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Schooling shapes the brain: neural specialization for words and numbers in early childhood.

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Abstract

Experience-dependent neuroplasticity refers to the brain's ability to reorganize in response to experience. An intriguing example occurs when children begin formal schooling, acquiring skills such as reading and symbolic number processing. Because the human brain is not evolutionarily predestined for these skills, it must adapt by recycling pre-existing cortical systems. Longitudinal fMRI studies have documented substantial functional changes during the ages 5 to 7, including increasing specialization of the left fusiform gyrus for words and the intraparietal sulcus (IPS) for symbolic numbers. However, because these changes coincide with formal school entry, it remains unclear whether these changes are driven by schooling or age. Using a quasi-experimental school cut-off design, we compared two similar-aged groups differing in exposure to formal schooling. Sixty-four children (36 schooling, Med_{age} = 68.5 months; 28 non-schooling, Med_{age} = 66 months) were scanned twice, one year apart, during a passive fMRI task involving words and digit sequences. Mixed-effects models in 57 children revealed that increased activation for words in the left fusiform gyrus and left supplementary motor area, and increased activation for numbers in the right inferior parietal cortex, occurred only in children who attended first grade. These findings indicate that schooling, beyond age, drives functional specialization for words and numbers.

Introduction

Experience-dependent neuroplasticity refers to the brain's capacity to alter its function and structure in response to individual experiences and environmental input (Blakemore & Frith, 2005; Galván, 2010; Kleim & Jones, 2008). One intriguing example of this process occurs during early childhood, when children enter formal schooling (Dehaene & Cohen, 2007). Indeed, given that the brain is likely not predestined to read words or process symbolic numbers, it needs to recycle and reorganize pre-existing cortical systems to learn these culturally-transmitted skills (Dehaene & Cohen, 2007, 2011). Longitudinal functional MRI (fMRI) studies have documented substantial changes in brain activity during the transition from informal to formal education (Chyl et al., 2019; Dehaene-Lambertz et al., 2018; Emerson & Cantlon, 2015; Yu et al., 2018). However, such studies are inherently confounded by age-related maturation, making it difficult to isolate the specific effects of formal schooling on the neural changes that have been observed. The present study will address this gap by employing a school cut-off design to disentangle schooling-induced from maturational changes on children's functional brain development, focusing on the domains of reading and mathematics, as elaborated below.

Learning to read is associated with widespread and dynamic changes in brain activity, involving a distributed network of regions including left ventral occipitotemporal, inferior frontal, inferior parietal, and superior temporal regions (Chyl et al., 2021, for a review). During the process of learning to read, a region located within the left fusiform gyrus develops rapidly into a region highly specialized to letter strings, the visual word form area (VWFA) (Dehaene-Lambertz et al., 2018; Dehaene & Cohen, 2011). For instance, Brem et al. (2010) showed that even just a few hours of grapheme-phoneme correspondence training in 6-year-olds resulted in increased sensitivity for printed words within the left ventral

occipitotemporal cortex. However, more recent evidence argued that the emergence of the VWFA is more gradual and highly dependent on reading experience, indicating that short-term exposure may not be sufficient for its development (Chyl et al., 2018). The precise location of the VWFA depends, at least partially, on its pre-existing functional and structural connectivity with other brain regions (Bouhali et al., 2014; Chen et al., 2019; Li et al., 2020; Moulton et al., 2019; Saygin et al., 2016; Yablonski et al., 2024). In addition, reading acquisition leads to reorganizing of language-related regions, including inferior frontal (Chyl et al., 2018; Liebig et al., 2021; Monzalvo & Dehaene-Lambertz, 2013; Yu et al., 2018) and temporal areas (Chyl et al., 2018; Evans et al., 2016; Liebig et al., 2021; Monzalvo & Dehaene-Lambertz, 2013). Although the mature reading network is typically left-lateralized, prereaders and beginning readers often show a more bilateral activation pattern (Benischek et al., 2020; Pugh et al., 2013; Raschle et al., 2012; Xiao et al., 2016), with initial recruitment and subsequent disengagement of right-hemisphere regions (Shaywitz et al., 2002; Turkeltaub et al., 2003; Yamada et al., 2011). Longitudinal studies that have investigated children before and after they started formal schooling have largely corroborated these findings. Yu et al. (2018), for instance, found increased activation in a network comprising left inferior frontal, left posterior occipitotemporal, and right angular gyri during an auditory phonological processing task after the start of school. Chyl et al. (2019) observed increased activation to print in typical readers after two years of reading instruction in the left fusiform gyrus, and in several language-related regions including bilateral inferior frontal gyri and precentral gyri, left supplementary motor area, bilateral superior parietal lobule, and right angular gyrus.

While considerable longitudinal research has documented neural changes associated with reading acquisition during the transition to formal education, comparatively little is known about how brain activity develops as children learn to process symbolic numbers and to calculate. Neuroimaging research on numerical cognition has shown that certain brain areas, notably regions within the parietal cortex (intraparietal sulcus (IPS), angular gyrus) and the inferior frontal gyrus are preferentially engaged during number processing (Ansari & Dhital, 2006; Cantlon et al., 2006; Emerson & Cantlon, 2012; Kersey et al., 2019; Kersey & Cantlon, 2017; Menon, 2014; Piazza et al., 2004). Yet, longitudinal data tracking the development of brain activity in these regions from before to after the start of formal schooling are almost non-existent. To the best of our knowledge, only one longitudinal study exists during this specific age period (ages 4 to 9) testing children twice with one or two year(s) in between (Emerson & Cantlon, 2015). They showed that while both the right and left IPS were longitudinally responsive to numbers, only increased activation in the left – not right – IPS was found to be associated with improved number skills over time. Cross-sectional research has similarly suggested that the neural representation of Arabic numerals becomes more precise with age in left – but not right – IPS (ages 6 to 14) (Vogel et al., 2015) and that generally, activation in the left IPS is more related to symbolic number processing, while processing of non-symbolic numbers elicits increased activity in the right IPS (Ansari & Dhital, 2006; Bugden et al., 2012; Cantlon & Li, 2013; Rivera et al., 2005; Sokolowski et al., 2017). Altogether, these findings suggest that the responsivity of the right IPS to numbers may emerge earlier in development (Cantlon et al., 2006; Kersey & Cantlon, 2017), while the left IPS becomes increasingly specialized for processing numbers with age and experience (Ansari, 2016; Bugden et al., 2021; Emerson & Cantlon,

2015; Vogel et al., 2015). Importantly, the predominant focus on the IPS in neuroimaging studies on number processing may have limited our understanding of other regions involved (Fias et al., 2013; Menon, 2014, for critical reflections). Particularly, more recent evidence indicates that number processing – both symbolic and non-symbolic – recruits a broader network across the parietal and frontal cortices (Skagenholt et al., 2018; Sokolowski et al., 2017).

Importantly, although some longitudinal studies have documented changes in brain activity during the transition from informal to formal education, such designs cannot unravel whether these changes are purely the result of age-related maturation or whether they are driven by schooling. Establishing a causal relationship between schooling and brain development requires experimental approaches that leverage environmental differences (i.e., difference in school grade), such as educational interventions (Steele & Zatorre, 2018). An increasing number of developmental neuroimaging studies have investigated the neural impact of such interventions, particularly in the domain of reading (Perdue et al., 2022, for a meta-analysis). However, most of these studies have focused on older children or those with, or at risk for, learning difficulties – limiting the generalizability of their findings to neurotypical children. Furthermore, the majority of intervention studies have focused on reading, with considerably fewer addressing the effects of educational interventions on mathematics.

Among the few studies targeting younger, prereading children – those typically around the age at which formal education begins – several have demonstrated rapid neural changes following short-term reading interventions. For instance, Brem et al. (2010) demonstrated that even a brief intervention of a few hours of grapheme-phoneme correspondence training in 6-year-old children at varying risk for reading difficulties led to increased neural sensitivity for printed words in the ventral occipitotemporal cortex and cuneus. In a follow-up study, Bach et al. (2013) found that activity in the left fusiform gyrus positively correlated with gains in letter knowledge following the intervention. Karipidis et al. (2018) observed that greater activation in the left occipitotemporal cortex during an implicit audiovisual target detection task predicted improvements in pseudoword reading fluency after a single session of artificial letter training in prereading children at risk for reading difficulties. Similarly, Yamada et al. (2011) reported bilateral activation and recruitment of frontal regions, including the anterior cingulate cortex, in 5-year-old children at risk for reading difficulties after three months of reading intervention.

