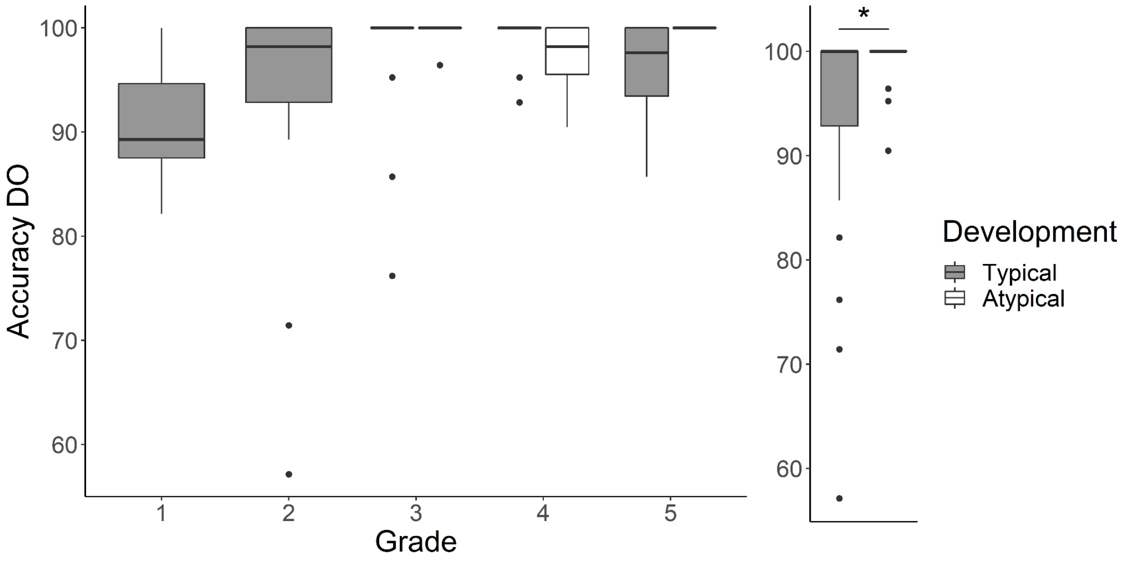

Figure 4: Accuracy in the forward digit span (DO) as a function of school grade and developmental group. Accuracy in the DO condition differed across grades and between developmental groups. First-grade children showed lower accuracy than children in grades 3, 4, and 5 (post hoc comparisons not shown). Children in the typical development group showed lower accuracy than children in the atypical development group.

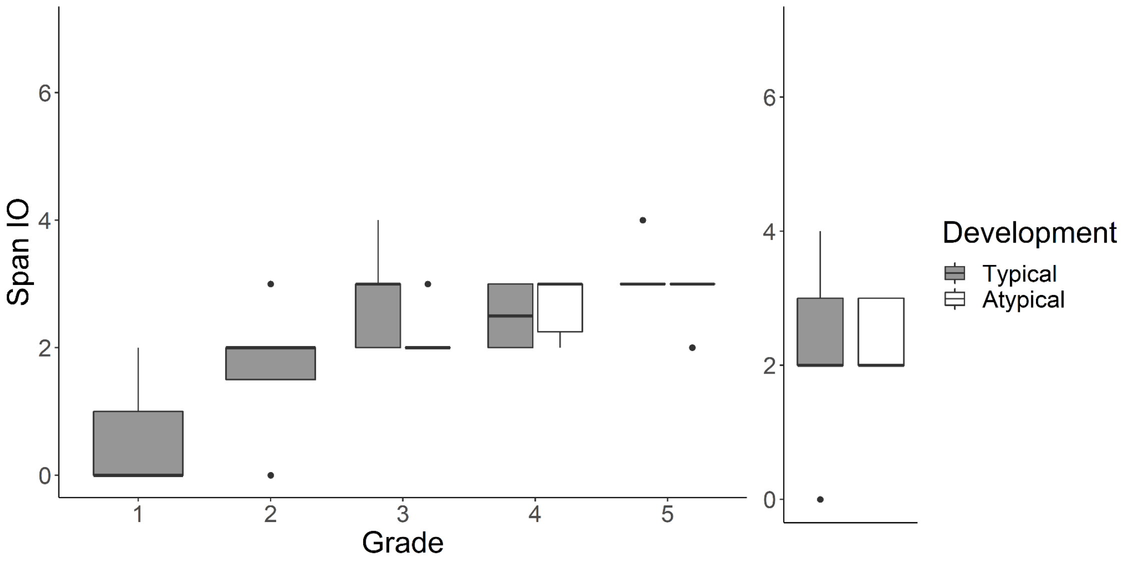

Figure 5: Inverse digit span (IO) as a function of school grade and developmental group. IO span differed significantly across grades. First-grade children showed lower IO span than children in grades 3, 4, and 5. In addition, children in grades 2 and 3 showed lower IO span compared to children in grade 5. No differences in IO span were observed between developmental groups

