# Impact of deafness on the lateralized brain responses to letters and digits: a fast periodic visual stimulation exploratory study in deaf and hearing children.

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https://osf.io/rbp4k/?view_only=0fb02282907c4ecb8862e246e627e60d .
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The Ethics Review Panel of the University of Luxembourg has approved this study that conforms to the Declaration of Helsinki: The brain network of numbers in deaf children (ERP 21-054 DEAF_FPVS).
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**Highlights**

- The neural specialization for letters vs digits is explored using Fast Periodic Visual Stimulation with EEG recordings to assess differences between deaf and hearing children;
- The topography of neural responses to letters is right-lateralized in deaf children, and bilateral with left dominance in hearing children;
- This result suggests that the lack of phonology and/or use of sign language in deaf children induces brain reorganization for visual letters' representation;
- Neural responses for Arabic digits are similar in both groups, indicating that numbers are possibly represented precisely with finger configurations.

**Abstract**

Numbers and letters are culturally created symbols that acquire meaning through extensive training, significantly influencing brain function. The distinct hemispheric specialization of cortical regions for these categories has been hypothesized to relate to the co-activated brain networks: the left language regions for letters, and the right intra-parietal sulcus for numbers. However, the potential influence of deafness and sign language on hemispheric specialization for letters and numbers remains unclear. The present study aims to explore this issue by using a FPVS-EEG approach with an oddball paradigm. Deaf and hearing children aged 8 to 13 were exposed to rapid streams of visual stimuli (6Hz), with a deviant category introduced periodically (every 5 items; at 1.2Hz) and eliciting a neural response in the frequency domain if discriminated from the base category. Here, digits served as base stimuli and letters as oddball stimuli, and vice-versa. Our results suggest disparities in hemispheric lateralization for letters between deaf and hearing children, while neural responses to digits did not significantly vary between the two groups. Both groups exhibited right-lateralized responses to digits, which were stronger compared to responses to letters. Importantly, in deaf children, the neural response to letters was stronger in the right hemisphere, whereas hearing children displayed a bilateral response with a non-significant trend towards left lateralization. The important implications of these exploratory results, suggesting an early impact of sensory deprivation and/or sign language on the organization of the brain, are discussed.

**Keywords**

Deafness, sign language, frequency-tagging EEG, reading, letters, digits, children

## Introduction

Literacy and numeracy are two culturally acquired abilities which differ in surface features (i.e., letters and words vs. digits and arithmetic symbols), but share some structural properties and overlapping processes (Dotan & Friedman, 2018). Primary units of symbolic representations (e.g., letters and digits) are used to build more elaborate representations: letters and words lead to lexical-semantic access, while Arabic digits, that can be combined in multi-digit numbers, lead to the representation and manipulation of increasingly larger quantities. Both letters and digits are arbitrary shapes that are distinguished only via instruction, letters being related to phonological representations and digits to numerosity representations. Here we explore how deafness and its related sign language experience may impact this learning process in a small sample of children.

In hearing, the development of literacy and numeracy expertise is followed by a major neural tuning of the human brain. It is indeed well established that the processing of letters and words selectively recruits the so-called Visual Word Form Area (i.e., VWFA; McCandliss, Cohen, & Dehaene, 2003; Dehaene & Cohen, 2011; Schlaggar & McCandliss, 2007) in the left ventro-occipito temporal cortex (vOTC). The processing of numbers, on the other hand, preferentially activates regions of the right ventral visual stream (Allison, McCarthy, Nobre, Puce, & Belger, 1994; Park, Hebrank, Polk, & Park, 2012; Roux, Lubrano, Lauwers-Cances, Giussani, & Demonet, 2008; Shum, Hermes, Foster, Dastjerdi, Rangarajan, Winawer, Miller, & Parvizi, 2013). This hemispheric double dissociation quickly manifests as children learn to read (Lochy, Van Reybroeck, & Rossion, 2016; Lochy & Schiltz, 2019), and is in line with both the Phonological Mapping Hypothesis (Maurer & McCandliss, 2007) and the Triple Code Model (Dehaene, 1992) of numerical processing. The Phonological Mapping hypothesis posits that the left-lateralization of reading is driven by automatized grapheme-phoneme mapping (i.e., rapid connections between visual and phonological brain regions). The Triple Code Model, on the other hand, assumes that the right intra-parietal sulcus (rIPS) plays a pivotal role in the processing of numerical magnitude (see Dehaene et al., 2003 for a review). The establishment of lateralized representations for letters and digits in the VOTC would therefore reflect the spatial associations with the related co-activated networks, respectively in the left hemisphere (LH) for phonological representations and in the right hemisphere (RH) for numerical representations. Furthermore, this was shown to occur as soon as these visual shapes are learnt, accordingly in 6-year-old children (Lochy & Schiltz, 2019), although previous studies had suggested that this neural tuning occurred only in older children (i.e., 10 years old, see Park, Chiang, brannon, & Woldorff, 2014; Park, van den Berg, Chiang, Woldorff, & Brannon, 2017).