More recently, Yeatman et al. (2024) conducted an intervention study with neurotypical prereaders, randomly assigning children to a two-week program focused on either letter knowledge/decoding or oral language skills. Magnetoencephalography (MEG) data were collected before and after the intervention to examine (change in) neural responses to words, faces, and cars. Their results showed increased activation in the VWFA in children receiving letter training, but only when responses to words were compared to cars, not to faces.

Together, these studies demonstrate that short-term reading interventions can rapidly shape the developing reading network, even before the onset of formal education. However, several important limitations remain. First, most intervention studies have been conducted in highly structured or remedial

settings, often involving children at risk for learning difficulties, which limits the generalizability to neurotypical children in the natural schooling environment. Second, the majority of these interventions span only a short time window. While such studies provide valuable insights into the brain's susceptibility to experience-dependent plasticity, they are less informative about the broader trajectory of brain development during early schooling. As a result, none of the studies discussed could disentangle whether neural changes were due to experience or age-related maturation.

This gap is even more pronounced in the domain of numerical cognition. To the best of our knowledge, not a single intervention study has examined the neural effects of training early numerical processing in children before the onset of formal schooling. Addressing this gap is essential for understanding how formal education shapes functional brain development across different academic domains.

To address this gap, previous studies have employed quasi-experimental approaches, such as school cut-off designs, which leverage the arbitrary cut-off that schools use for school entry, i.e., the child's birth date (Morrison et al., 2019). In such designs, two groups of children are compared: one group whose date-of-birth falls shortly before the arbitrary school enrollment cut-off date, and a second group whose date-of-birth falls shortly after the cut-off. As a result, the two groups are closely matched in age but differ in their exposure to formal schooling. By tracking these groups longitudinally, researchers can more precisely isolate the effects of schooling from those attributable to maturation.

Behavioral studies employing this method have successfully unraveled the unique impact of schooling on academic abilities and their precursors, both in the domain of reading (e.g., Christian et al., 2000; Kim & Morrison, 2018) and mathematics (Bisanz et al., 2005; Naito & Miura, 2001). To date, only two developmental fMRI studies have employed a school cut-off design to isolate the specific effects of schooling (Brod et al., 2017; Nolden et al., 2021). Brod et al. (2017) investigated executive functioning and corresponding brain activity in "young" first graders (i.e., schooling group) and "old" preschoolers (i.e., non-schooling group) before and after the first graders were enrolled in primary school, whereas the preschoolers remained in play-oriented preschool. Being similar in age (5-year-olds), they only differed in the amount of schooling that they received. After this year, the schooling group made larger behavioral improvements on the go/no-go task and their brain activity in the posterior parietal cortex – a region involved in sustained attention – increased more over time during the task than for the non-schooling group. Nolden et al. (2021), on the other hand, examined episodic memory performance and its neural correlates and comparing the longitudinal change between children who attended first grade (i.e., schooling group) with children who remained in preschool (i.e., non-schooling group). Their findings demonstrated that both groups improved in their memory performance, but there were no longitudinal changes nor group differences in neural activation. These studies examined the impact of schooling on more general aspects of cognition, yet they did not investigate the impact of schooling on brain networks related to academic performance, such as brain activity related to processing words or numbers, as we will do in the current study.

The current study will significantly extend the existing literature by examining schooling effects on neural responses to word reading and number processing, using a quasi-experimental school cut-off design. While previous work has shown that learning to read and calculate is associated with brain reorganization (Dehaene & Cohen, 2007), it remains unclear to what extent these changes are driven by formal schooling versus maturation. To examine these changes, we used a passive fMRI paradigm in which children were exposed to words, numbers, and control stimuli (faces and fixation). Passive paradigms are particularly well-suited for developmental research with young children, and have been widely used in comparable studies (Benischek et al., 2020; Dehaene-Lambertz et al., 2018; Feng et al., 2022; Liebig et al., 2021; Price & Ansari, 2011; Vogel et al., 2015).

Our paradigm was inspired by Dehaene-Lambertz et al. (2018), who studied children of a similar age but pursued a different research question. Whereas their study focused on investigating the longitudinal evolution of the visual cortex and more specifically, its neural responses to multiple visual categories – words, numbers, tools, houses, faces, and bodies – during reading acquisition, our study aimed to investigate schooling-related changes in neural responses to words and numbers. To align with our goal, we adapted the paradigm to include more meaningful stimuli. In the numbers condition, we replaced the original four-digit strings with ascending sequences of three single digits (e.g., *4 5 6*). This choice was motivated by earlier findings showing that isolated digit formats often fail to elicit number-related activation in young children (Cantlon et al., 2011; Dehaene-Lambertz et al., 2018; Park et al., 2018). By exposing children to ordered digit sequences, our paradigm may likely tap into some early numerical understanding, such as counting or ordinal recognition.

We applied this paradigm at two timepoints: at the first timepoint, when all children were still attending preschool (pretest), and again at the second timepoint, one year later (posttest) when about half of the sample had transitioned into first grade (i.e., schooling group), whereas the other half remained in play-oriented preschool (i.e., non-schooling group). Children were assigned to the two groups based on their birth dates, which fell just before or after the school entry cut-off date (January 1st in our country). This age range was deliberately selected to create two groups that were closely matched in age but differed in their exposure to formal schooling, following the logic of the school cut-off design (Morrison et al., 2019). By leveraging this quasi-experimental approach, we were able to disentangle schooling-related effects from age-related maturation by examining group-by-time interactions in neural responses to words and numbers.

The primary aim of the current study was to investigate whether neural responses to words and numbers were impacted by formal schooling. Specifically, we examined brain activation for words versus fixation and numbers versus fixation contrasts. We hypothesized increased activation in regions associated with emergent reading and mathematical skills. For words, we expected activation in the left fusiform gyrus, inferior frontal gyrus, superior temporal regions, and supplementary motor cortex. For numbers, we anticipated engagement of parietal regions (including the IPS), as well as prefrontal and inferior frontal regions. Given that children typically enter school with some basic number knowledge, whereas reading instruction begins more explicitly in first grade (Bakker et al., 2019, 2023; Hjetland et al., 2020) we further

hypothesized that schooling-related changes would be more pronounced for words than for numbers. A secondary, exploratory aim was to assess the category specificity of neural responses – that is, whether words and numbers elicit distinct patterns of brain activation. To address this, we directly contrasted activation for words versus numbers. While previous studies have consistently identified the VWFA for letters and words, evidence for a number form area (NFA) remains mixed (Merkley et al., 2016; Yeo et al., 2017, for a critical review and meta-analysis).

This study offers a unique opportunity to investigate experience-dependent neuroplasticity associated with acquiring culturally-transmitted skills – reading and mathematics – during a critical developmental period (Dehaene & Cohen, 2007), and is therefore destined to yield novel insights into the field of educational neuroscience.

Methods

3.1 Participants and general procedure

The present study was carried out in the context of a larger longitudinal study, in which also anatomical MRI data (Authors, in review), diffusion-weighted MRI data (Authors, 2024), and behavioral data were collected, none of which were analyzed and reported here. This research was approved by the Medical Ethical Committee of the University of Leuven (S64318). Informed consent was obtained from the parents of all participants according to the Declaration of Helsinki. The current study followed a classic school cut-off approach (Morrison et al., 2019) and involved two timepoints of data collection (pretest and posttest). At the first measurement point (T1) or pretest, conducted during summer 2021, all children attended preschool. One year later, at the second measurement point (T2) or posttest, half of the sample attended the first grade of primary school, whereas the other half remained in preschool.

We recruited 64 children from preschool, allocated to a non-schooling (n = 28; Med_{age} = 66 months; range = 64–67 months, 19 girls) and schooling (n = 36; Med_{age} = 68.5 months; range = 65–70 months, 19 girls) group, respectively. The age groups under study were specifically chosen because their date-of-birth falls shortly on either side of the cut-off for school entry (January 1st in our country). As a result, and following the logic of the school cut-off design (Morrison et al., 2019), we created two groups that were similar in age, but different in the amount of formal instruction they received. In particular, children in first grade have received massive structured and formal reading and arithmetic instruction. Children in preschool, on the other hand, received a very limited informal introduction in learning to read and to calculate), in accordance with Flemish government guidelines (http://www.ond.vlaanderen.be). We selected typically developing, monolingual children, without any medical history or history of developmental problems. Children who had a heart pacemaker or any other metallic foreign body were not allowed to participate because the magnetic field of the MRI scanner may dislodge the metal. The groups were matched on sex and socioeconomic status (SES). As a proxy for SES, we used parental educational attainment as this is suggested to be the more powerful predictor of children's cognitive and academic outcomes (Davis-Kean et al., 2021).