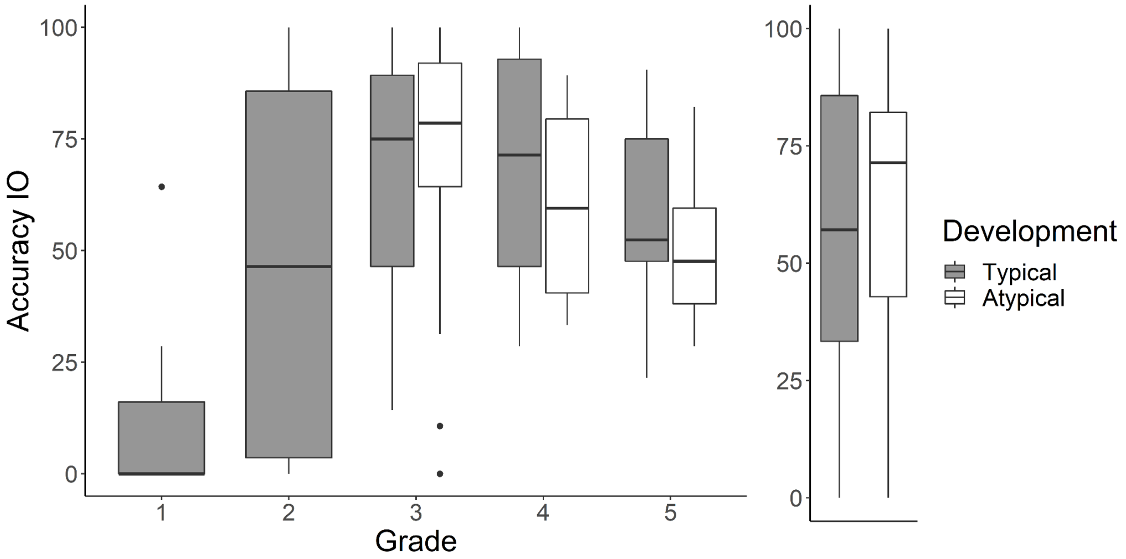

Figure 6: Accuracy in the inverse digit span (IO) as a function of school grade and developmental group**.** A main effect of grade was observed for IO accuracy, with no differences between developmental groups. First-grade children showed lower accuracy compared to children in grades 3 and 4 (post hoc comparisons not shown).

fNIRS Performance

Children in the atypical development group showed greater prefrontal activation than children in the typical development group during the Digit Span Task. In the DO condition, the atypical group exhibited higher deoxy-Hb in the right DLPFC (Kruskal–Wallis, $\chi^2 = 3.945$, $p < 0.05$; Figure 7) and in the left DLPFC higher oxy-Hb related signal (Kruskal–Wallis, $\chi^2 = 7.414$, $p < 0.05$; Figure 8). Similarly, during the IO condition, the atypical group showed greater activation in the right DLPFC (oxy-Hb; Kruskal–Wallis, $\chi^2=4.008$, $p<0.05$; Figure 9) and in the DMPFC (oxy-Hb; Kruskal–Wallis, $\chi^2=3.977$, $p<0.05$; Figure 10). When controlling for age using an ANCOVA with grade as a covariate, the difference between right and left DLPFC activation during the DO condition remained significant (Supplementary Materials 2).

A significant effect of grade was observed for the relative lateralization index (LI) of the DLPFC during the DO condition (oxy-Hb; Kruskal–Wallis, $\chi^2=10.677$, $p<0.05$). Bonferroni-corrected post hoc analyses indicated that children in grade 2 showed a higher LI compared to children in grade 3 ($p<0.05$), suggesting relatively greater right DLPFC activation or reduced left DLPFC activation in second-grade children (Supplementary Materials 3).

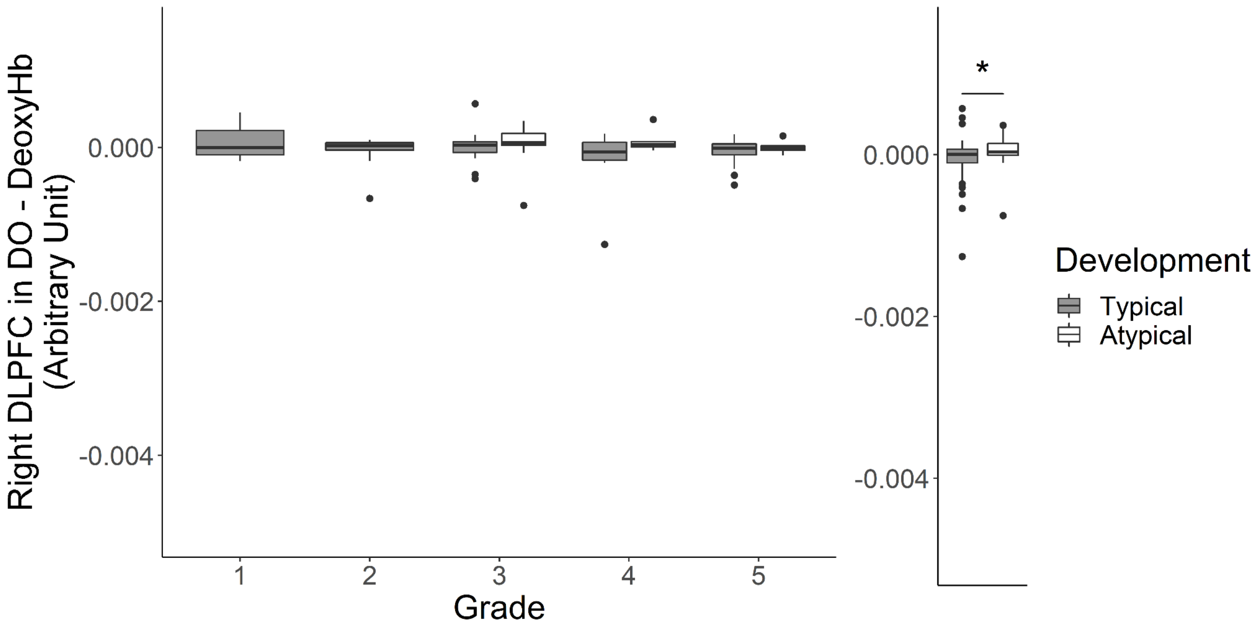

Figure 7: Right DLPFC activation (deoxy-Hb) during the DO condition across grades. Children in the atypical development group showed higher right DLPFC activation than children in the typical development group. No differences between grades were observed.