For deaf people, who are unable to access auditory information directly and often use sign language to communicate, learning to read and to calculate are difficult tasks. While several studies have reported an activation of the left vOTC in congenitally deaf participants while reading (Aparicio, Gounot, demont, & Metz-Lutz, 2007; Emmorey, Weisberg, McCullough, & Petrich, 2013), it has recently been demonstrated that the brain reading network of deaf individuals shows its specificities. A greater activation in the right homolog of the VWFA was first highlighted in adults (Emmorey & Lee, 2021; Wang et al., 2015) and related to orthographic tuning in skilled deaf readers (Glezer et al., 2018). Secondly, a distinctive VWFA's connection to the language network (Emmorey & Lee, 2021; Wang et al., 2015) appears in deaf individuals: while the VWFA in hearing individuals has positive intrinsic functional connectivity with speech-related regions, it appears to be less connected to language aural representations in deaf individuals (Emmorey & Lee, 2021; Wang, Caramazza, Peelen, Han, & Bi, 2015). A greater activation of the brain areas related to phonological processes was also demonstrated (Aparicio et al., 2007; Emmorey et al., 2013; Li, Peng, Liu, Booth, & Ding, 2014), reflecting the extra cognitive effort phonology processing requires in deaf people. Indeed, no automatic access to phonology seems to occur in deaf individuals, as revealed by a lack of the pseudohomophone effect in deaf adults using a transparent language (Costello, Caffarra, Fariña, Dunabeitia, & Carreiras, 2021). Again, the reading network was shown to be left-lateralized in hearing but right-lateralized in deaf individuals (Emmorey, Midgley, Kohen, Sehyr, & Holcomb, 2017). Finally, it has been demonstrated that deaf people activate a broader network than hearing individuals when processing printed and fingerspelled letters (Dufour, Brochard, Després, Scheiber & Robert, 2004).

Cerebral studies examining the brain network of numerical processing in deaf individuals are, in contrast, relatively scarce and lead to inconsistent conclusions. While some studies suggest that deaf signers may more strongly recruit the magnitude manipulation network when performing numerical order processing (Andin, Fransson, Rönnberg, & Rudner, 2018) or simple arithmetic (Andin, Fransson, Dahlström, Rönnberg, & Rudner, 2019), other studies did not find any brain difference between deaf and hearing individuals (for arithmetic, see Andin, Elwér, & Mäki-Torkko, 2023; Berteletti, Kimbley, Sullivan, Quandt, & Miyakoshi, 2022). For instance, deaf and hearing individuals activate the same number networks while learning the numerals of a new sign language (Masataka, Ohnishi, Imabayashi, Hirakata, & Matsuda, 2006). Nevertheless, the processing of these finger number configurations seems to be more salient in deaf signers as compared to hearing non-signers (Buyle, Lochy, Vencato, & Crollen, 2023). To our knowledge, no hemispheric lateralization difference between deaf and hearing individuals was ever reported regarding numerical processing.