3.2 Functional imaging paradigm

In our fMRI paradigm, participants were presented with word and number stimuli (see Fig. 1, for an example). Word stimuli consisted of monosyllabic three-letter strings (e.g., *bal*), selected for their high frequency of occurrence in beginning readers, as established by the 'Drie-Minuten-Toets' (Jongen & Krom, 2009). Number stimuli were congruent, ascending digit sequences of three single digits (e.g., *2 3 4*) that were meaningful for young children. In addition to the word and number stimuli, the paradigm additionally included faces as an additional stimulus category. These face stimuli comprised black-and-white photographs of male and female children's faces, yet they were not further analyzed in the context of this study.

Stimuli were presented using a miniblock design, similar to Dehaene-Lambertz et al. (2018). Each block consisted of six images from the same category, presented sequentially for one second each (block duration: six seconds). Blocks were separated by a variable interblock interval of 2.4, 3.6, or 4.8 seconds (mean = 3.6 seconds). The order of categories was randomized across participants, with the constraint that each category appeared twice within a functional run (3 categories x 2 repetitions = 6 blocks, each containing 6 images). To help maintain children's attention throughout the miniblocks, we implemented a simple incidental target-detection task (Dehaene-Lambertz et al., 2018; Dehaene et al., 2010). Specifically, within each block, there was a 33% probability that a target stimulus – a picture of Diego, the cartoon character from *Ice Age* would replace the sixth and final image in the sequence. Consequently, two target stimuli were presented per run, with their distribution counterbalanced across conditions to ensure that each category contained exactly two targets over three runs.

Children were instructed to press a button as soon as they detected the target image. This task was intended to sustain attention towards the visual stimuli without introducing task demands related to reading or mathematics. Each fMRI session comprised three functional runs, yielding a total of 18 blocks per session (6 blocks per run x 3 runs). Stimuli were presented using E-Prime 2.0 Software (Psychology Software Tools, PST, Pittsburgh, PA). Each run began with an eight-second fixation cross and concluded with a five-second fixation period. The total duration of each run was 1.22 minutes.

3.3 MRI data acquisition

Functional and structural images were acquired on a 3T MRI scanner (Philips, Eindhoven, The Netherlands) with a SENSE 32-channel head-coil, located at the Department of Radiology of the University Hospital in Leuven, Belgium. For the fMRI data, 52 slices were recorded in an interleaved ascending order, with transverse slice orientation, using a T2*-weighted echo-planar images with a multi-band acceleration factor of 2, TR = 2000 ms, TE = 30 ms, slice thickness = 2.5 mm, flip angle 68°, 96 x 94 acquisition matrix, 2.5 x 2.5 x 2.5 mm voxel size. Each functional run consisted of 35 volumes. Anatomical 3D T1-weighted images were acquired using a CS-SENSE TFE (compressed sensing-sensitivity encoding turbo field echo) sequence with the following parameters: 240 sagittal slices, 0.9 mm^3 isotropic voxel size, repetition time/echo time (ms) = 9.1/4.2, flip angle 90°, 284 × 270 acquisition matrix, acquisition time = 3 min 30 s. Prior to the actual MRI session, children completed a practice

session in which they got used to the scanner environment and protocol (Theys et al., 2014). Children's heads were stabilized by using washcloths in order to minimize head motion.

3.4 fMRI data analyses

3.4.1 Preprocessing

All preprocessing steps were conducted with the Statistical Parametric Mapping (SPM12, Wellcome Department of Cognitive Neurology, London) software using Matlab for pretest and posttest sessions separately. All functional images were first spatially realigned to the mean functional image and then slice-timing corrected by interpolating them and resampling them to the first slice. The realigned images were then co-registered to the anatomical image, and then normalized to the standard Montreal Neurological Institute (MNI) space. Finally, the normalized functional images were smoothed with a spatial filter of 8 mm full-width at half maximum (FWHM) Gaussian smoothing kernel. In line with previous studies (e.g., Das et al., 2011; Declercq et al., 2022; Emerson & Cantlon, 2012; Liebig et al., 2021), this larger smoothing kernel was chosen as this study had a young population, where (too much) motion is of a larger concern compared to adults. Runs with excessive motion (i.e., if the absolute displacement on any of the motion parameters exceeded the voxel size) were excluded from further analyses. Out of 64 participants, 37 participants at pretest (67%, 21 from schooling, 16 from non-schooling group) and 50 participants at posttest (89%, 32 from schooling, 16 from non-schooling group) were included. Specifically, we analyzed 86 runs from the pretest and 125 runs from the posttest.

3.4.2 ROI definition and preliminary analyses

A general linear model was built for each subject in each session in which a hemodynamic response function and its time derivative were convolved with block onsets for each category. The six motion realignment parameters were entered as regressors of non-interest. The three experimental conditions (numbers, words and faces) were modeled as boxcar function for the duration of the block together with all fixations. For the current study, only contrasts using words, numbers, and fixation were built. Specifically, contrasts of interest were words>fixation and numbers>fixation, to investigate our primary aim, that is whether neural responses to words and numbers were impacted by formal schooling. For our second aim, that is assessing the category specificity of these responses – namely, whether words and numbers elicit distinct patterns of activation in the brain, we directly contrasted words and numbers.

To assess whether there were changes in activation related to words or numbers across time that differed by group (schooling versus non-schooling), our analyses comprised several steps. The first step was to test for differences between the groups at posttest (similar to Brod et al., 2017). We created z-statistic images with a voxel-wise threshold of $z > 2.3$ and an uncorrected cluster threshold of $p < .001$ (similar to Bouhali et al., 2014; Das et al., 2011; Davis et al., 2009; Grotheer et al., 2016; Powers et al., 2016; Skagenholt et al., 2018). Only clusters of 10 or more voxels were considered. Significant clusters were labeled using the anatomical automatic labeling toolbox (AAL3, Rolls et al., 2020). ROIs were defined at the group level as a 6 mm radius sphere (Chen et al., 2019; Karipidis et al., 2021; Reynolds,

Long, et al., 2019) around the peak coordinates of the significant group clusters, which were provided in the MNI space. Group-level ROIs were chosen to ensure that all participants' parameter estimates were extracted from anatomically homologous locations identified as significant in the initial whole-brain analysis, thereby maximizing statistical power and enabling group comparisons. Parameter estimates (β weights) were then extracted from these ROIs for each participant using the MarsBar toolbox (http://marsbar.sourceforge.net) and loaded into R (version 4.2.1) (R Core Team, 2022) for statistical testing. For each ROI and participant we then calculated the mean beta for each condition and the within-subject contrasts (e.g., words versus fixation).

3.4.3 Linear mixed-effects models

The parameter estimates (β weights) of each ROI were loaded into R and used to fit linear mixed models (LMMs), which was the second step of our analyses. We implemented linear mixed models using the *lme4* package (Bates et al., 2015) with timepoint (pretest versus posttest) and group (non-schooling versus schooling) as fixed categorical within- and between- subjects factors, respectively. A random intercept for participants was further incorporated into the model. For all linear mixed-effect models, Type III-analysis of variance tables were computed to obtain *F*-statistics and *p*-values using the Satterthwaite's degrees of freedom approximation (Kuznetsova et al., 2017). In all models, statistical inference was conducted by calculating 95% confidence intervals and *p*-values using parametric bootstrapping (1000 iterations) as implemented in the *parameters* package (Lüdecke et al., 2020).

For ROIs that demonstrated a significant group-by-timepoint interaction effect, follow-up pairwise comparisons of the estimated marginal means (*emmeans* package, Lenth, 2017) were conducted with false discovery rate (FDR) correction (q = 0.05) (Benjamini & Hochberg, 1995). Standardized regression coefficients (*β*) are reported as effect sizes for all models.

Results

4.1 Participant and group characteristics

Participant and group characteristics are summarized in Table 1. Seven out of 64 original participants (5 from non-schooling, 2 from schooling group) were excluded due to unusable scans at both pre- and posttest, and these are therefore not included in the table or subsequent analyses.

The non-schooling and schooling groups did not differ significantly with respect to sex or the number of exclusions at either timepoint. Although the age difference between groups was minimal (2–3 months), it was statistically significant, yet inherent to our cut-off design.

Table 1
Demographic participant and group characteristics.