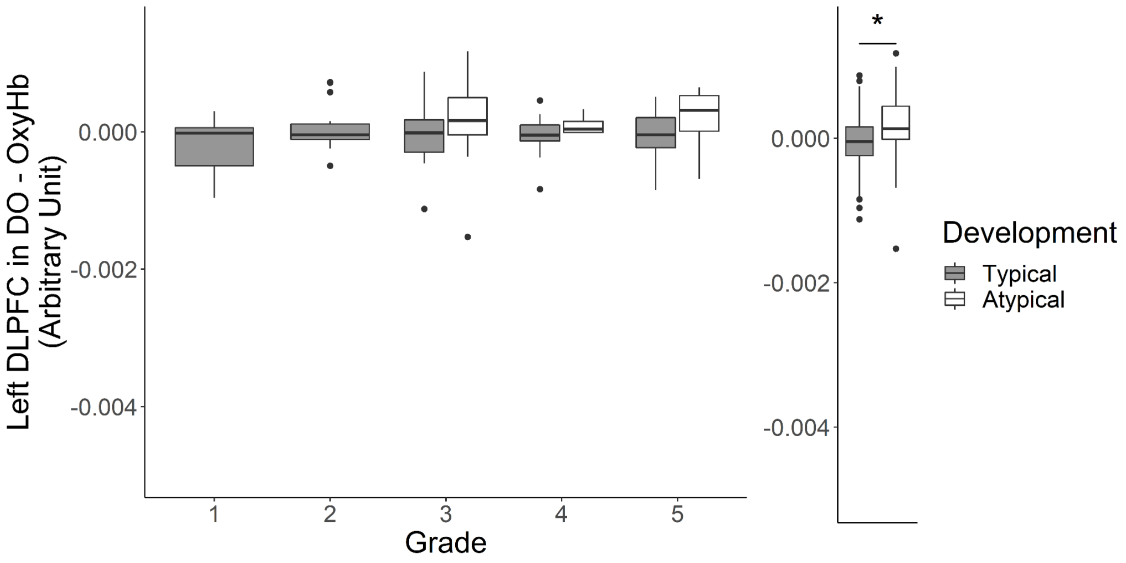

Figure 8: Left DLPFC activation (oxy-Hb) during the DO condition across grades. Children in the atypical development group showed higher left DLPFC activation compared to children in the typical development group. No differences between grades were observed.

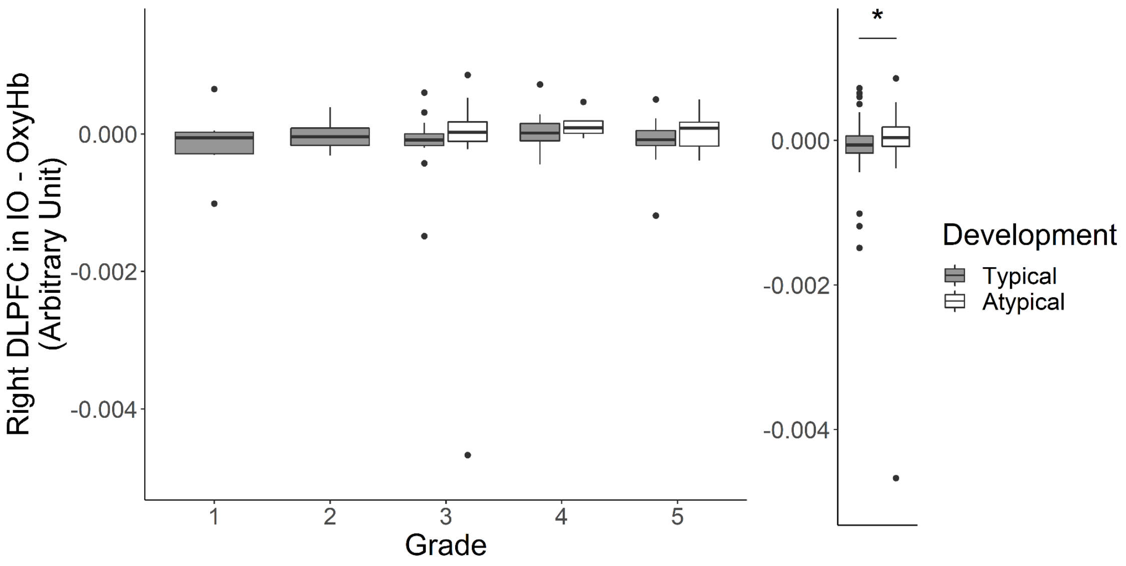

Figure 9: Right DLPFC activation (oxy-Hb) during the IO condition across grades. Children with atypical development showed higher right DLPFC activation than children with typical development. No differences between grades were observed.