In this paper, we report the results of an exploratory study, where the main objective was to examine whether deafness could impact the hemispheric specialization for letter and number processing early in development. To do so, the same FPVS (Fast Periodic Visual Stimulation) oddball EEG experiment than the one used in Lochy and Schiltz (2019) was presented to congenitally deaf and hearing children (from 8 to 13 years old). This approach relies on frequency-tagging, i.e., the observation that the periodic presentation of a stimulus generates an evoked response that has the exact same periodic time course (Regan, 1968). The oddball design used here consists in modulating a specific stimulus feature (i.e., the oddball, or the deviant) at fixed intervals within a rapid stream of standard (or base) stimuli (Norcia, Appelbaum, Ales, Cottereau, & Rossion, 2015). In the present study, two different conditions were used: the digits-LETTERS (dig-LETT) vs the letters-DIGITS (lett-DIG)'s conditions. In the first dig-LETT condition, digits were presented as base stimuli at a fast rate (6 Hz), and LETTERS were periodically inserted in the stream as deviant stimuli (e.g., 1 every 5, thus at 1.2 Hz). In the second lett-DIG condition, letters were presented as base stimuli and DIGITS were periodically inserted in the stream. If the deviants (letters in the first condition and digits in the second condition) are discriminated from the base stimuli, a measurable neural response should occur at the frequency of stimulation of this category of stimuli (i.e., at 1.2 Hz and harmonics). Moreover, if deafness and the use of sign language does not influence the hemispheric brain specialization of letters and digits processing, then deaf and hearing children should both present a left-lateralized response for letters and a right-lateralized response for digits. In contrast, if deafness and related sign language experience shapes the classic letter-digit hemispheric specialization, then deaf children should display different response topographies than the hearing children. Given the above-reviewed literature, deafness may particularly impact the hemispheric specialization of letters' processing. As this study is the first comparing deaf and hearing children with the current paradigm, a second objective was also to provide essential information for conducting future studies including a priori power and sample size analyses.

## Material and methods

All stimuli, results, raw EEG data files and scripts of the analyses are available at https://osf.io/rbp4k/?view_only=0fb02282907c4ecb8862e246e627e60d .

1. Participants

The sample was constituted of 24 participants, 12 deaf children (boys= 7; mean age = 10.92 years, range = 8 – 13 years) and 12 hearing children (6 females, mean age = 10.42 years, range = 8 – 12 years), that did not differ in terms of age, $F(1, 22) = .849$, $p = .405$. The parents gave their written informed consent to a study that conforms to the Declaration of Helsinki and was approved by the Ethics Panel Committee of the University of Luxembourg. To exclude the possibility of a cognitive disorder, all participants had to perform a short version of the Raven Progressive Matrices, except for one child (Raven, 1989). The two groups did not differ in estimated non-verbal IQ, $t(21) = - 1.732$, $p = .1$.

The deaf participants included 11 children that had hearing loss since birth and 1 child that had slight hearing loss since birth and completely lost her hearing ability at the age of 8 (at the time of testing, the child was 12 years old). Five children had cochlear implants, the others classic hearing aids. All children had hearing parents, only one child had a cousin with profound hearing loss. No other disabilities were present in the children. At the time of testing, the deaf children were enrolled at the Centre de Logopédie (this Centre is the unique schooling system in the country for deaf children learning sign language). The whole sample of children that could be included participated in this study (inclusion criteria: right-handers, profound deafness; exclusion criteria: attention disorder, intellectual disability).

2. Stimuli and tasks

2.1. Behavioral tasks

*Naming tasks*

Children were asked to determine as quickly and accurately as possible the name of the number or letter presented in written code and displayed at the center of a computer screen using E-Prime 2.0 (Psychology Software Tools, USA). The 26 letters of the alphabet were presented once in upper case and once in lower case in font Courier New (100 pixels). For the digits, the 9 Arabic digits from 1 to 9 were used and presented once.