Variables	Group				Test statistic (df)	*p*	BF_{01} [d]
	Non-schooling		Schooling				
	n	Summary statistic [a]	*n*	Summary statistic [a]			
Sex (female/male)	23	15/8	34	17/17	χ^2 (1) = 1.290	.256 [c]	1.705
Exclusion at pretest [e] np/inc/tech/mot	23	0/0/3/4	34	0/0/3/10	χ^2 (1) = 0.367	.545 [c]	2.586
Exclusion at posttest [e] np/inc/tech/mot	23	1/1/0/3	34	1/0/0/1	χ^2 (1) = 3.202	.074 [c]	0.502
Age at pretest (months)	16	66 (64–67)	21	68 (65–70)	*W* = 39.00	< .001 [b]	0.030
Age at posttest (months)	18	78 (76–79)	32	81 (77–82)	*W* = 39.00	< .001 [b]	0.007

[a] Median/Mean (range) or occurrence. [b] Independent samples Mann-Whitney U test. [c] Chi-squared test. [d] Bayes' factors in support of no group difference are presented (null hypothesis, BF_{01}). Expectations and activities data are from pretest. **BF_{01} between 0–3**: *anecdotal support;* **between 3–10**: *moderate support;* **between 10–30**: *strong support;* **between 30–100**: *very strong support;* **>100**: *extremely strong support for the null hypothesis of no group differences (see* Andraszewicz et al., 2015, *for the classification). [e] Exclusion due to drop-out (np), incomplete assessment (inc), technical issues (tech) or excessive motion (mot).*

4.2 fMRI results

4.2.1 Group differences at posttest

We first aimed to test for differences between the groups at posttest. Significant group differences per contrast are listed here. Reported results are significant at $p < .001$ (uncorrected) and with a cluster size of at least 10 voxels.

4.2.1.1 Schooling > Non-schooling

Table 2 shows significant differences for each contrast where the schooling group exhibited more positive activation values as compared to the non-schooling group. The raw condition-specific parameter estimates (β) from each ROI can be found in Supplementary Table 1.

Table 2
Significant group differences on each contrast, for which the schooling group shows larger activation as compared to the non-schooling group.

Contrast	Area of activation	Peak MNI coordinates (x, y, z)	Cluster size	*Z*-score
Words - Fixation	Left supplementary motor area	-32, -5, 52	122	3.52
	Left fusiform gyrus	-42, -60, -8	58	3.11
	Left middle frontal cortex	-30, 13, 36	115	3.06
Numbers – Fixation	Right inferior parietal cortex	13, -22, 28	876	3.98
	Left superior frontal cortex	-10, 36, 50	294	3.69
	Left insula	-34, 13, -8	186	3.52
Words - Numbers	Left fusiform gyrus	-27, -47, -15	17	2.96
Numbers - Words	Right cuneus/ superior occipital/ calcarine cortex	18, -92, 12	291	3.63
	Right supramarginal gyrus	40, -40, 32	64	3.60
	Left middle cingulate cortex	-17, -34, 32	33	3.15
	Right superior frontal cortex	18, 3, 72	19	3.07
	Left cuneus/occipital cortex	-32, -90, 12	107	3.04
	Left superior/middle frontal cortex	-12, 38, 50	36	3.01

4.2.1.2 Non-schooling > Schooling

Table 3 demonstrates significant differences for each contrast where the non-schooling group exhibited more positive activation values as compared to the schooling group. The raw condition-specific parameter estimates (β) from each ROI can be found in Supplementary Table 2.

Table 3
Significant group differences on each contrast, for which the non-schooling group shows larger activation as compared to the schooling group.

Contrast	Area of activation	Peak MNI coordinates (x, y, z)	Cluster size	Z-score
Words – Fixation	Right cuneus/ superior occipital/ calcarine cortex	28, -87, 10	65	2.94
Numbers – Fixation	*No significant clusters*			
Words - Numbers	Right cuneus/ superior occipital/ calcarine cortex	18, -92, 12	291	3.63
	Right supramarginal gyrus	40, -40, 32	64	3.60
	Left middle cingulate cortex	-17, -34, 32	33	3.15
	Right superior frontal cortex	18, 3, 72	19	3.07
	Left cuneus/occipital cortex	-32, -90, 12	107	3.04
	Left superior/middle frontal cortex	-12, 38, 50	36	3.01
Numbers - Words	Left fusiform gyrus	-27, -47, -15	17	2.96
	Right postcentral cortex	28, -44, 60	10	2.72

4.2.2 Linear mixed-effects models

To ensure that the group differences at posttest were not driven by group differences at pretest, we extracted the parameter estimates (β weights) of each cluster (6 mm radius sphere around the peak voxel) from these contrasts. Linear mixed effects models were built with these estimates to investigate whether there existed group-by-timepoint interaction effects on these contrasts. The significant interaction effects are depicted in the same order as in the results at posttest, i.e., first the ROIs for which the schooling group exhibited larger activation as compared to the non-schooling group.

4.2.2.1 Words – Fixation

As shown in Table 4, we found group-by-timepoint interaction effects for the contrast words - fixation in four areas: **left supplementary motor area**, **left fusiform gyrus**, **left middle frontal cortex** and **right cuneus/ superior occipital/ calcarine cortex**. Follow-up analyses showed that for the first three ROIs, there was a significant increase in activation from pre- to posttest for the schooling group and no change for the non-schooling group. For the right superior occipital/calcarine cortex, there was a significant decrease in activation from pre- to posttest for the schooling group, and a significant increase in activation for the non-schooling group. Post-hoc pairwise comparisons of the estimated marginal means are presented in Table 5. After applying FDR-correction, the differences between pre- and posttest for the

schooling group remained significant, except for the left middle frontal gyrus (p_{fdr} = .051). Figure 2 shows the significant group-by-timepoint interaction effects.

Table 4
Statistical results of significant group-by-timepoint interaction effects for contrast words - fixation. Standardized regression coefficients (β) are given, with 95% confidence intervals. Bold values represent significant effects.

Area of activation	Std. Coeff. (*β*) [95% CI]	Statistic(df)	*p*
Left supplementary motor area	-0.36 [-0.72, 0.01]	*t*(80) = -2.06	**.042**
Left fusiform gyrus	-0.33 [-0.64, -0.06]	*t*(78) = -2.12	**.037**
Left middle frontal cortex	-0.45 [-0.80, -0.10]	*t*(81) = -2.70	**.009**
Right cuneus/ superior occipital / calcarine cortex	0.46 [0.21, 0.74]	*t*(81) = 3.21	**.002**

Table 5
Post-hoc pairwise comparisons of the estimated marginal means of the significant group-by-timepoint interaction effects for contrast words - fixation. Bold values represent significant effects.

Area of activation	Group	Estimate [95% asymp. CI]	*t*-ratio	*p* (p_{fdr})
Left supplementary motor area	Schooling	Δ Act. = 0.59 [0.09, 1.08]	2.40	**.021 (.041)**
	Non-schooling	Δ Act. = -0.21 [-0.82, 0.40]	-0.70	.490 (.490)
Left fusiform gyrus	Schooling	Δ Act. = 1.04 [0.50, 1.57]	3.92	**< .001 (< .001)**
	Non-schooling	Δ Act. = 0.12 [-0.57, 0.82]	0.36	.719 (.719)
Left middle frontal cortex	Schooling	Δ Act. = 0.48 [0.06, 0.90]	2.31	**.026** (.051)
	Non-schooling	Δ Act. = -0.40 [-0.92, 0.11]	-1.56	.125 (.125)
Right cuneus/ superior occipital/ calcarine cortex	Schooling	Δ Act. = -0.88 [-1.65, -0.11]	-2.32	**.026 (.026)**
	Non-schooling	Δ Act. = 1.10 [0.14, 2.07]	2.31	**.026 (.026)**

4.2.2.2 Numbers – Fixation

As shown in Table 6, we found group-by-timepoint interaction effects for the contrast numbers - fixation in two areas: **the right inferior parietal cortex** and **left superior frontal cortex**. Follow-up analyses showed that for the right inferior parietal cortex, there was a significant increase in activation from pre-

to posttest in the schooling group, and a significant decrease for the non-schooling group. With regard to the left superior frontal cortex, there was no change in activation for the schooling group from pre- to posttest, but a significant decrease in activation for the non-schooling group (Table 7). Both effects remained significant after applying FDR-correction. Figure 3 shows the significant group-by-timepoint interaction effects.

Table 6
Statistical results of significant group-by-timepoint interaction effects for contrast numbers - fixation. Standardized regression coefficients (β) are given, with 95% confidence intervals. Bold values represent significant effects.

Area of activation	**Std. Coeff. (*β*) [95% CI]**	**Statistic(df)**	***p***
Right inferior parietal cortex	-0.62 [-0.94, -0.28]	*t*(81) = -3.70	**< .001**
Left superior frontal cortex	-0.46 [-0.81, -0.14]	*t*(81) = -2.66	**.009**

Table 7
Post-hoc pairwise comparisons of the estimated marginal means of the significant group-by-timepoint interaction effects for contrast numbers - fixation. Bold values represent significant effects.