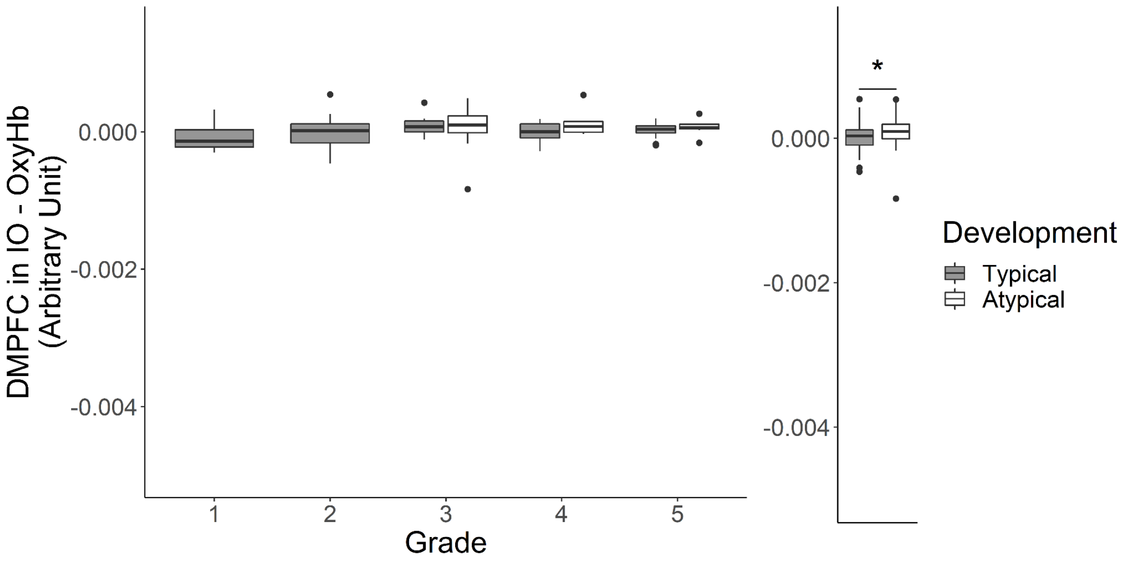

Figure 10: DMPFC activation (oxy-Hb) during the IO condition across grades. Children in the atypical development group showed higher DMPFC activation than children in the typical development group. No grade-related differences were observed.

Regression Analysis

Linear regression analyses were conducted to examine whether performance on the Word Reading Test, accuracy (hits) and reading time, predicted behavioral performance on the Digit Span Task (DST) and prefrontal activation measured with fNIRS (Table 2). Word reading accuracy (hits) and reading time were entered as predictors in separate models for behavioral and neural outcome measures.

Word reading accuracy (hits) significantly predicted left DLPFC activation during the DO condition for both oxy-Hb and deoxy-Hb signals (Figure 11), as well as the subtractive lateralization index (deoxy-Hb) during DO and left DLPFC activation (deoxy-Hb) during the IO condition. In all cases, higher word reading accuracy was associated with lower prefrontal activation, indicating greater neural efficiency in children with stronger reading skills.

Word reading time also showed significant predictive value for prefrontal activation. Longer reading times were associated with greater activation in the right DLPFC (oxy-Hb) and left DLPFC (deoxy-Hb), as well as with higher subtractive lateralization indices (oxy-Hb and deoxy-Hb) during the DO condition. During the IO condition, reading time significantly predicted left DLPFC activation (deoxy-Hb) and the subtractive lateralization index (deoxy-Hb). These findings indicate that slower reading performance is associated with increased reliance on prefrontal resources during VeSTM processing.

The full set of regression coefficients is reported in Table 2.

Table 2: Beta coefficients from linear regression analyses.

#: variables that also showed significant differences between developmental groups in Kruskal–Wallis tests.

*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

WR = Word Reading; ACC = Accuracy; LI Sub. = Subtractive Laterality Index; LI Rel. = Relative Laterality Index.

		Variable	**Intercept**	**Beta c. WR (Hits)**	**Beta c. WR (Time)**
		Development	1.364*	-0.025	-0.000
OD		Span	2.776*	0.045	0.001
		ACC.	9.940e-1***	-3.196e-4	-5.053e-6
OI		Span	2.418*	0.012	-0.002
		ACC.	0.806*	-0.003	-0.000
OD	**OxyHb**	DMPFC	3.062e-4	-5.961e-6	-3.980e-7
		Left DLPFC #	8.555e-4	**-1.923e-5***	3.693e-7
		Right DLPFC	-6.163e-4	4.574e-6	**5.686e-6****
		LI Sub.	-1.472e-3	3.380e-5	**5.317e-6****
		LI Rel.	-1.449	-0.013	0.004
	DeoxyHb	DMPFC	9.301e-5	-1.748e-6	-9.574e-8
		Left DLPFC	-8.385e-4*	**1.574e-5***	**1.803e-6***
		Right DLPFC #	2.493e-4	-4.479e-6	-1.179e-6
		LI Sub.	1.088e-3*	**-2.022e-5***	**-3.000e-6***

		LI Rel.	-9.717	0.202	0.028
OI	**OxyHb**	DMPFC #	1.682e-5	2.520e-6	-7.492e-7
		Left DLPFC	8.234e-4	-1.285e-5	-1.819e-6
		Right DLPFC #	3.181e-5	2.175e-7	-2.089e-7
		LI Sub.	-7.916e-4	1.306e-5	1.610e-6
		LI Rel.	2.795	-0.126	-0.007
	DeoxyHb	DMPFC	-6.531e-6	4.049e-7	-1.942e-7
		Left DLPFC	-7.120e-4**	**1.389e-5****	**1.792e-6****
		Right DLPFC	1.873e-4	-3.178e-6	-3.051e-7
		LI Sub.	8.994e-4	-1.707e-5	**-2.097e-6***
		LI Rel.	-1.398	0.009	0.003