In each trial, a central fixation cross was presented for 500 milliseconds, followed by a brief presentation of the stimulus for 300 milliseconds. This was immediately followed by two successive masks of 100 milliseconds which featured black and white checkerboard patterns covering the entire screen. In the final phase of each trial, a question mark appeared on the screen, prompting the child to provide the answer as quickly and accurately as possible. Once the child gave his/her answer, the experimenter pressed the space bar and encoded the participant's answer on an external keypad. Deaf children could respond with fingerspelled letters/numbers in addition to the oral response.

*Raven task*

A short version of the Standard Progressive Matrices (Raven, 1989) was used to measure logical reasoning by multiple choice problems of increasing complexity. In the present experiment, the short version consisting of 15 items was used (Langener, Kramer, den Bos, & Huizenga, 2022).

2.2. EEG task

A selection of the letters and digits from the experiment of Lochy and Schiltz (2019) were used. They consisted in 5 different Arabic digits (1 to 5) and 5 upper-case letters (I, S, E, H, Z), presented in 3 different fonts for a total of 15 images per category. Letters and digits were matched in overall shape and number of strokes, and different fonts were chosen to maximize variability in each category. Images were 236 x 236 pixels, displayed at a distance of 1m at an 800 x 600 pixels resolution, the average size was 6 x 6 degrees of visual angle. They were presented at the center of the screen.

The EEG experiment consisted of 6 sequences of 40 seconds of stimulation. Each sequence displayed base stimuli of one category at a fast periodic rate of 6Hz (6 images per second, 167ms per image), and every fifth item was an oddball stimulus of the other category (at 1.2Hz). There were two types of sequences, using digits as base stimuli and letters as deviant (dig-LETT; eg., 1523S4879Z…) and the reverse, using letters as base stimuli and digits as deviant (lett-DIG). Each sequence type was repeated 3 times. A pause was made between each of the sequences.

As in previous studies using this approach in children (van de Walle de Ghelcke, 2020; Lochy et al., 2016; Lochy & Schiltz, 2019), each sequence started with a fixation dot at the center of the screen (2-5 sec), 2s of gradual fade-in, 40s of stimulation, and 2s of gradual fade-out. Stimuli were presented by means of sinusoidal contrast modulation with a software running over JavaScript (Java SE Version 8, Oracle Corporation, USA). Because of this sinusoidal contrast modulation, the full visibility of each stimulus was slightly lower than 167ms (e.g., was delayed of approximately 20ms until the contrast was sufficient), but it has been shown not to affect the amplitude or topography of responses in the frequency domain (Dzhelyova et al., 2017) even if it delays responses of 20ms in the time-domain. In order to maintain a constant level of attention, the children were instructed to monitor the fixation dot, which remained visible during the whole stimulation sequence, and to press the space bar whenever the color of the fixation dot briefly changed from blue to red. The color change lasted 200 ms and there were 8 random color changes taking place per sequence. This task was performed with accuracy around 90% and RT around 520ms, with no significant differences (all $F<1$) between Conditions, Groups, and no interaction. For RT, deaf children responded to the lett-DIG sequences ($M$=529ms, $SD$= .024) and the dig-LETT sequences ($M$= 535ms, $SD$=.025) with the same speed as hearing children (lett-DIG: $M$=514ms, $SD$= .024; dig-LETT: $M$=520ms, $SD$=.026). For accuracy, the performance of deaf children for the lett-DIG sequences ($M$=88.89%, $SD$= 2.97) and the dig-LETT sequences ($M$= 88.37%, $SD$=3.43) did not differ from the performance of hearing children (lett-DIG: $M$=96.53%, $SD$= 2.97; dig-LETT: $M$=94.79%, $SD$=3.43).