Area of activation	**Group**	**Estimate [95% asymp. CI]**	***t*-ratio**	***p*** (p_{fdr})
Right inferior parietal cortex	Schooling	Δ Act. = 0.83 [0.11, 1.54]	2.33	**.024 (.024)**
	Non-schooling	Δ Act. = -1.23 [-2.10, -0.36]	-2.83	**.007 (.013)**
Left superior frontal cortex	Schooling	Δ Act. = 0.27 [-0.22, 0.75]	1.11	.273 (.273)
	Non-schooling	Δ Act. = -0.74 [-1.33, -0.14]	-2.50	**.016 (.032)**

4.2.2.3 Words – Numbers

As shown in Table 8, we found group-by-timepoint interaction effects for the contrast words - numbers in two areas: **the right cuneus/superior occipital/calcarine cortex** and **the right supramarginal gyrus**. Follow-up analyses showed that for both ROIs, the schooling group exhibited no significant change from pre- to posttest, while there was a significant increase in activation for the non-schooling group (Table 9). Both effects remained significant after applying FDR-correction. Figure 4 shows the significant group-by-timepoint interaction effects.

Table 8
Statistical results of significant group-by-timepoint interaction effects for contrast words - numbers. Standardized regression coefficients (β) are given, with 95% confidence intervals.

Area of activation	Std. Coeff. (*β*) [95% CI]	Statistic(df)	*p*
Right cuneus/ superior occipital/ calcarine cortex	0.43 [0.06, 0.76]	*t*(81) = 2.54	**.013**
Right supramarginal gyrus	0.34 [0.01, 0.72]	*t*(81) = 2.05	**.044**

Table 9
Post-hoc pairwise comparisons of the estimated marginal means of the significant group-by-timepoint interaction effects for contrast words - numbers.

Area of activation	Group	Estimate [95% asymp. CI]	*t*-ratio	*p* (p_{fdr})
Right cuneus/ superior occipital/ calcarine cortex	Schooling	Δ Act. = -0.18 [-0.93, 0.57]	-0.48	.630 (.630)
	Non-schooling	Δ Act. = 1.30 [0.39, 2.22]	2.85	**.006 (.012)**
Right supramarginal gyrus	Schooling	Δ Act. = -0.04 [-0.34, 0.27]	-0.23	.816 (.816)
	Non-schooling	Δ Act. = 0.45 [0.08, 0.83]	2.42	**.019 (.039)**

4.2.2.4 Numbers - Words

As shown in Table 10, we found group-by-timepoint interaction effects for the contrast numbers - words in two areas: **the right cuneus/superior occipital/calcarine cortex** and **the right supramarginal gyrus**. Follow-up analyses showed that for both ROIs, the schooling group exhibited no significant change from pre- to posttest, while there was a significant decrease in activation for the non-schooling group (Table 11). Both effects remained significant after applying FDR. Figure 5 shows the significant group-by-timepoint interaction effects.

Table 10
Statistical results of significant group-by-timepoint interaction effects for contrast numbers - words. Standardized regression coefficients (β) are given, with 95% confidence intervals.

Area of activation	Std. Coeff. (*β*) [95% CI]	Statistic(df)	*p*
Right cuneus/ superior occipital/ calcarine cortex	-0.43 [-0.75, -0.09]	*t*(81) = -2.54	**.013**
Right supramarginal gyrus	-0.34 [-0.66, -0.03]	*t*(81) = -2.05	**.044**

Table 11
Post-hoc pairwise comparisons of the estimated marginal means of the significant group-by-timepoint interaction effects for contrast numbers - words.

Area of activation	Group	Estimate [95% asymp. CI]	*t*-ratio	*p* (p_{fdr})
Right cuneus/ superior occipital/ calcarine cortex	Schooling	Δ Act. = 0.18 [-0.93, 0.57]	0.48	.630 (.630)
	Non-schooling	Δ Act. = -1.30 [-2.22, -0.39]	-2.85	**.006 (.012)**
Right supramarginal gyrus	Schooling	Δ Act. = 0.04 [-0.27, 0.34]	0.23	.816 (.816)
	Non-schooling	Δ Act. = -0.45 [-0.83, -0.08]	2.42	**.019 (.039)**

Discussion

This study investigated changes in neural activation in response to words and numbers in children transitioning from preschool to primary school, aiming to disentangle schooling-induced effects from age-related maturational changes. Using a school cut-off design with two similar-aged groups differing only in exposure to formal education, we examined to which extent neural changes in 5- to 7-year-old children in response to words and numbers can be attributed to schooling. Our results showed that one year of schooling resulted in significant changes in neural responses to both words and numbers. Specifically, an increase in activation for words was specifically present in the schooling group for the left fusiform and left supplementary motor area, while for numbers this effect was present in the right inferior parietal cortex. These findings provide an intriguing example of experience-dependent plasticity and show how the brain functionally changes in response to formal schooling.

Upon entering formal education, children learn to read words and understand symbolic numbers – skills for which the brain is not predestined. According to the *neuronal recycling* hypothesis, culturally acquired skills recycle and reorganize pre-existing cortical circuits (Dehaene & Cohen, 2007, 2011). While some longitudinal fMRI studies have examined changes in neural activation before and after formal school entry (Chyl et al., 2019; Dehaene-Lambertz et al., 2018; Emerson & Cantlon, 2015; Yu et al., 2018), these

studies have generally been unable to disentangle effects to which extent these neural changes are driven by the exposure of formal schooling – as opposed to general age-related maturation.

In the current study, we observed increased activation for words in the left fusiform gyrus following one year of schooling. A region within the left fusiform gyrus, often referred to as the visual word form area (VWFA), is known to gradually specialize for letter strings during reading acquisition (Chyl et al., 2018, 2021; Dehaene-Lambertz et al., 2018), which is often considered the anatomical signature of emergent reading (Dehaene & Dehaene-Lambertz, 2016). While earlier findings suggested that just a few hours of training could increase VWFA responsiveness to print (Brem et al., 2010), more recent research challenges this view, indicating that the emergence of the VWFA is a gradual process that depends on sustained reading experience and that short-term exposure is likely insufficient (Chyl et al., 2018; Dehaene-Lambertz et al., 2018). Consistent activation in the VWFA has been observed in both children and adults during word and pseudoword reading, but not in illiterate individuals (Dehaene et al., 2015). Moreover, increased letter specificity in this region has been correlated with reading proficiency in young children (Centanni et al., 2018). Longitudinal evidence, although limited, has shown similar patterns. Chyl et al. (2019) reported increased activation to print in the left fusiform gyrus following two years of reading instruction in typical readers, while Dehaene-Lambertz et al. (2018) found enhanced word-selective activation in the left fusiform gyrus just months after school entry.

In addition to the left fusiform gyrus, we observed schooling-related increases in the left supplementary motor area (SMA). Although this region is also activated in adults during reading, it appears especially engaged in children (Houdé et al., 2010; Martin et al., 2015, for meta-analyses). Evans et al. (2016) found that younger participants showed greater left SMA activation than older participants during a reading task (ages 7–29). Chyl et al. (2023) similarly reported increased activation in the bilateral SMA among beginning readers as compared to prereaders. Generally, the SMA has been proposed to support control functions during speech and language, particularly under conditions of increased cognitive demands (Hertrich et al., 2016; Martin et al., 2015). Research has suggested that it can be subdivided into a more posterior region – named the SMA– associated with motor-related and automatized processes such as regular word reading in adults (Cummine et al., 2017), and a more anterior region – the pre-SMA – implicated in higher-order cognitive control, as evidenced by its engagement during more demanding tasks involving pseudo-homophones (Cummine et al., 2017). However, the subdivision of the SMA stems predominantly from research in adults, leaving it unresolved whether the schooling-related cluster identified in our study (MNI − 32, -5, 52) falls within the pre-SMA or the SMA.

Longitudinal studies that have investigated children before and after the onset of formal schooling have also previously identified changes in these regions. For instance, Chyl et al. (2019) reported increased activation to print in typical readers after two years of reading instruction in the left fusiform gyrus, and in several language-related regions including bilateral inferior frontal gyri and precentral gyri, left SMA, bilateral superior parietal lobule, and right angular gyrus. Yu et al. (2018) found increased activation in a network comprising left inferior frontal, left posterior occipitotemporal, and right angular gyri during an auditory phonological processing task after the start of school. Lastly, Dehaene-Lambertz et al. (2018)

reported increased activation in 6-year-old beginning readers in left-lateralized regions, including the VWFA, posterior temporal sulcus, and parietal and inferior frontal regions.

Taken together, our results are broadly consistent with prior research but extend the existing literature in two key ways. First, our findings demonstrate that functional changes in the left fusiform gyrus and left SMA observed during the transition from informal to formal education are specifically attributable to schooling itself, over and above age-related effects. Second, we did not observe significant changes in other regions previously reported in the literature, suggesting that those changes may reflect age-related maturation rather than schooling-induced, experience-dependent neuroplasticity.