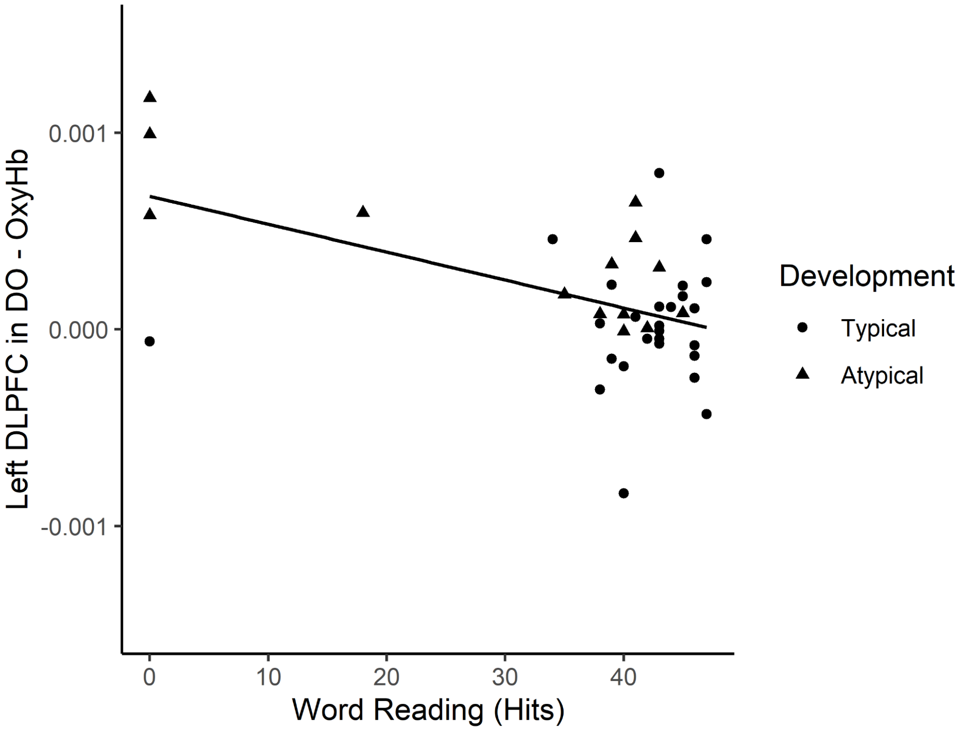

Figure 11: Left DLPFC activation (oxy-Hb) during the DO condition as a function of word reading accuracy (hits). A significant negative relationship was observed between left DLPFC activation

and word reading accuracy, indicating that children with higher reading scores showed lower activation in the left DLPFC. A higher proportion of children with atypical reading development were located above the regression line.

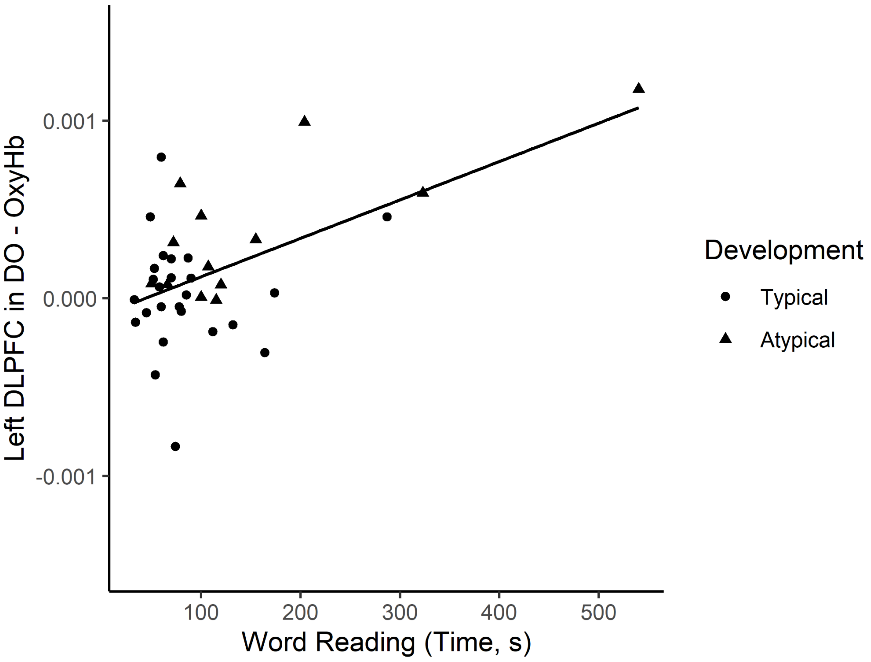

Figure 12: Left DLPFC activation (oxy-Hb) during the DO condition as a function of word reading time. A significant positive relationship was observed between left DLPFC activation and reading time, indicating that greater activation in the left DLPFC was associated with slower reading performance. A higher proportion of children with atypical reading development were located above the regression line

Discussion

The present study examined developmental and literacy-related variations in verbal short-term memory (VeSTM) and associated prefrontal cortex (PFC) activation in 5- to 11-year-old children using a digit span task and functional near-infrared spectroscopy (fNIRS). Key findings revealed a dissociation between behavioral performance and neural activation: children with lower literacy levels exhibited greater PFC recruitment during verbal memory tasks while achieving comparable behavioral outcomes, consistent with compensatory neural mechanisms (Horowitz-Kraus, 2014; Sinha et al., 2024).

