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Nurturing the mathematical brain:

Home numeracy practices are associated with children's neural responses to Arabic numerals

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Running head: Home numeracy practices and the numerical brain

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Abstract

Disparities in home numeracy environment contribute to large variations in children's mathematical skills. However, the neural mechanisms underlying the relation between home numeracy experiences and mathematical learning are unknown. Here, parents of 66 8-year-olds completed a questionnaire assessing the frequency of home numeracy practices. Neural adaptation to the repetition of Arabic numerals and words was measured in children using fMRI ($n=50$), thereby assessing how sensitive was the brain to the presentation of numerical and non-numerical information. Disparities in home numeracy practices were related to differences in digit (but not word) processing in a region of the left intraparietal sulcus (IPS) that was also related to child arithmetic fluency. Furthermore, digit-related processing in the IPS influenced the relation between home numeracy practices and arithmetic fluency. Results are consistent with a model hypothesizing that home numeracy practices may affect children's mathematical skills by modulating the IPS response to symbolic numerical information.

Statement of Relevance

Both before and after they enter school, children are exposed to vastly different numeracy experiences at home. Although these disparities are increasingly thought to affect mathematical achievement, little is known about how children's environment and experiences beyond the classroom impact the development of the numerical brain. Using functional magnetic resonance imaging (fMRI) in 8-year-olds, we found that brain responses to the repeated presentation of symbolic numerical magnitudes (Arabic numerals) in the intraparietal sulcus (IPS) are related to differences in the frequency of numeracy practices shared with parents. Our findings are consistent with the proposal that the processing of symbolic magnitudes in the IPS mediates the relation between home numeracy practices and children's mathematical skills. Thus, children's home environment may not only affect language-related brain functions, as suggested by prior research. It might also influence the way symbolic numerical magnitudes are processed in the brain.

Introduction

Children's mathematical development is characterized by large individual differences that critically impact career prospects in a technology-driven society. Although these individual differences are often attributed to school-related factors (Sokolowski & Ansari, 2018), variations in mathematical achievement through elementary and middle school are predicted by disparities in numerical knowledge even before children enter kindergarten (Duncan et al., 2007). This suggests that experiences with numeracy outside of the classroom might influence the acquisition of numerical skills (Elliott & Bachman, 2018).

Current neuroimaging research suggests that children's home environment and experiences mainly affect mathematical learning by influencing language-related brain functions. For example, several studies have investigated the relation between brain development and family socio-economic status (SES), a construct that includes measures of parental education and income and therefore serves as a proxy for children's environmental inputs and experiences (Farah, 2017). This literature has predominantly associated SES with structural differences in left perisylvian and prefrontal areas supporting language and executive functions (Farah, 2017). SES has also been associated with tasks that involve the left perisylvian/language system in children (Merz et al., 2019). Finally, studies suggest that even the link between SES and mathematical knowledge is supported by language-related brain systems (Demir et al., 2015; Demir-Lira et al., 2016).

But prior studies have two major limitations. First, SES is a *distal* construct that may affect mathematical development through more *proximal* environmental factors. For instance, SES may be associated with the quality and frequency of mathematical activities and resources that are provided by parents at home, i.e., the *home numeracy environment* (Dunst et al., 2017; Elliott & Bachman, 2018; Mutař-Yıldız et al., 2020). Indeed, children who benefit from more frequent home numeracy practices than their peers show improved mathematical knowledge, though this relation depends upon the type (formal versus informal) and complexity (advanced versus basic) of home practices (Elliott & Bachman, 2018). Thus, home numeracy practices may provide a more proximal index of a child's home numeracy environment than family SES.

Second, previous studies investigating the relation between SES and mathematical processing have exclusively focused on single-digit arithmetic (Demir et al., 2015; Demir-Lira et al., 2016). However, single-digit arithmetic largely relies on the retrieval of phonological information from long-term memory (Zamarian et al., 2009). This raises the possibility that the relation between SES and language-related areas observed in these studies may be due to the phonological nature of the task.

Cognitive neuroscience research suggests that human mathematical competence is likely *not* grounded in the brain systems for language (Amalric & Dehaene, 2016). Instead, studies show that non-symbolic numerical processing (e.g., estimating the numerosity of an array of dots) as well as symbolic numerical processing (e.g., understanding the meaning of an Arabic numeral) involves brain circuits in and around the intraparietal sulcus (IPS) (Nieder, 2016). Although a growing number of studies suggest that non-symbolic and symbolic numerical processing does not rely on similar mechanisms in the IPS (Wilkey & Ansari, 2020), the progressive recruitment of that region is largely believed to support mathematical learning in children (Dehaene & Cohen, 2007). Individual differences in mathematical skills have also been shown to be associated with symbolic number processing in the IPS (Bugden et al., 2012), a finding in line with accumulating evidence suggesting that symbolic number understanding strongly predicts mathematical skills in children (to a greater extent than non-symbolic estimation skills) (De Smedt et al., 2013). Therefore, it is possible that children who experience more frequent numeracy activities at home may show enhanced response to symbolic numerical information in the IPS, which in turn may influence mathematical skills. This hypothesized model (**Fig. 1a**) parallels models arguing that a supportive home literacy environment may influence the structure and function of language-related brain regions, which are then thought to affect children's linguistic skills (see Romeo et al., 2018 and Fig. 1 in Merz, Maskus, Melvin, He, & Noble, 2020 for an example of such a model).