We additionally found a group-by-timepoint interaction for words in the right calcarine cortex, extending to the cuneus. This interaction was, however, characterized by a decrease in word-related activation over time in the schooling group, coupled with increased activation in the non-schooling group. The calcarine cortex, part of the visual system (Emerson et al., 2015), shows early sensitivity to visual features relevant to reading as well as to non-reading-related stimuli, such as grids or checkerboards – even before formal reading instruction begins (Chyl et al., 2018; Dehaene-Lambertz et al., 2018; Dehaene et al., 2010, 2015; Liebig et al., 2021). Some researchers have argued that it may serve as a neural marker of "reading readiness" at the end of preschool (Dehaene-Lambertz et al., 2018; Dehaene & Cohen, 2007; Liebig et al., 2021). As reading acquisition progresses, the functional specialization for words tends to shift from the right to the left hemisphere (e.g., VWFA) (Brem et al., 2010; Dehaene-Lambertz et al., 2018). Our findings are consistent with this developmental trajectory: in the schooling group, who have learned to read, activation for words shifted leftwards; in contrast, the non-schooling group retained stronger right-hemispheric involvement (Benischek et al., 2020; Raschle et al., 2012; Xiao et al., 2016).

Turning to the processing of symbolic numbers, schooling led to increased activation in the right inferior parietal cortex in response to ascending digit sequences (e.g., *2 3 4*). The parietal cortex, particularly the intraparietal sulcus (IPS) has been widely investigated in number processing (Fias et al., 2013; Menon, 2014; Sokolowski et al., 2017). In early development, the right IPS is thought to be involved before the left IPS (Cantlon et al., 2006; Kersey & Cantlon, 2017), with the left IPS becoming increasingly specialized for symbolic number processing with age and experience (Ansari, 2016; Bugden et al., 2021; Vogel et al., 2015). Our findings, pointing to broader inferior parietal involvement than the IPS alone (Skagenholt et al., 2018), align with recent meta-analyses suggesting a more distributed and right-lateralized network for early number tasks (Arsalidou et al., 2018; Sokolowski et al., 2017). Recently, cortical representations of both Arabic numerals and non-symbolic quantities (i.e., dots) were measured and compared between children at the beginning of (age 5) or four years into formal education (age 8) (Nakai et al., 2023). They found that, for the 5-year-olds, both quantity representations were represented in the right parietal cortex. Importantly, our stimuli required children to process ordered digit sequences, rather than simply viewing digits. This design likely engaged some degree of numerical understanding or counting. Prior studies with isolated digits have often failed to elicit number-specific activation in young children, both before (Cantlon et al., 2011, 4-year-olds) or shortly after formal school entry (Dehaene-Lambertz et al.,

2018; Park et al., 2018, 7-year-olds). Our findings thus extend the literature by showing that passive but more meaningful digit sequences can elicit number-specific activation in schooling children.

To the best of our knowledge, only one longitudinal brain imaging study has examined number processing within this specific developmental window (ages 4 to 9), testing children twice with one or two year(s) in between (Emerson & Cantlon, 2015). This study reported increased activation over time in the bilateral IPS and anterior cingulate cortex for numerical stimuli compared to non-numerical categories (words, faces, shapes). Notably, our findings provide the first evidence that changes in the right inferior parietal cortex during this period are specifically attributable to schooling, rather than to age-related maturation. The absence of effects in the anterior cingulate cortex and left parietal regions in our study suggests that changes in these areas may be more closely linked to age than to schooling experience.

We also found a significant group-by-timepoint interaction for numbers in the left superior frontal cortex, where activation decreased over time in the non-schooling group. Although we observed a trend towards increased activation in the schooling group, it was not statistically significant. Developmentally, numerical processing tends to shift from frontal to parietal regions (Cantlon et al., 2006; Kaufmann et al., 2011; Rivera et al., 2005; Sokolowski et al., 2017), but frontal areas, including the superior frontal cortex, remain often involved – particularly for symbolic tasks (Skagenholt et al., 2018; Sokolowski et al., 2017; Yeo et al., 2017), albeit predominantly in the right hemisphere.

In addition to disentangling schooling effects from age-related maturation, we directly contrasted neural responses to words and numbers to explore the category-specificity of these activations. This exploratory analysis aimed to assess whether words and numbers elicit distinct patterns of brain activation. We found schooling-related effects for numbers versus words in the right calcarine cortex and right supramarginal gyrus, primarily driven by a decrease in activation in the non-schooling group. Although the schooling group showed a trend towards increased activation, this difference did not reach significance.

Previous studies have reliably identified the VWFA for letters and words, but evidence for a number form area (NFA) remains inconsistent. The NFA is thought to be located in the inferior temporal gyrus (Shum et al., 2013), with connectivity to the intraparietal cortex emerging before formal education and strengthening with age (Abboud et al., 2015; Hannagan et al., 2015; Nemmi et al., 2018). However, few studies have reliably detected the NFA with fMRI (Yeo et al., 2017, for a meta-analysis), and many have failed to replicate its presence (Artemenko et al., 2018; Merkley et al., 2019; Price & Ansari, 2011). Accordingly, there is ongoing debate about whether letters and numbers are processed in distinct neural systems or within overlapping networks (Soltanlou et al., 2019). In our study, we did not observe activation consistent with the putative NFA. For the VWFA, we observed schooling-induced effects in the left fusiform gyrus when contrasting words with fixation. Although a significant group difference emerged in this region at posttest for the words versus numbers contrast, it was not significant in the longitudinal analysis. Importantly, our paradigm was not specifically optimized to examine category-

specific responses to letters and numbers. Prior studies typically used simple symbolic stimuli such as single letters and digits (e.g., Hannagan et al., 2015; Merkley et al., 2016, 2019; Yeo et al., 2017), whereas our task involved more complex, meaningful stimuli. This may have engaged additional higher-level cognitive processes, particularly for the numerical items (Hannagan et al., 2015; Pollack & Price, 2019), thereby probably reducing the specificity of the activation.

Several limitations of the present study should be acknowledged. First, we employed a passive viewing paradigm to assess neural responses to words and numbers. Although the task was designed to elicit meaningful processing of these symbolic stimuli, we cannot definitively determine how participants processed our stimuli. Nonetheless, passive paradigms are widely used in developmental neuroimaging due to their suitability for young children and have been adopted in several comparable studies (Benischek et al., 2020; Dehaene-Lambertz et al., 2018; Feng et al., 2022; Liebig et al., 2021; Price & Ansari, 2011; Vogel et al., 2015). Recent longitudinal work by Nordt et al. (2023) has for example demonstrated that distinctiveness of pseudoword-related activity in left lateral ventral temporal cortex predicted children's reading performance of pseudowords, highlighting the potential of passive paradigms to capture behaviorally relevant neural findings. Third, although we used a child-appropriate scanning protocol, our sample size – especially the number of high-quality, complete pre-post datasets (n = 30) – limited our ability to conduct individual-level correlational analyses linking behavioral gains in reading or arithmetic to neural changes. The need to exclude data for quality reasons, while essential for reliable results, further reduced statistical power and may have obscured additional effects. This limitations highlights the persistent methodological challenges of conducting longitudinal neuroimaging studies in young children (Turesky et al., 2021). Increasing sample sizes – through longer recruitment periods, but also multi-center projects (Poldrack et al., 2013, 2017) – would boost statistical power and allow individual-level correlational analyses.

Finally, the generalizability of our findings is constrained by sample characteristics. All participants were monolingual Dutch speakers of on average middle-to-high SES background. Neural trajectories may differ in children learning a different orthography, in bilingual children, or in educational contexts with different school entry-ages or instructional practices. Replicating this research across orthographies, cultural, and educational settings will be essential to establish the universality – or specificity – of schooling-related neurodevelopmental effects.

In sum, this study provides evidence that one year of formal schooling leads to experience-dependent changes in neural responses to words and numbers. Children who had entered first grade showed increased activation to words in the left fusiform gyrus and supplementary motor area, and to numerical sequences in the right inferior parietal cortex. These effects, absent in similar-aged peers who remained in preschool, underscore the role of formal education in shaping the developing brain. Our findings support the notion that schooling acts as a key driver of functional specialization for words and numbers, above and beyond age-related maturation – providing an intriguing example of experience-dependent neuroplasticity and the *neuronal recycling* hypothesis (Dehaene et al., 2005; Dehaene & Cohen, 2007). Future research should expand on these findings using more fine-grained analytic approaches

and larger longitudinal cohorts across educational and cultural settings to further clarify how formal education interacts with individual developmental trajectories in shaping reading and mathematical networks in the brain.