Developmental improvements of VeSTM

Behavioral results revealed clear developmental effects across school grades for both forward (DO) and backward (IO) digit span, consistent with evidence that VeSTM capacity and executive control processes continue to mature throughout childhood (Gathercole, 2004; Cowan et al., 2015). In our study, these developmental effects were primarily observed in span length rather than accuracy, reflecting the experimental adjustment of task difficulty to each participant's maximum capacity. By equating task demands across individuals, accuracy remained high across age groups, while age-related improvements were expressed as increases in span length. Both forward and backward digit span increased across school years, particularly from 1st to 3rd grade, followed by stabilization through 5th grade; a pattern closely aligned with previous reports (Gathercole et al., 2014; Alloway & Alloway, 2013; Roberts et al., 2015).

Evidence from very large, nationally representative samples further supports this developmental pattern by showing a consistent increase in forward digit span from early childhood onward. The backward digit span, which places greater demands on manipulation and updating, typically emerges later, around age five, with more gradual improvement (Ahmed et al., 2022). Together, these findings suggest partially distinct developmental courses for basic VeSTM storage processes and more complex executive working memory functions.

VeSTM and reading development

A growing body of evidence highlights a strong relationship between VeSTM and other cognitive functions, such as language and reading development (Newbury et al., 2016). Children with stronger verbal memory capacities tend to demonstrate larger vocabularies, more grammatically complex sentence production, and more proficient speech output compared to peers with reduced VeSTM capacity (Adams & Gathercole, 1995; Waring, Rickard, & Eadie, 2019; Vugs et al., 2016). VeSTM also shows the strongest association with reading skills during early literacy development, even when controlling for vocabulary knowledge (Peng et al., 2018). A meta-analysis examining VeSTM and reading reported particularly strong associations at or beyond fourth grade (Peng et al., 2018). In line with this, our data and data showed that third-grade children with delayed reading skills demonstrated a lower median digit span (two digits) compared to typically performing peers, who achieved a median span of three digits. The behavioral data from larger study with the same population showed among grade improvement up to the fifth grade (Fernandes et a., 2025).

Evidence from longitudinal studies further supports a close relationship between VeSTM and reading in early readers. Serial-order processing of verbal information and precise phonemic representations are critical for decoding. In a longitudinal study of 780 children aged 4 to 9 years, VeSTM predicted later reading achievement; however, reading did not reciprocally predict VeSTM outcomes when memory was assessed using digit span. In contrast, when VeSTM was measured using nonword repetition tasks, requiring precise phonological representations, a bidirectional relationship with reading was observed (Cunningham et al., 2021). These findings suggest that as decoding strategies improve and reading becomes automatized through lexical representations, demands on precise phoneme storage increase. Consequently, improvements in reading skills may, in turn, promote the development of phonological representations and VeSTM capacity (Ellis et al., 1990).

The relationship between VeSTM and reading decoding appears to reflect not only a shared reliance on phonological processing, but also a more direct association between VeSTM capacity and decoding skills themselves (Majerus et al., 2008; Mosse & Jarrold, 2008). In particular, the ability to temporarily maintain sequential information in VeSTM is strengthened as children engage in decoding phonological sequences and acquire new phonological representations, supporting the short-term storage and updating of the ordered phoneme sequences that define new word forms (Martinez et al., 2012).

VeSTM neural efficiency and reading skills

As noted earlier, in serial-order tasks such as forward and backward digit span, the capacity to maintain verbal information in VeSTM is functionally distinct from the executive processes required to manipulate that information during backward recall. Our findings indicate that neural activation associated with forward digit span, reflecting VeSTM maintenance, was most strongly related to early reading acquisition.

Despite similar behavioral performance in the digit task, children with atypical reading development consistently showed greater activation in prefrontal regions, including bilateral DLPFC and DMPFC, during both DO and IO conditions. Such findings suggest reduced neural efficiency in atypical readers, who appear to recruit additional executive resources to support phonological maintenance and manipulation. As proposed by Perlman et al. (2016), increased prefrontal activation during working memory tasks may reflect the need for additional neural support or to integrate working memory with other cognitive processes, such as attention and cognitive load.

Children with more advanced reading skills may rely on more automatized phonological rehearsal mechanisms, reducing the need for sustained top-down control from the PFC. In contrast, children with atypical reading development may depend more heavily on executive strategies to compensate for less stable or less accessible phonological representations. Within a multiple-component model of working memory (Baddeley et al., 2003), literacy acquisition is thought to refine phonological representations and strengthen the coupling between auditory, articulatory, and orthographic systems (Ziegler, 2004; Cunningham et al., 2021).

Developmental reorganization and lateralization

Grade-related differences in the lateralization index during the DO condition further indicate that the neural architecture supporting VeSTM undergoes reorganization across childhood. The increased rightward lateralization observed in second-grade children compared to third-grade children may reflect a transitional stage characterized by greater reliance on domain-general executive resources. As children gain literacy experience and phonological processing becomes more automatized, engagement may shift toward more left-lateralized and specialized networks and a shift from effortful, executive-based processing toward more efficient, possibly posteriorly mediated phonological processing. Importantly, regression analyses showed that reading time and accuracy predicted lateralization indices independently of grade, suggesting that the literacy experience could be one of the factors that contributes to hemispheric organization beyond chronological age alone (Killanin et al. 2024). This finding reinforces the notion that schooling and reading acquisition actively shape the functional organization of verbal working memory networks (Xu et al., 2018).

One important takeaway from the present study is that, during the early stages of literacy development, children may benefit from activities that jointly support phonological processing and working memory training within an executive functions framework (Nevo & Brenitz, 2014; Farah et al., 2024) to promote the development of reading skills. Such additional support may ease the transition from effortful to more efficient reading-related processing, especially for children at risk of reading difficulties or reading impairments (Yang et al. 2017).