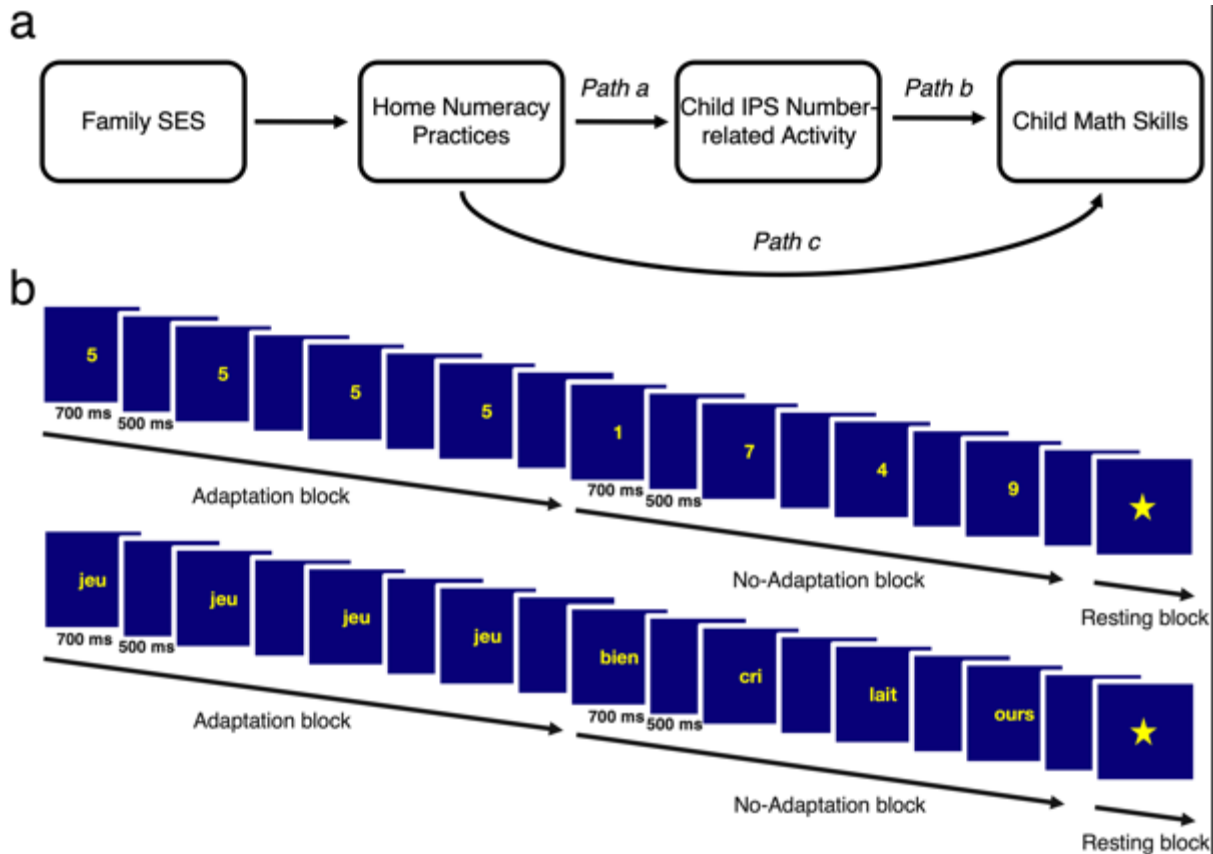


Figure 1. Model and experimental design. (a) Hypothesized model of the relations between SES, home numeracy practices, brain activity and mathematical skills (adapted from a model of the relations between SES, home literacy practices, brain activity and reading skills; Merz et al., 2020). (b) Experimental task. Participants were sequentially presented with digits (top) or words (bottom) that were identical (adaptation blocks) or different (no-adaptation blocks).

In the present study, we explored the relation between home numeracy practices and the brain circuits underlying symbolic numerical processing in children. We recruited 73 8-year-olds with their parents. While both parents and children completed the same test of arithmetic fluency (thereby measuring a skill that is at the heart of elementary mathematics and relates to higher-level mathematical competence; Price, Mazzocco, & Ansari, 2013), parents also responded to a questionnaire assessing home numeracy practices (final behavioral sample, $n=66$). Finally, children underwent fMRI scanning (final fMRI sample, $n=50$). In the scanner, children were presented with a blocked passive visual adaptation task inspired by Perrachione and colleagues (2016). fMRI-

adaptation paradigms rely on the idea that presenting a given stimulus repeatedly leads to a decrease of signal in the region that processes this stimulus (because firing rates of the neuronal population decrease; Grill-Spector and Malach, 2001). Thus, comparing activity associated with blocks of different stimuli (no-adaptation) versus activity associated with blocks of identical stimuli (adaptation) captures a *neural adaptation effect* in task-relevant regions. Here, children were presented with adaptation and no-adaptation blocks of either digits or words (the latter being considered a control) (**Fig. 1b**).

Testing the causal aspects of the assumptions in **Fig. 1a** requires interventional designs, which are particularly challenging in pediatric neuroimaging. However, our cross-sectional design may still provide critical evidence for the plausibility of this model. Specifically, we aim to test whether associations between home numeracy practices, digit processing in the IPS, and mathematical skills observed at age 8 are *consistent* with this model. This would mirror recent studies showing that relations between home literacy, language-related structure and function, and literacy skills are consistent with a model of how home literacy experiences affect literacy skills (Merz et al., 2020; Romeo et al., 2018).

Here we first aimed to confirm that home numeracy practices relate to children's arithmetic fluency (consistent with Path c in **Fig. 1a**). We then used the framework of mass-univariate Mediation Effect Parametric Mapping (MEPM; Wager, Davidson, Hughes, Lindquist, & Ochsner, 2008) to assess (1) whether home numeracy practices relate to digit-related (but not word-related) activity in the IPS (consistent with Path a in **Fig. 1a**), (2) whether digit-related (but not word-related) activity in the IPS relate to child arithmetic fluency, controlling for home numeracy practices (consistent with Path b in **Fig. 1a**), and (3) whether digit-related (but not word-related) IPS activity may explain some of the relation between home numeracy practices and child arithmetic fluency. This would be consistent with the idea that home numeracy practices may affect children's numerical skills through symbolic numerical processing in the IPS.

Method

Participants

Seventy-three right-handed elementary school children of approximately 8 years of age and one of their parents were invited to participate in the experiment. Participants were contacted through flyers sent to schools and advertisements on social media. All parents and children came to the lab for a first behavioral session during which they were given tests and questionnaires. Seven children were excluded from the behavioral analyses because they (1) were seeing a speech-language pathologist on a regular basis ($n=3$), (2) had an intelligence quotient (IQ) lower than the 25th percentile ($n=2$), (3) had a delay in speech and language acquisition ($n=1$), and (4) were diagnosed with attention deficit disorder ($n=1$). Therefore, 66 participants were included in the behavioral analyses of this first session. Fifty-eight of these children participated a second session involving fMRI scanning with the digit and word adaptation tasks. After fMRI motion correction (see below), 50 children had at least one run of usable data in the digit adaptation task (22 of these participants had two usable runs in that task) and 44 children had at least one run of usable data in the word adaptation task (22 of these participants had two usable runs in that task). Details about justification of final fMRI sample sizes are given in Supplemental information, as well as sensitivity curves across a range of effect sizes for our samples (**Fig. S1**). Demographic information about children and parents can be found in **Table 1**. All children and parents were native French speakers. Parents gave written informed consent and children gave their assent to participate in the study. The study was approved by a French ethics committee (Comité de Protection des Personnes Sud-Est 2). Families were paid 80 euros for their participation.

Table 1. Demographic information and test scores of children and parents.

Measure	Behavioral sample (n=66)		fMRI sample (n=50)	
	Children	Parents	Children	Parents
Age (years) ¹	8.46 (0.36)	39.53 (4.95)	8.48 (0.35)	39.74 (4.80)
Sex (female)	30%	89%	30%	86%
Child grade (2 rd grade) ²	30%	-	26%	-
Parental education ³	-	3.05 (2.36)	-	3.10 (2.57)
Approximate monthly income (euros) ⁴	-	1,727 (1,078)	-	1,680 (1,101)
Arithmetic fluency (raw score)	40 (12)	122 (22)	41 (12)	122 (23)
Arithmetic fluency (standard score)	104 (24)	102 (9)	107 (24)	102 (10)
IQ composite (standard score)	112 (11)	-	112 (12)	-

Notes. All values except sex and child grade represent mean (SD). ¹, All children were 8 years of age, except for one who was younger (7.51) and 3 who were slightly older (9.06 to 9.22) at the time of testing ², Children were either in 2nd or 3rd grade. ³, See main text for explanation about how parental education was calculated. ⁴, As a reference, the median monthly income in France is about €1,700 (Robin, 2019).

Testing

Arithmetic fluency of children and parents were assessed during the first session using the Math-Fluency subtest of the Woodcock-Johnson-III Tests of Achievement (WJ-III) (Woodcock et al., 2001). In this test, participants solve simple addition, subtraction, and multiplication problems within a 3-min time limit. The test consists of 2 pages of 80 problems involving operands from 0 to 10. A raw score corresponding to the number of correct responses was obtained for each child and parent. An age-normalized score was also calculated based on US and French norms for adults and children, respectively (Schwartz et al., 2018). Given the homogeneity of the sample in terms of age (**Table 1**), raw scores were used in all analyses. In addition to mathematical skills, children's IQ was estimated using the NEMI-2 standardized intelligence test (Cognet, 2006). The test uses measures of verbal intelligence and matrix reasoning to provide a standardized score of full-scale IQ. Math-Fluency and IQ scores are indicated in **Table 1**.

Parental questionnaires

Parents were given electronic questionnaires on a tablet to gather measures of home numeracy practices. First, information about family SES was collected based on parent's education level and monthly income. Education level was measured using the number of years pre- or post- high school graduation, with high school graduation set at 0 (i.e., positive numbers indicated that parents

completed some years of education after graduating). Approximate monthly income was measured using ranges with increments of €1,000. The minimum possible range was €0 to €999 and the maximum possible range was more than €10,000. For all analyses, we used the median of the reported income range (e.g., €500 for a range between €0 to €1,000) as an approximation of parents' income.