Declarations

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Author Contribution

Floor Vandecruys : Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – original draft. **Maaike Vandermosten** : Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Bert De Smedt** : Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Data Availability

The datasets generated during and/or analyzed during the current study will be made publicly available on the Open Science Framework repository of the corresponding author.

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Figures

Figure 1

Example of our two categories of stimuli: words and digit sequences.

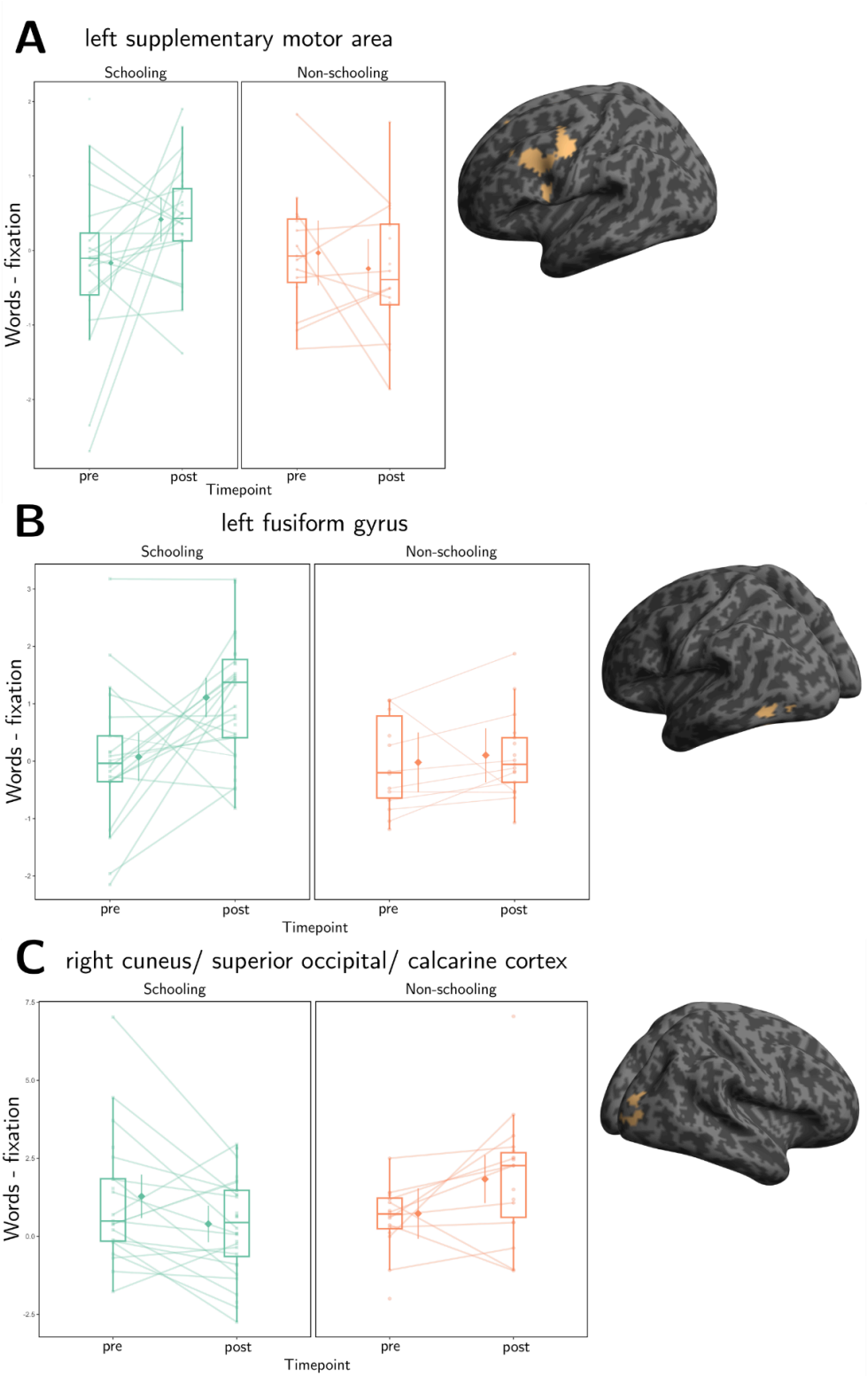

Figure 2

Significant group-by-timepoint interaction effects for the contrast words – fixation of the A) left supplementary motor area, B) left fusiform gyrus, and C) right cuneus/ superior occipital/ calcarine cortex. Boxplots and semitransparent dots and lines represent individual subject longitudinal changes. The solid diamonds represent model-predicted contrast values with 95% confidence bands across the two time points for the two groups. Significant ROIs are visualized in three views.

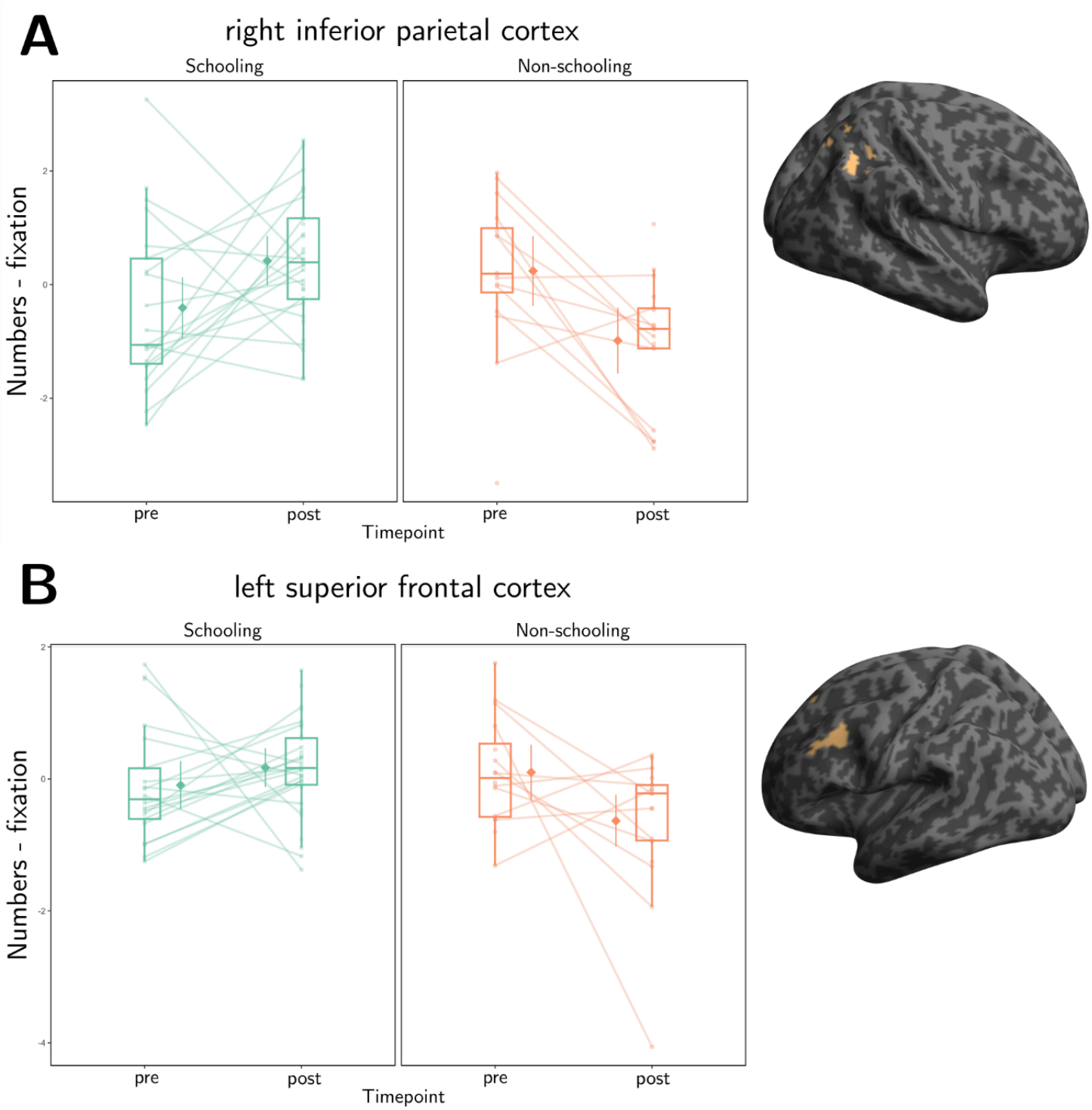

Figure 3

Significant group-by-timepoint interaction effects for the contrast numbers – fixation of the A) right inferior parietal cortex, and B) left superior frontal cortex. Boxplots and semitransparent dots and lines represent individual subject longitudinal changes. The solid diamonds represent model-predicted contrast values with 95% confidence bands across the two time points for the two groups. Significant ROIs are visualized in three views.