Limitations and Future Directions

Several limitations of the present study should be acknowledged. The sample size of participants who completed both the fNIRS protocol and the word reading test was relatively small, largely due to interruptions in data collection caused by the COVID-19 pandemic. This may have limited statistical power, particularly in the regression analyses, and restricts the generalizability of the observed associations between reading skills and neural activation. In addition, the cross-sectional design prevents conclusions about developmental trajectories or causal relationships between literacy development, VeSTM, and prefrontal activation, which should be addressed in future longitudinal studies.

Task difficulty was individually adjusted to each participant's maximum digit span in order to equate performance across ages and reading levels. While this approach successfully reduced behavioral confounds, namely error perception and correction unwanted for brain task related activation, it also limited behavioral variability, potentially masking subtle group differences. As a result, relationships between behavioral performance and neural activation may have been underestimated. Future studies could combine individualized task difficulty with additional conditions that systematically manipulate cognitive load.

Important methodological constraints related to fNIRS should be considered. fNIRS measures hemodynamic responses restricted to superficial cortical regions and is sensitive to inter-individual differences in scalp and skull characteristics, hair density, and optode placement, despite the use of short-distance channels and signal quality control (Katusa et al., 2019). Moreover, the focus on prefrontal regions limits conclusions about the broader neural network supporting VeSTM. Future research using extended montages or multimodal imaging approaches, along with more comprehensive standardized assessments of reading and language skills, would help refine and extend the present findings.

Conclusions

In summary, the present findings demonstrate that literacy acquisition plays an important role in shaping the neural efficiency of VeSTM systems during childhood. Children with atypical reading development exhibit increased prefrontal activation during digit span tasks despite comparable behavioral performance, indicating greater reliance on executive control mechanisms. Regression analyses further show that reading accuracy and speed predict prefrontal activation and hemispheric lateralization, providing strong evidence that literacy experience modulates the functional organization of VeSTM networks. These results underscore the importance of considering both neural and behavioral measures when examining cognitive development and suggest that interventions targeting verbal memory processing may have broader effects on the reading skills and vice versa.

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Data availability statement:

The data that support the findings of this study are available on request from the corresponding author.

Conflito de interesses:

The authors declare that there are no conflicts of interest related to this manuscript.

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Supplementary information:

Development of PFC function supporting verbal short-term memory assessed by fNIRS in early school age period - Supplementary Material

Supplementary Table 1: Behavioral and fNIRS data by group. Data represented as: 1st quartile / Median / 3rd quartile (Mean ± MSE). *: Significant difference in Kruskal-Wallis test for group (p < 0.050)

	Typical	**Atypical**
Span DO	3 / 4 / 5 (4.029 ± 0.114)	3 / 4 / 4 (3.692 ± 0.094)
ACC DO*	0.952 / 1 / 1 (0.963 ± 0.008)	1 / 1 / 1 (0.988 ± 0.003)
Span IO	2 / 2 / 3 (2.079 ± 0.106)	2 / 2 / 2 (2.250 ± 0.05)
ACC IO	0.351 / 0.786 / 1 (0.651 ± 0.041)	0.390 / 0.714 / 1 (0.655 ± 0.033)
WR (Hits)*	40 / 43 / 45,75 (41,077 ± 1,803)	22,25 / 39,5 / 41 (30,143 ± 4,861)
WR (Time)*	54 / 70 / 87 (85 ± 11.249)	79 / 107 / 155 (156,231 ± 39,230)
Right DLPFC oxyHb DO*	-1.304e-4 / -5.965e-5 / 7.788e-5 (-1.891e-5 ± 4.689e-5)	-1.301e-4 / 3,730e-7 / 2.171e-4 (1.133e-4 ± 8,275e-5)
Left DLPFC oxyHb DO	-1.546e-4 / -4,215e-5 / 1.030e-4 (-7,588e-5 ± 4,657e-5)	-1,452e-4 / 1,377e-5 / 2,102e-4 (7,421e-6 ± 5,634e-5)
DMPFC oxyHb DO	-9.990e-05 / 1.215e-6 / 1.505e-4 (1.221e-5 ± 2.534e-5)	-1.38e-4 / -1.357e-5 / 1.259e-4 (-8.795e-6 ± 4.824e-5)
LI Sub. oxyHb DO	-2.201e-4 / 1.635e-5 / 1.935e-4 (5.697e-5 ± 6.306e-5)	-2.031e-4 / 5,72E-07 / 2.832e-4 (1.059e-4 ± 8.512e-5)
LI Red. oxyHb DO	-0.594 / -0.055 / 0.772 (1,038 ± 1,212)	-1.032 / -0.169 / 0.437 (-0.139 ± 0.436)
Right DLPFC deoxyHb DO	-5.6425e-5 / 1.765e-5 / 7,900e-5 (6,794e-6 ± 2,887e-5)	-4.318e-5 / 2,105e-5 / 8.725e-5 (-5,176e-6 ± 2,414e-5)
Left DLPFC deoxyHb DO	-7.323e-5 / 1.810e-5 / 9.510e-5 (1.549e-5 ± 2.972e-5)	-5.308e-5 / 2.930e-5 / 1.079e-4 (-1,387e-6 ± 2.739e-5)