Second, parents were asked how often they engaged in home learning activities that involve mathematics with their child. To reduce the math-focus of the study, parents were also asked about activities involving other academic and non-academic domains (e.g., reading, music, biology). These items were considered filler items and were not analyzed in the present study. Activities were adapted from the questionnaire used in LeFevre et al. (LeFevre et al., 2009). For each activity, parents rated the frequency with which they engaged in that activity with their child at home during the past month. A six-point rating scale was used (Did not occur/Activity is not relevant to my child, 1-3 times per month, Once per week, 2-4 times per week, Almost daily, Daily). Parents could also indicate if they used to engage in an activity in the past but no longer did at the time of testing ("The activity occurred in the past but no longer occurs; rated 1 point). Finally, they could indicate if the child engaged in that activity on her own ("My child does this activity without my help"; rated 1 point).

Among the 77 home learning activities mentioned in the questionnaire, 36 were related to mathematics. Following previous studies (LeFevre et al., 2009), 17 of these activities were considered *informal* (**Fig. 2**) and 19 were considered *formal* (**Fig. 3**). Informal activities are those whose purpose is not to teach numerical skills but nonetheless expose children to various mathematical concepts (e.g., fraction when cooking) (Elliott & Bachman, 2018; LeFevre et al., 2009; Mutaş-Yıldız et al., 2020). Formal activities are those in which parents explicitly intend to teach numerical skills to their child (e.g., multiplication tables). Formal activities were further considered *basic* or *advanced*, depending on their complexity for an 8-year-old child (Elliott & Bachman, 2018; Mutaş-Yıldız et al., 2020). For example, subtracting, multiplying or dividing numbers were considered either *basic* or *advanced* depending on the size of the operands (i.e., single-digit versus double-digit). Similarly, whereas activities such as reading and writing numbers up to 100 were considered relatively *basic*, reading and writing numbers up to 1,000 were considered more *advanced* in 8-year-olds. Thus, each *advanced* activity was always related to a more *basic* activity. To avoid having parents repeatedly answering no

to questions that were about the same topic but only differed in terms of the complexity of the activity (e.g., “Did you count up to 100 with your child?” followed by “Did you count up to 1,000 with your child?”), advanced formal activities were not presented to parents if they stated that the corresponding more basic activity had never occurred at home. To account for the inherent relation between basic and advanced formal practices, the frequency of basic practices was systematically included as covariate in models investigating effects of advanced practices in both behavioral and fMRI analyses (and vice versa). Parental responses to the questionnaire are shown on **Fig. 2** and **Fig. 3**. Finally, parents were asked to provide a subjective estimate of their child’s skills in mathematics (and other domains) using a six-point rating scale (i.e., Not sure, Severe difficulty, Difficulty, Average skills, Good skills, Very good skills).

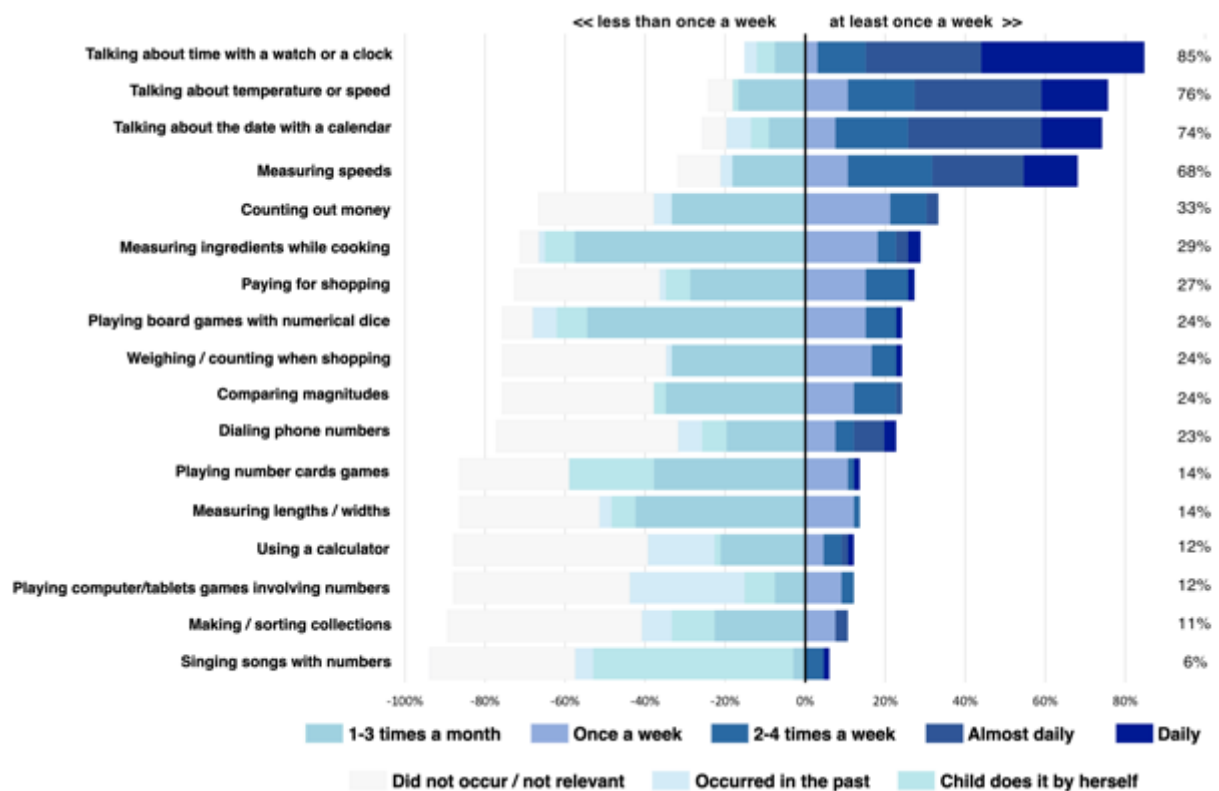


Figure 2. Divergent stacked bar chart showing the frequencies of informal practices among parents (n=66). Percentages on the right indicate the share of parents who engage in each practice at least once a week. Practices are ordered from the most (top) to the least frequent (bottom).