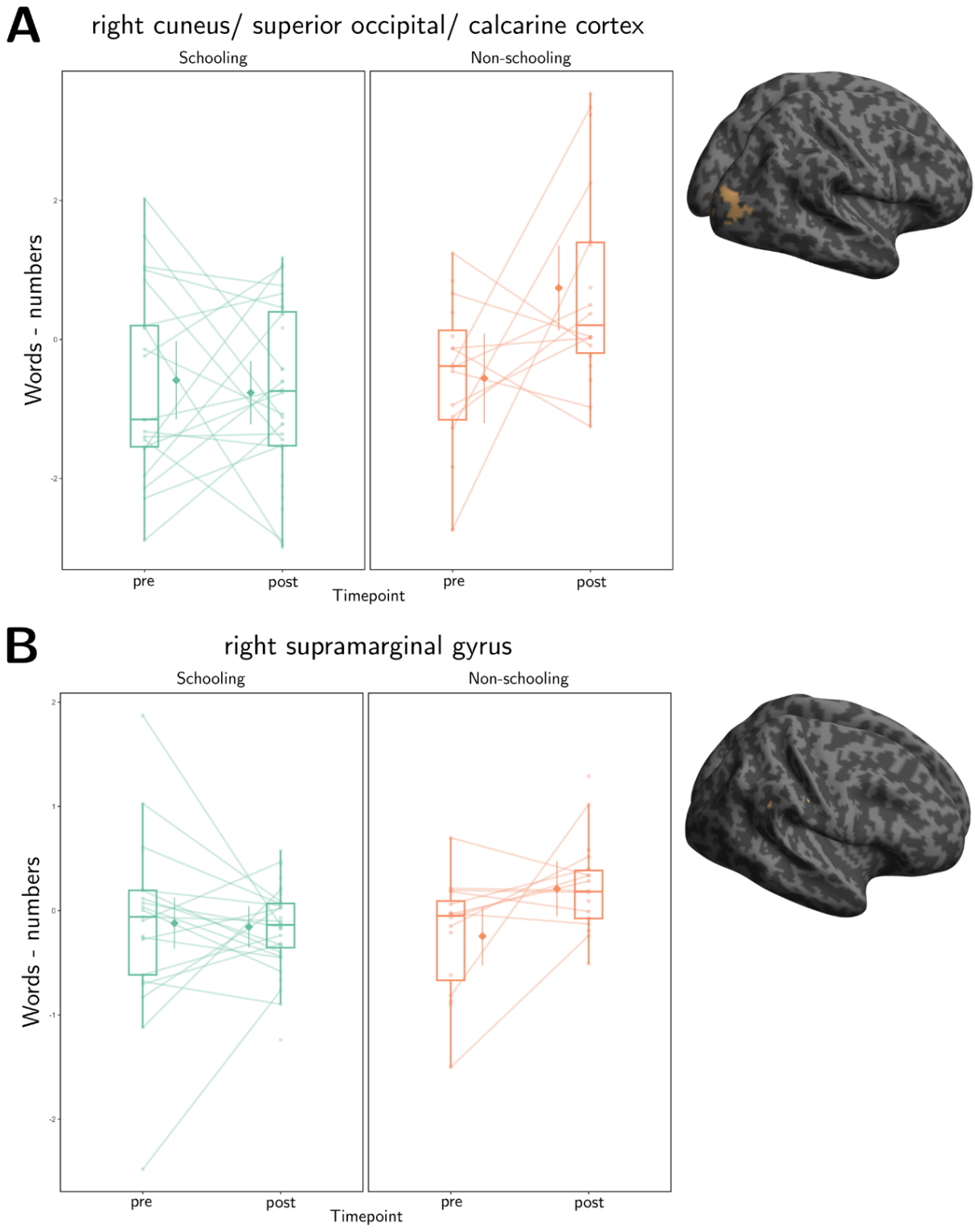

Figure 4

Significant group-by-timepoint interaction effects for the contrast words – numbers of the A) right cuneus/ superior occipital/ calcarine cortex, and B) right supramarginal gyrus. Boxplots and semitransparent dots and lines represent individual subject longitudinal changes. The solid diamonds represent model-predicted contrast values with 95% confidence bands across the two time points for the two groups. Significant ROIs are visualized in three views.

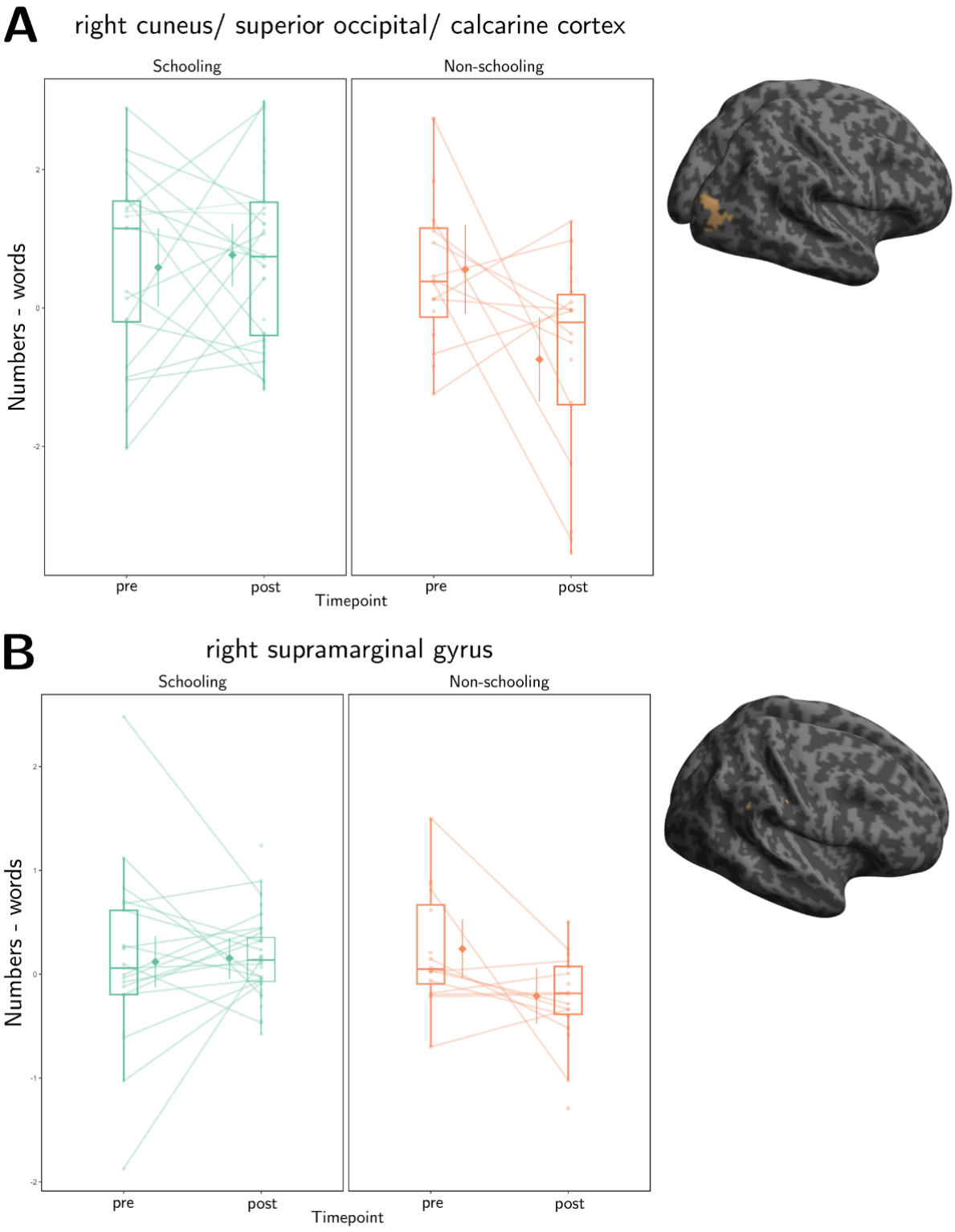

Figure 5

Significant group-by-timepoint interaction effects for the contrast numbers – words of the A) right cuneus/ superior occipital/ calcarine cortex, and B) right supramarginal gyrus. Boxplots and semitransparent dots and lines represent individual subject longitudinal changes. The solid diamonds represent model-predicted contrast values with 95% confidence bands across the two time points for the two groups. Significant ROIs are visualized in three views.

Supplementary Files

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