DMPFC deoxyHb DO	-1.498e-5 / 1.620e-5 / 8.540e-5 (2.791e-5 ± 1.145e-5)	-4.053e-5 / 1.480e-5 / 8.645e-5 (2.461e-5 ± 2.163e-5)
LI Sub. deoxyHb DO	-1.169e-4 / 1.650e-6 / 1.177e-4 (-8.700e-6 ± 3.732e-5)	-1.605e-4 / -5.565e-6 / 1.411e-4 (-3.791e-6 ± 3.491e-5)
LI Red. deoxyHb DO	-0.878 / -0.121 / 0.693 (-2.269 ± 2.121)	-1.000 / -0.317 / 0.833 (1.107 ± 0.824)
Right DLPFC oxyHb IO	-1.467e-4 / -2.385e-5 / 1.572e-4 (-1.697e-5 ± 5.664e-5)	-1,285e-4 / 1,905e-5 / 1,566e-4 (-3.068e-5 ± 8.465e-5)
Left DLPFC oxyHb IO*	-2.402e-4 / -2,485e-5 / 1.682e-4 (-5.388e-5 ± 4.689e-5)	-1.626e-4 / 2.860e-5 / 2.348e-4 (-2.992e-5 ± 6.834e-5)
DMPFC oxyHb IO*	-1.550e-4 / 1.202e-5 / 1.576e-4 (1,370e-5 ± 2.608e-5)	-2.188e-5 / 8.060e-5 / 2.200e-4 (5.402e-5 ± 8.624e-5)
LI Sub. oxyHb IO	-2.030e-4 / 1.678e-5 / 2.782e-4 (3.691e-5 ± 6.214e-5)	-2.476e-4 / 5.745e-6 / 2.511e-4 (-7.578e-7 ± 1.076e-4)
LI Red. oxyHb IO	-0.899 / -0.333 / 0.396 (-1,631 ± 1,494)	-1.000 / -0.313 / 0.718 (-0.302 ± 0.204)
Right DLPFC deoxyHb IO	-5.373e-5 / 1.390e-5 / 9,232e-5 (1.334e-5 ± 2.788e-5)	-5.8425e-5 / -7.750e-7 / 6.015e-5 (-8.781e-6 ± 2.065e-5)
Left DLPFC deoxyHb IO	-7.980e-5 / 1.170e-5 / 1.016e-4 (2.407e-5 ± 2.394e-5)	-1.532e-4 / 1.464e-5 / 1.243e-4 (-1.356e-5 ± 2.974e-5)
DMPFC deoxyHb IO	-4.060e-5 / 1.605e-7 / 6.075e-5 (1.225e-5 ± 9,985e-6)	-7.175e-5 / -6.870e-6 / 7.485e-5 (-9.422e-5 ± 7.040e-5)
LI Sub. deoxyHb IO	-1.346e-4 / -6.900e-6 / 9.390e-5 (-1.072e-5 ± 3.697e-5)	-1.781e-4 / -2.955e-6 / 1.950e-4 (4.774e-6 ± 3.542e-5)
LI Red. deoxyHb IO	-0.932 / -0,194 / 0,816 (-0,509 ± 0.549)	-1.137 / -0.396 / 0.473 (-3.255 ± 2.613)

Supplementary Table 2: p-values from the ANCOVA analysis comparing the fNIRS data with grade as a cofactor. *p < 0.05.

			Grade	**Group**
OD	**oxyHb**	**DMPFC**	0.918	0.685
		Left DLPFC	0.949	0.030*
		Right DLPFC Direito	0.536	0.278
		LI Sub.	0.520	0.525
		LI Rel.	0.201	0.736
	deoxyHb	**DMPFC**	0.519	0.810

		Left DLPFC	0.723	0.823
		Right DLPFC	0.124	0.050*
		LI Sub.	0.191	0.254
		LI Rel.	0.887	0.255
OI	**oxyHb**	**DMPFC**	0.440	0.175
		Left DLPFC	0.665	0.422
		Right DLPFC	0.732	0.970
		LI Sub.	0.973	0.605
		LI Rel.	0.072	0.262
	deoxyHb	**DMPFC**	0.451	0.835
		Left DLPFC	0.791	0.662
		Right DLPFC	0.601	0.289
		LI Sub.	0.888	0.719
		LI Rel.	0.568	0.972

Supplementary Table 3: Relative LI oxyHB of DLPFC during DO described by grade. Data represented as: 1st quartile / Median / 3rd quartile (Mean ± MSE).

Grade	All	Typical	Atypical
1	-0.546 / -0.101 / 0.489 (0.035 ± 0.351)	-0.546 / -0.101 / 0.489 (0.035 ± 0.351)	---
2	-0.993 / -0.171 / 0.476 (0.664 ± 1.285)	-0.930 / -0.067 / 0.550 (1.442 ± 1.904)	-1.111 / -0.420 / 0.072 (-0.892 ± 0.657)
3	-1.369 / -0.242 / 0.440 (-0.023 ± 0.853)	-1.359 / -0.416 / 0.490 (-0.479 ± 1.292)	-1.270 / -0.003 / 0.375 (0.557 ± 1.080)
4	-1.492 / -0.294 / 0.261 (-0.464 ± 0.883)	-1.697 / -0.244 / 0.123 (-0.326 ± 1.371)	-1.022 / -0.322 / 0.307 (-0.701 ± 0.650)
5	-0.522 / 0.004 / 0.735 (0.052 ± 0.324)	-0.528 / 0.010 / 0.640 (-0.112 ± 0.234)	-0.502 / 0.004 / 0.786 (0.441 ± 0.973)

This preprint was submitted under the following conditions:

- The authors declare that the necessary Terms of Free and Informed Consent of participants or patients in the research were obtained and are described in the manuscript, when applicable.
- The authors declare that the preparation of the manuscript followed the ethical norms of scientific communication.
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