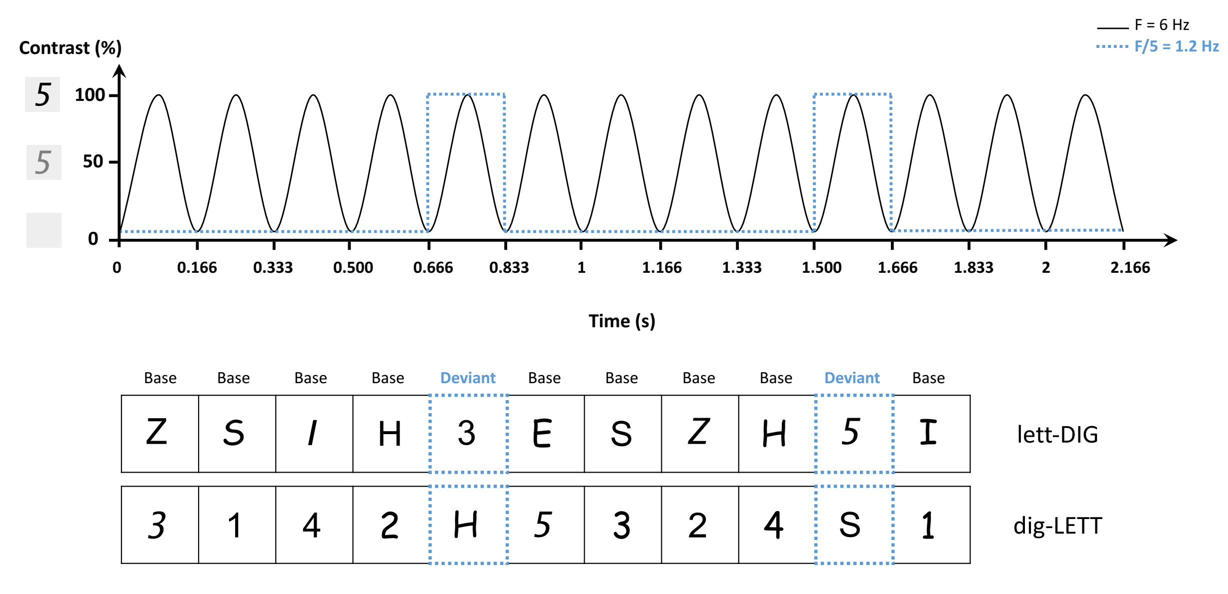



**Figure 1. Experimental paradigm of the EEG experiment**. **Top:** Stimulation over time of six stimuli per second (6 Hz) was presented with a sinusoidal contrast modulation and deviant stimuli were presented at 6 Hz/5 = 1.2 Hz. **Bottom:** Examples of the different numbers and letters used in the EEG experiment. In the lett-DIG condition, the letters (base stimuli) are presented at the base frequency and the digits (deviant stimuli framed with blue dotted lines) are periodically inserted every fifth item. The dig-LETT condition demonstrates how digits are presented as base stimuli (at base frequency), while the letters are presented as deviant stimuli every fifth item.

3. Procedure

Children were tested in two different sessions for behavioral and EEG testing respectively. These sessions included another experiment not reported here, and they occurred on different days. The Raven's Matrices and naming tasks were administered in a counterbalanced order across participants. The total behavioral experiment time was around 40-60 minutes, depending on the playing breaks taken by the children between the tasks.

4. EEG acquisition and preprocessing

The participant was seated 1m in front of a monitor screen in a quiet room of the school with the ceiling lights being turned on. EEG was acquired at 2048 Hz with a Biosemi Active II system (Biosemi, Amsterdam, The Netherlands), with 64 channels at standard 10-20 system locations plus a row of posterior electrodes including PO9, I1, I2, PO10 and two ocular electrodes. The magnitude of the offset of all electrodes, referenced to the common mode sense (CMS), was held below 50 mV. EEG analyses were carried out using Letswave 6 (https://github.com/NOCIONS/letswave6), and Matlab 2016b (The Mathworks).

After FFT band-pass filtering between 0.1 and 100Hz, EEG data were segmented to include 2 seconds before and after each sequence, resulting in 64-second segments (-2 – 62 s). Data files were then resampled to 512Hz to reduce file size and data processing time. Artefact-ridden or noisy channels were replaced using linear interpolation (on average, 3 % of channels). All channels were re-referenced to the common average. EEG recordings were then segmented again from stimulation onset until 39.996 seconds, corresponding to the largest number of complete cycles of 833 ms (48 cycles) at the 1.2 Hz frequency within the 40 seconds of stimulation period. The data were analyzed following the same procedure as in previous studies with similar paradigms (e.g., Lochy, Van Belle, & Rossion, 2015; Lochy et al., 2016) but is nevertheless detailed here.