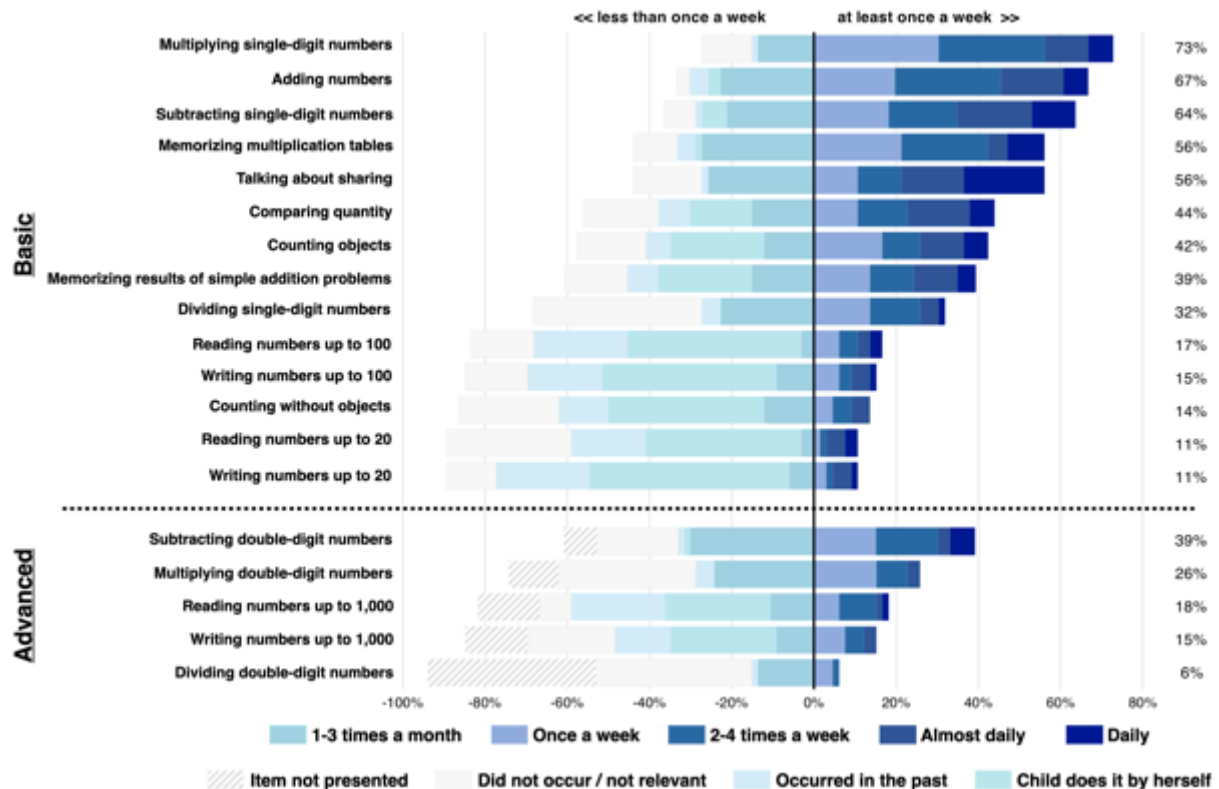


Figure 3. Divergent stacked bar chart showing the frequencies of basic formal and advanced formal practices among parents (n=66). Percentages on the right indicate the share of parents who engage in each practice at least once a week. Practices are ordered from the most (top) to the least frequent (bottom) for each level of complexity.

Experimental tasks

We directly adapted from Perrachione et al. (2016) a task in which series of symbolic stimuli were passively presented in blocks at the center of the screen. We chose this task because (1) it does not require an active response (thereby avoiding confounding individual differences in activity with individual differences in performance; Luna, Velanova, & Geier, 2010), and (2) block designs have more power and reliability than even-related designs (which makes them particularly well-suited for pediatric neuroimaging; Bennett & Miller, 2013). As in Perrachione et al., one version of the task (i.e., word adaptation task) involved series of words. Words were 3 to 5 letters monosyllabic French nouns of equal frequency (mode=4) (<http://www.lexique.org/shiny/openlexicon/>). None of these words were number words or quantifiers. This word adaptation task served as a control task in the present study. In

another version of the task specifically developed for the purpose of the current study (i.e., digit adaptation task), words were replaced by Arabic numerals ranging from 1 to 8. Word and digit adaptation tasks were each composed of 2 runs. In each of these runs, participants were presented with adaptation and no-adaptation blocks (**Fig. 1b**). Adaptation blocks consisted in the repetition of the same stimulus (word or digit) 8 times. No-adaptation blocks consisted in the presentation of 8 different stimuli.

Experimental timeline

Experimental timeline was identical to Perrachione et al. (2016). The task was presented using Psychopy (Peirce et al., 2019). In each block of the adaptation tasks, stimuli (word or digit) remained on the screen for 700 ms, with a 500 ms inter-stimulus interval (for a total block duration of 9.6 seconds). Ten adaptation blocks and 10 no-adaptation blocks were presented along with 10 blocks of visual fixation (duration = 9.6 seconds) in each run. Block presentation was pseudo-randomized such that 2 blocks of the same type could not follow each other.

To ensure that tasks did not differ in levels of attentional engagement, 10 target stimuli (a picture of rocket) randomly appeared in each run (outside of blocks). Participants were asked to press a button every time this target appeared. On average, children detected 90% of targets ($SD = 18$) in the digit adaptation task and 89% of targets ($SD = 15$) in the word adaptation task. There was no difference in target detection rate between tasks (Wilcoxon rank sum test: $p = .73$), indicating that children paid equal attention to the stimuli in both tasks. Spearman rank correlations indicated that target detection rates were not correlated with education, income, home numeracy practices, or child arithmetic fluency in any of the tasks (digit adaptation: all ρ s $< .16$, all p s $> .14$; word adaptation: all ρ s $< .19$, all p s $> .11$).

fMRI data preprocessing

Details about fMRI data acquisition are given in Supplemental information. Functional images were corrected for slice acquisition delays and spatially realigned to the first image of the first run to correct for head movements. Realigned images were smoothed with a Gaussian filter ($4 \times 4 \times 7$ mm full-

width at half maximum). Following Romeo et al. (2018), ArtRepair (<https://cibsr.stanford.edu/tools/human-brain-project/artrepair-software.html>) was used to identify functional volumes with a global mean intensity greater than 3 standard deviations from the average of the run or a volume-to-volume motion greater than 2 mm. These outlier volumes were substituted by the interpolation of the 2 nearest non-repaired volumes. Participants with outliers in more than 20% of volumes were excluded from the analyses. After outlier exclusion, the movement range was on average 0.02 (SD = 0.07), 0.14 (SD = 0.30), and 0.18 (SD = 0.60) mm in the x, y, and z direction, with 0.24 (SD = 0.82), 0.32 (SD = 1.10), 0.40 (SD = 0.37) degrees of roll, pitch, and yaw. Finally, functional images were normalized into the standard Montreal Neurological Institute (MNI) space (normalized voxel size, $2 \times 2 \times 3.5$ mm³).

fMRI data analysis

Statistical analysis of fMRI data was performed according to the GLM. Brain activity associated with periods of adaptation and no-adaptation was modeled as epochs with onsets time-locked to the beginning of each block and a duration of 9.6 sec. All epochs were convolved with a canonical hemodynamic response function. The time series data were high-pass filtered (1/128Hz), and serial correlations were corrected using an auto-regressive AR(1) model.

For each subject and task, the neural adaptation effect was measured across the whole brain by subtracting activity associated with adaptation blocks from activity associated with no-adaptation blocks. Relations between home numeracy practices, neural adaptation effects, and arithmetic fluency were assessed using the mass-univariate MEPM framework implemented in the M3 toolbox (Wager et al., 2008). MEPM is a form of structural equation modeling that allows for the voxelwise mapping of multiple brain regions that satisfy the formal criteria for mediators in a standard three-variable path model involving a predictor, a brain response, and an outcome. For each voxel, MEPM estimates 3 paths: (1) Path a (i.e., the relation between the predictor and the brain response), (2) Path b (i.e., the relation between the brain response and the outcome, controlling for the predictor), and (3) Path a*b (i.e., the formal test of mediation, indicating whether the relation between the predictor and the outcome, or Path c, is significantly reduced by including the brain response in the model). Here, Path a

reflects whether home numeracy practices relate to neural adaptation. Path b reflects whether neural adaptation predicts arithmetic fluency (controlling for home numeracy practices). Path $a*b$ is the formal test of mediation, reflecting whether these effects are jointly strong enough to mediate the relation between home numeracy practices and arithmetic fluency (see **Fig. 1a**).

Bias-corrected bootstrap tests with 1,000 iterations were performed to estimate statistical significance at each voxel. Bootstrapping was used as formal test of mediation because this method is more powerful to assess mediation than the Sobel test for small to moderate sample sizes (Shrout & Bolger, 2002). One-sided voxelwise maps of p values for the Paths a, b, and $a*b$ were corrected for multiple comparisons using AFNI 3dClustSim, version AFNI_20.3.01 (Oct 19 2020; version update accounts for software bugs identified by Eklund, Nichols, & Knutsson, 2016). Smoothness estimates entered into 3dClustSim were spatial autocorrelation function (acf) parameters averaged from each individual's first level model residuals as calculated by 3dFWHMx using a whole brain mask (acf parameters: 0.452647 4.07555 16.563). Given the a priori focus on the study on the IPS, clusters were considered significant at a Family-Wise Error- (FWE) corrected threshold of $p < 0.05$, either across the whole-brain or within an anatomical mask of the IPS (i.e., small volume correction) defined using the Anatomy Toolbox v2.2 (Eickhoff et al., 2005). The IPS mask consisted in voxels with at least 50% probability of belonging to one of the IPS subdivisions (hIP1, hIP2, and hIP3) as defined in the Anatomy Toolbox. The same mask was used for similar small volume corrections in our previous studies (e.g. Schwartz et al., 2018). FWE-corrected clusters are reported using an uncorrected voxel-wise threshold of $p=.0025$ (NN=1). Note that because Path a and Path b effects are conditionally independent, the probability of voxels from each path being significant by chance is therefore $p = 0.00000625$ or lower. Because our hypotheses were directional (i.e., we were only interested in lesser activity in adaptation than no-adaptation blocks, as well as increases in either arithmetic fluency or neural adaptation effects as a function of home numeracy practices), p values for behavioral and fMRI results are one-sided. Accordingly, only 95% lower bound confidence intervals (95% CI Lower) are reported.

Results

Behavioral results

We first investigated the relations between SES, home numeracy practices, and arithmetic fluency across the entire behavioral sample ($n=66$). As can be seen on **Fig. 2** and **Fig. 3**, there was large individual variability in the reported frequencies of home numeracy practices. Between parents, average responses on the rating scale ranged from 0.65 to 2.88 for informal practices ($M = 1.47$, $SD = 0.50$), from 0.143 to 4.64 for basic formal practices ($M = 1.68$, $SD = 0.85$), and from 0 to 3.80 for advanced formal practices ($M = 0.95$, $SD = 0.76$). After adjusting for differences in parental income, relatively higher education was not associated with more frequent informal practices (partial $r(64) = -.14$, $p = .865$, 95% CI Lower = $-.33$). There was also no positive relation between education and basic formal practices (adjusting for parental income and advanced formal practices, partial $r(64) = -.32$, $p = .996$, 95% CI Lower = $-.49$). However, relatively higher education was associated with more frequent advanced formal practices (adjusting for parental income and basic formal practices, partial $r(64) = .23$, $p = .034$, 95% CI Lower = $.02$) (**Fig. 4a**). Finally, there was no positive relation between parental income and any numeracy practices after adjusting for parental education (all r s $< .13$, all p s $> .163$). Therefore, more educated (but not necessarily wealthier) parents engaged in more frequent advanced formal numeracy practices with their children. Parental education was thus included as covariate in all further analyses of home numeracy practices.

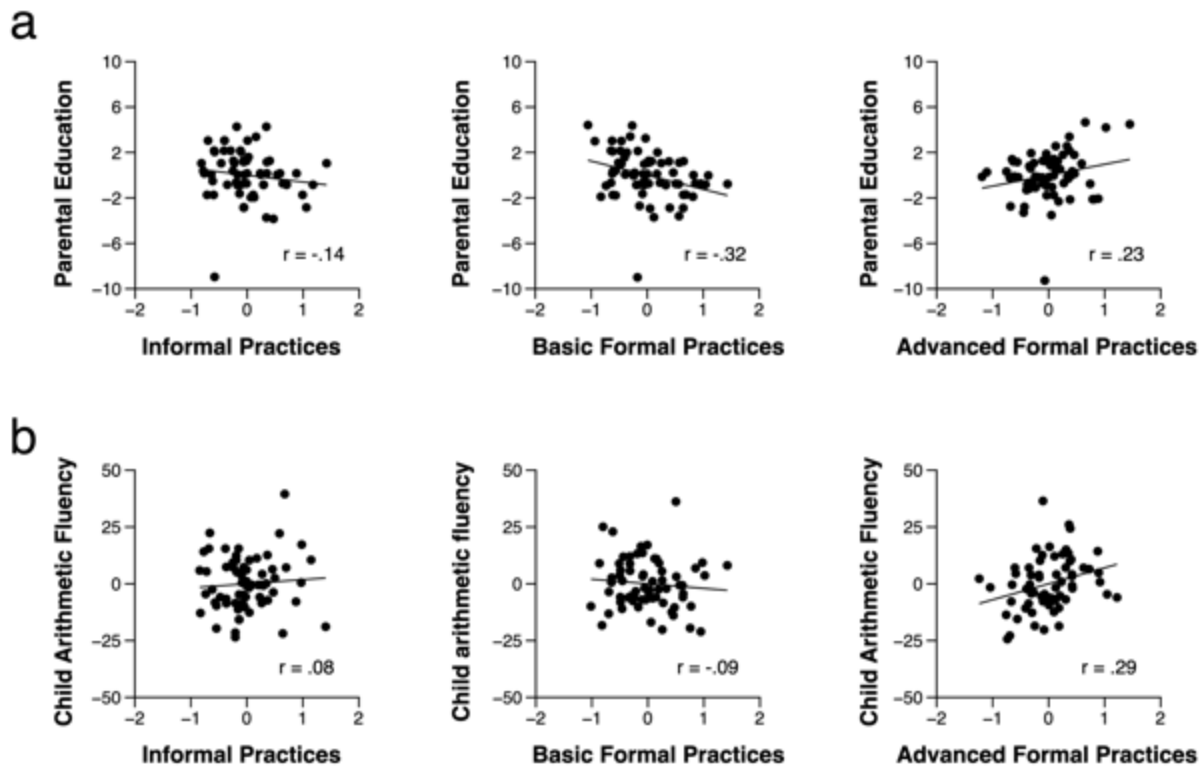


Figure 4. Relations between SES, home numeracy practices and children's mathematical skills ($n=66$). (a) Scatterplots of parental education as a function of informal numeracy practices, basic formal numeracy practices (adjusted for advanced formal numeracy practices), and advanced formal numeracy practices (adjusted for basic formal numeracy practices). Correlations are also adjusted for parental income. (b) Scatterplots of child arithmetic fluency as a function of informal numeracy practices, basic formal numeracy practices (adjusted for advanced formal numeracy practices), and advanced formal numeracy practices (adjusted for basic formal numeracy practices). Correlations are also adjusted for parental education. All variables are mean-centered.

Child arithmetic fluency was positively correlated with advanced formal practices (adjusting for parental education and basic formal practices, partial $r(64) = .29$, $p = .008$, 95% CI Lower = .09) (**Fig. 4b**). However, there was no positive correlation between child arithmetic fluency and basic formal practices (adjusting for parental education and advanced formal practices, partial $r(64) = -.09$, $p = .775$, 95% CI Lower = $-.29$) or between child arithmetic fluency and informal practices (adjusting for parental education, partial $r(64) = .08$, $p = .274$, 95% CI Lower = $-.13$). Thus, higher child arithmetic fluency was associated with more frequent home numeracy practices, but only when these

practices were formal and relatively advanced. The MEPM analyses below thus focus on these advanced formal practices.

MEPM results: Digit adaptation

We used the framework of MEPM to evaluate the relations between advanced formal numeracy practices, neural adaptation to digits, and child arithmetic fluency (controlling for education and basic formal numeracy practices). The results of these analyses are shown in **Fig. 5**. First, consistent with Path a in **Fig. 1a**, we found a significant positive relation between the frequency of advanced formal home numeracy practices and digit adaptation in a cluster of the left IPS ($x = -34$, $y = -60$, $z = 55$, cluster size = 0.1 cc, $-\log_{10}(\text{max p-value}) = 2.75$, $r(48) = .35$) (**Fig. 5a**, left). This indicates greater neural adaptation to digits in children who were exposed to more frequent numeracy practices. Second, controlling for advanced formal practices, there was a significant positive relation between digit adaptation and child arithmetic fluency in several frontal, parietal and occipital regions, including the right Middle Occipital Gyrus ($x = 32$, $y = -84$, $z = 6$, cluster size = 9.2 cc, $-\log_{10}(\text{max p-value}) = 6.84$, $r(48) = .59$), left Superior Frontal Gyrus ($x = -18$, $y = 50$, $z = 17$, cluster size = 4.9 cc, $-\log_{10}(\text{max p-value}) = 6.53$, $r(48) = .54$), right Middle Frontal Gyrus ($x = 42$, $y = 26$, $z = 17$, cluster size = 1.9 cc, $-\log_{10}(\text{max p-value}) = 3.77$, $r(48) = .45$), and left IPS ($x = -34$, $y = -60$, $z = 55$, cluster size = 0.3 cc, $-\log_{10}(\text{max p-value}) = 4.51$, $r(48) = .44$). This showed that children who exhibited greater neural adaptation in these regions also showed higher level of arithmetic fluency (**Fig. 5a**, right). Finally, the formal test of mediation identified one cluster in the left IPS ($x = -34$, $y = -60$, $z = 55$, cluster size = 0.1 cc, $-\log_{10}(\text{max p-value}) = 3.05$) in which digit adaptation explained the relation between advanced numeracy practices and child arithmetic fluency (**Fig. 5b**). This suggests that the neural processing of symbolic numerical information in the IPS mediates the relation between home numeracy practices and children's mathematical skills (Path a*b). The partially standardized effect size of this indirect effect (i.e., ratio of the indirect effect to the standard deviation of the outcome; Hayes, 2018) in the left IPS cluster was .35. Therefore, arithmetic fluency increased by .35 standard deviations for every one-unit increase in frequency of reported advanced formal practices indirectly via digit adaptation in the IPS. The relation between advanced formal practices and child arithmetic

fluency in the fMRI sample (total effect, or Path c: partial $r(48) = .30, p = .017$, 95% CI Lower = .07, **Fig. 5c**, left) was no longer significant after accounting for digit adaptation in the left IPS cluster identified in the formal test of mediation (direct effect, or Path c': partial $r(48) = .15, p = .146$, 95% CI Lower = -.09, **Fig. 5c**, right).

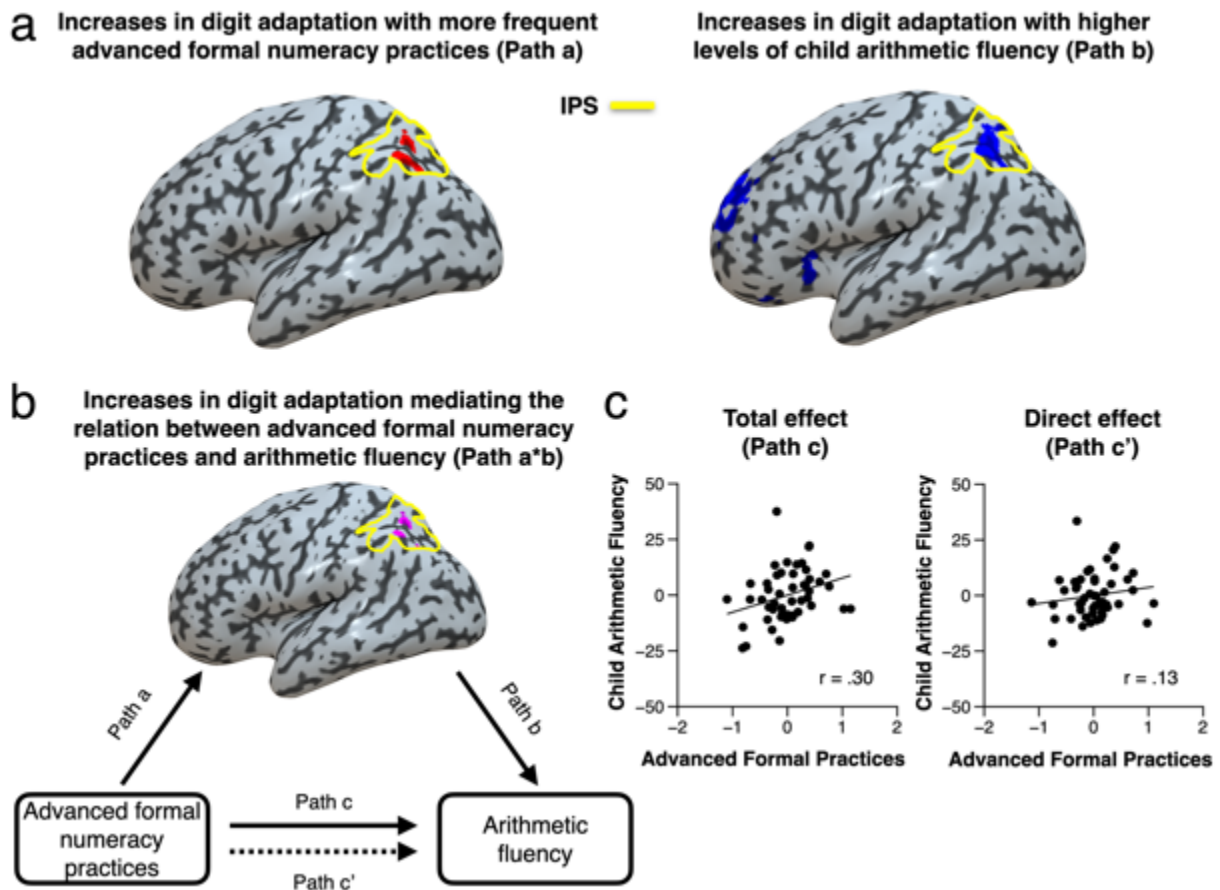


Figure 5. MEPM analysis of the digit adaptation task ($n=50$). (a) Lateral views of the left hemisphere showing voxels in which digit adaptation increased with advanced formal numeracy practices (Path a, left) and child arithmetic fluency (adjusted for advanced formal numeracy practices, Path b, right). (b) Mediation diagram showing voxels in which digit adaptation explained the relation between advanced formal numeracy practices and child arithmetic fluency (Path $a*b$). (c) Scatterplot of child arithmetic fluency as a function of advanced formal numeracy practices (adjusted for basic formal numeracy practices) in the fMRI sample (total effect or Path c, left) and scatterplot of child arithmetic fluency as a function of advanced formal numeracy practices (adjusted for basic formal numeracy practices) when digit adaptation in the left IPS was included in the model (direct effect or Path c', right). All

variables are mean-centered and all analyses were adjusted for parental education and basic formal numeracy practices.

It is important, however, to acknowledge that our design is cross-sectional. Therefore, advanced formal home numeracy practices may be related to child arithmetic fluency and digit adaptation in the IPS (1) because practices impact arithmetic fluency and brain activity (as hypothesized in the model in **Fig. 1a**), or (2) because parents engage in more frequent advanced numeracy practices as they perceive that their child is skilled in mathematics (which may be reflected in both greater arithmetic fluency and enhanced brain sensitivity to numerical information). To disentangle between these possibilities, we asked parents to indicate their perception of their child's mathematical skills. As expected, this parental estimate was positively correlated with child arithmetic fluency ($r(48) = .32, p = .012, 95\% \text{ CI Lower} = .09$). However, this parental perception was neither correlated with advanced home numeracy practices (adjusting for parental education and basic formal practices, partial $r(64) = -.01, p = .528, 95\% \text{ CI Lower} = -.21$), nor with digit adaptation in the IPS (adjusting for parental education, partial $r(48) = .19, p = .099, 95\% \text{ CI Lower} = -.05$). When adjusting for this parental estimate of child's mathematical skill, advanced formal numeracy practices also remained related to child arithmetic fluency (adjusting for parental education and basic formal practices, partial $r(48) = .33, p = .01, 95\% \text{ CI Lower} = .01$) (**Fig. S2a**, left) and digit adaptation in the IPS (adjusting for parental education and basic formal practices, partial $r(48) = .37, p = .004, 95\% \text{ CI Lower} = .14$) (**Fig. S2a**, right). Therefore, even though parents were aware of their child's mathematical competence, this awareness did not appear to drive an increase in the frequency of numeracy practices. This is consistent with the causal assumptions of the model in **Fig. 1a**.

It has also been argued that associations between home practices and children's skills may not uniquely reflect environmental influences but may also stem (at least in part) from genetic predispositions to high academic achievement that parents may pass on to children (these parents are likely to maintain higher quality learning environments than others; Hart et al., 2021). Following a recent proposal by Hart et al. (2021), we attempted to control for this confound by measuring parental arithmetic fluency as a genetic proxy for predisposition to mathematical achievement. There was no

significant positive correlation between parent and children arithmetic fluency ($r(64) = .01, p = .477$, 95% CI Lower = $-.23$). The relation between advanced formal numeracy practices and child arithmetic fluency also remained significant when controlled for parent arithmetic fluency (adjusting for parental education and basic formal practices, partial $r(64) = .32, p = .004$, 95% CI Lower = $.12$). Overall, then, the association between advanced formal home numeracy practices and child arithmetic fluency may not be easily explained by the idea that parents have a predisposition to high mathematical achievement.

MEPM results: Word adaptation

Because digits were systematically presented at the center of the screen in the digit adaptation task, it is possible that the relations found above reflect general perceptual adaptation effects to any kind of symbolic stimuli. To test for this possibility, we ran another MEPM analysis in which we used neural adaptation to words as brain mediator of the relation between advanced formal numeracy practices and child arithmetic fluency. Indeed, much like in the digit adaptation task, the word adaptation task involved symbols (i.e., words) that were repeatedly presented at the center of the screen. Critically, however, these symbols did not carry any numerical information. We did not find any region in which word adaptation was significantly related to numeracy practices (Path a) or child arithmetic fluency (Path b) (see unthresholded maps of p values on **Fig. 6**). We also did not find any brain region in which word adaptation affected the relation between numeracy practices and child arithmetic fluency (Path a*b). Therefore, the relation between advanced formal numeracy practices and child arithmetic fluency was specifically explained by symbolic numerical information in the IPS.

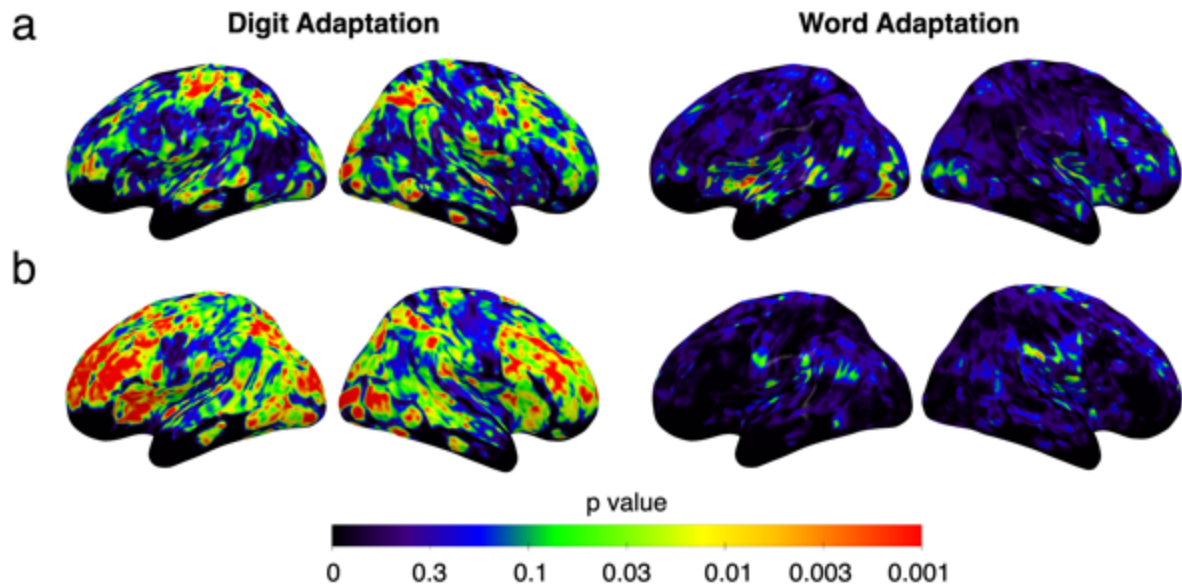


Figure 6. Unthresholded maps of p values showing the relations between digit and word adaptation, home numeracy practices and child arithmetic fluency identified in the MEPM analyses across the whole brain ($n=50$ for digit adaptation, $n=44$ for word adaptation). (a) Lateral views of the left and right hemispheres showing voxels in which neural adaptation to digits (left) and words (right) increased with advanced formal numeracy practices (Path a). (b) Lateral views of the left and right hemispheres showing voxels in which digit adaptation (left) and word adaptation (right) increased with child arithmetic fluency (adjusting for advanced formal numeracy practices; Path b). All analyses were adjusted for parental education.

Supplemental analyses

Finally, we performed four sets of supplemental analyses to rule out alternative explanations of our findings. First, the MEPM analyses above show that word adaptation did not account for the relation between advanced formal numeracy practices and child arithmetic fluency (see above). However, this lack of effect might result from a general lack of sensitivity to detect adaptation to words across our sample. To test for this possibility, we examined the significance of word adaptation effects (i.e., difference between no-adaptation and adaptation blocks) across all participants ($n=44$). Adaptation to words was significant in the left Inferior Frontal Gyrus and left Inferior Temporal Gyrus (**Fig. S3a** and **Table S1**), which are regions of the left language-related network that were also found

in Perrachione et al. (2016) (see Fig. 3b in Perrachione et al., 2016). Thus, findings from Perrachione et al. regarding overall adaptation to English words were largely replicated using the same task in a different language (i.e., French), demonstrating the reliability of the task.

Second, the MEPM analyses also show that digit adaptation relates to both numeracy practices and arithmetic fluency. However, it remains unclear whether adaptation to digits may be significant *in itself* in the IPS across participants. Averaging across all participants ($n=50$), digit adaptation effects were significant in a network of frontal and occipital brain regions, but not the IPS (**Fig. S3b** and **Table S1**). Because digit adaptation in these regions was neither related to numeracy practices nor arithmetic fluency, these regions might support perceptual or domain-general aspects of digit processing that are not dependent upon skills or environmental stimulations. Interestingly, however, overall adaptation to digits was significant ($x = 32, y = -94, z = -5$, cluster size = 2.3 cc, $-\log_{10}(\text{max } p\text{-value}) = 5.23$, $d = 0.62$) when considering the participants with the highest levels of arithmetic fluency ($n = 23$ after median split of the sample as a function of arithmetic fluency) (**Fig. S3c**). This was not the case for participants with the lowest levels of fluency ($d = -0.36$, $n = 23$). Therefore, the presence of significant adaptation to digits in the IPS might index a relatively high level of arithmetic fluency, which points to a link between automaticity in symbolic number processing in the IPS and symbolic math skills

Third, as is standard in mediation models, the relation between the mediator (i.e., brain activity) and the outcome (i.e., child arithmetic fluency) in our MEPM analysis of digit adaptation was controlled for the predictor (i.e., home numeracy practices). However, the same variable cannot be both the outcome and a covariate. Thus, the relation between home numeracy practices and brain activity was not adjusted for child arithmetic fluency. This raises the question of whether the relation between advanced formal numeracy practices and digit adaptation in the IPS was entirely driven by child arithmetic fluency. When adjusting for child arithmetic fluency (as well as education and basic formal numeracy practices), advanced formal numeracy practices remained positively related to digit adaptation in the left IPS (partial $r(48) = .24, p = .043$, 95% CI Lower = .01; **Fig. S2a**). Therefore, the relation between home numeracy practices and digit adaptation in the IPS does not appear to be uniquely driven by child arithmetic fluency.

Fourth, because previous studies show that symbolic mathematical skills relate more strongly to symbolic than non-symbolic number processing (De Smedt et al., 2013), the present study focuses on symbolic number processing in the IPS. Nonetheless, non-symbolic numerical skills have also been related to both mathematical skills (Chen & Li, 2014) and home numeracy practices (Elliott & Bachman, 2018), though evidence for these relations are inconsistent and disputed (De Smedt et al., 2013; Mutaş-Yıldız et al., 2020; Wilkey & Ansari, 2020). To investigate whether the effects shown above would also be obtained using non-symbolic numerical stimuli, we also presented participants with an exploratory non-symbolic numerical adaptation task in which dot arrays were repeatedly presented, either with the same numerosity (adaptation blocks) or with a different numerosity (no-adaptation blocks). Stimuli were controlled for a variety of parameters (see Supplemental information and **Fig. S4**). In contrast to digit adaptation, we did not find any relation between adaptation to numerosities and advanced formal numeracy practices anywhere in the brain. However, numerosity adaptation increased with the frequency of basic formal numeracy practices in a network of fronto-parietal regions that included the left IPS (**Fig. S4** and **Table S1**). This suggests that non-symbolic numerical processing may relate to different aspects of the home numeracy environment than symbolic numerical processing. We also found a significant positive relation between arithmetic fluency and numerosity adaptation in the right (rather than the left) IPS, in keeping with studies demonstrating that symbolic and non-symbolic numerical processing rely on different neural mechanisms (Wilkey & Ansari, 2020) (**Fig. S4** and **Table S1**). MEPM analyses, however, showed that numerosity adaptation did not explain the relation between either basic or advanced formal practices and arithmetic fluency anywhere in the brain. Thus, only symbolic (not non-symbolic) number processing appears to account for the relation between numeracy practices and mathematical skills.

Discussion

Here we set out to explore the relations between home numeracy practices, number-related brain regions, and mathematical skills in 8-year-olds. First, consistent with previous studies (Elliott & Bachman, 2018), we found that children's mathematical skills increased with the frequency of home numeracy practices, but only if those activities were formal and relatively challenging.

Second, we found an association between children's arithmetic skills and digit-related activity in the IPS, a region that is at the core of human mathematical competence (Nieder, 2016). Such a relation has been suggested in the past (e.g., Bugden et al., 2012). However, previous studies have tended to use active tasks in relatively heterogeneous samples (Arsalidou et al., 2018), such that differences in brain activity can be confounded by differences in age and task performance (Church et al., 2010). Here, we demonstrate that this relation can be captured using a passive digit adaptation task in a homogeneous sample of 8-year-olds, thereby measuring how sensitive is the IPS to the passive presentation of symbolic numerical information.

Third, a major novel finding of the present study is that home numeracy practices also relate to digit-related activity in the IPS. This suggests that children benefiting from a higher quality home numeracy environment may have heightened sensitivity to symbolic magnitudes in the IPS. Our results are noteworthy because the only two prior studies that have investigated the relation between the neural bases of mathematical skills and children's home environment (using family SES as a proxy) have found such a relation in language-related regions (Demir et al., 2015; Demir-Lira et al., 2016). Therefore, our study provides the first evidence that disparities in children's home numeracy environment may relate to functional differences in how IPS mechanisms process symbolic magnitudes.

Fourth, we found that the relation between advanced formal numeracy practices and children's arithmetic skills was influenced by the neural response to digits in the left IPS. This is consistent with a model positing that core numerical processing mechanisms in the IPS mediate the relation between home numeracy environment and children's mathematical skills (**Fig. 1a**). Critically, the relation between advanced formal numeracy practices and children's arithmetic skills was not influenced by neural adaptation to words, demonstrating that this effect was not explained by a domain-general processing of symbolic information. That relation was also not influenced by neural adaptation to non-symbolic numerosities, in line with a growing body of studies showing that symbolic number processing is a more consistent predictor of mathematical skills than non-symbolic processing in children (De Smedt et al., 2013).

Finally, we highlight two main limitations of this work. A first limitation is that our design is cross-sectional and therefore cannot speak to the causal aspects of the model in **Fig. 1a**. That is, although the relations observed are consistent with this model, other models may be compatible with our results. Several of our analyses attempt to undermine alternative models. However, the choice of the most plausible mediation model ultimately rests on prior findings, logic, and theoretical considerations (Fiedler et al., 2018). Specifically, the model in **Fig. 1a** is derived from similar research on how the home literacy environment may influence literacy skills. It also rests on the general theoretical framework that disparities in environmental experiences affect brain development, which in turn influence behavioral traits (Farah, 2017). Finally, it should be noted that, although parents filled out our questionnaire at the time of scanning, it was retrospective in that it asked parents to reflect on practices that they engaged in the past. Furthermore, because the HNE is relatively stable over the years (Tamis-LeMonda et al., 2019), our measure might have captured the quality of the home numeracy environment not only at the time of the study but also when children were younger. Thus, we speculate that there may be temporal precedence of home numeracy practices over IPS activity and mathematical skills measured at age 8. Nonetheless, interventional studies are needed to substantiate this claim and our findings should be taken as a first critical test for the plausibility of the model in **Fig. 1a**.

A second limitation concerns our sample size. To our knowledge, our study involves the largest sample of children completing a passive number processing task in an MRI scanner (Arsalidou et al., 2018). Our sample is also in line with previous studies investigating relations between home literacy environment and language-related brain regions (Merz et al., 2020; Romeo et al., 2018). Yet, recent reports have raised concerns about the replicability of brain-behavior correlations in samples sizes that are typical in neuroimaging studies (Marek et al., 2020), though replicability depends on experimental considerations (Nee, 2019). Given the complexity of acquiring task-based neuroimaging data in children (Raschle et al., 2012), we believe that an important avenue for addressing replicability concerns in developmental cognitive neuroscience is data sharing. Here we have made available all individual neuroimaging data, which we hope will encourage meta-analyses, re-analyses, and comparisons with other datasets.

In sum, our findings show that the neural processing of symbolic numerical magnitudes may be affected by experiences beyond the classroom. Our results are consistent with a mechanistic model of how home numeracy practices might affect children's mathematical skills, inspired by similar models of the home literacy environment and children's reading skills (Merz et al., 2020; Romeo et al., 2018). Therefore, our study provides broad support for interventions that aim to foster the development of the numerical brain by improving home numeracy practices (Gibson et al., 2020).

Open Practices

The task, electronic version of the questionnaire (in French) and all behavioral data are publicly available via Zenodo at <http://doi.org/10.5281/zenodo.4965716>. The IPS mask and the whole-brain unthresholded p-maps corresponding for Fig. 5 and Fig. 6 are available via NeuroVault at <https://identifiers.org/neurovault.collection:9250>. The Matlab scripts used to analyze fMRI data are available via GitHub at <https://github.com/BBL-lab/BBL-batch-system>. The M3 toolbox is also available via GitHub at <https://github.com/canlab/MediationToolbox>. Finally, individual MRI data are available via Zenodo at <http://doi.org/10.5281/zenodo.4965716>.

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Author Contributions

C. Girard and J. Prado conceived and designed the study. C. Girard programmed the experiment. C. Girard, T. Bastelica, J. Léone, J. Epinat-Duclos, and L. Longo performed the experiment. C. Girard

analyzed the data under the supervision of J. Prado. C. Girard and J. Prado wrote and revised the manuscript. All authors read and approved the final manuscript for submission.

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