*Frequency domain analysis.*

Per condition, the three stimulation sequences were averaged in the time domain for each participant, in order to increase SNR. A Fast Fourier Transform (FFT) was applied to the averaged time-window, and normalized amplitude spectra were extracted for all channels. This yielded EEG spectra with a high frequency resolution (1/39.996 s = 0.025Hz), increasing SNR and allowing unambiguous identification of the response at the exact frequencies of interest (i.e., 6Hz for the base stimulation rate and 1.2Hz and harmonics for the other category stimulation). Given that our response of interest falls into a strictly defined frequency bin (related to stimulation frequency), we considered surrounding bins as noise, or baseline. The latter is defined as the 20 surrounding bins of each target bin, excluding the immediately adjacent and the extreme (min and max) bins (Liu-Shuang, Norcia, & Rossion, 2014; Rossion, Prieto, Boremanse, Kuefner, & Van Belle, 2012; Srinivasan, Russell, Edelman, & Tononi, 1999). We then computed three indices. First, the signal-to-noise ratio (SNR) was estimated across the EEG spectrum, by dividing the amplitude at each frequency bin by the average amplitude of 20 surrounding bins (10 on each side; Liu-Shuang et al., 2014) and was used for visualization purposes (response spectrum, Figure 2A and 2B) Second, to quantify the responses of interest in microvolts, the average voltage amplitude of the 20 surrounding bins (i.e., the noise) was subtracted out (Retter et al., 2021;

Retter & Rossion, 2016). This is done because the amplitude at any given frequency is considered as a combination of signal and noise (Heinrich, Mell, & Bach, 2009). Finally, the selection of harmonics was done on the basis of significance threshold ( Z-scores). To assess the significance of the response at the group level, we grand-averaged the amplitude spectrum for each condition and computed the Z-score ($Z(x)= x\text{-}mean(baseline)/SD\ (baseline)$) at each stimulation frequency (base-6Hz, categorical change-1.2Hz) and harmonics (Liu-Shuang et al., 2014; Lochy et al., 2015). Z-scores were considered significant if larger than 3.1 ($p < 0.001$, one-tailed, signal > noise)

In order to quantify the periodic response distributed across several harmonics, the baseline subtracted amplitudes of significant harmonics (excluding the base stimulation frequency) were summed for each participant, task, and condition (Retter et al., 2021; Retter & Rossion, 2016).

**Results**

1. Behavioral naming tasks

Accuracy in the task was computed as correct naming responses. For deaf children, fingerspelled responses were counted as correct even if the spoken response was incorrect, as our aim was to investigate letter/number recognition and knowledge.

Both deaf and hearing children performed at ceiling or near-ceiling in the Arabic digit naming task (no error in the hearing group vs. 2 errors in the deaf group) as well as in the letter naming task (1 error in the hearing group vs. 4 errors in the deaf group). Those data were therefore not analyzed further and confirm that every child was able to recognize the digits and the letters presented in the FPVS EEG design.

2. EEG data

Given the exploratory approach of the study, a thorough check of robustness of the data was performed. We also carefully verified that the assumptions underlying statistical tests were not violated and report effect sizes as well as observed power of all analyses (see Supp Mat1).

The normality of our data was confirmed by the QQ plot distribution of our residuals (Supp. Mat 1), and by the Shapiro-Wilk and Kolmogorov-Smirnov tests, $p_s$ = .1. We therefore decided to pursue the analyses with untransformed data. When the assumption of sphericity was violated, we applied the Greenhouse-Geisser correction which adjusts the degrees of freedom to increase robustness of the test. However, for the ease of comprehension, non-corrected degrees of freedom are reported throughout the result section. We also systematically looked at individual data to check the homogeneity of the variances (see figure 3C).

*Base rate response*

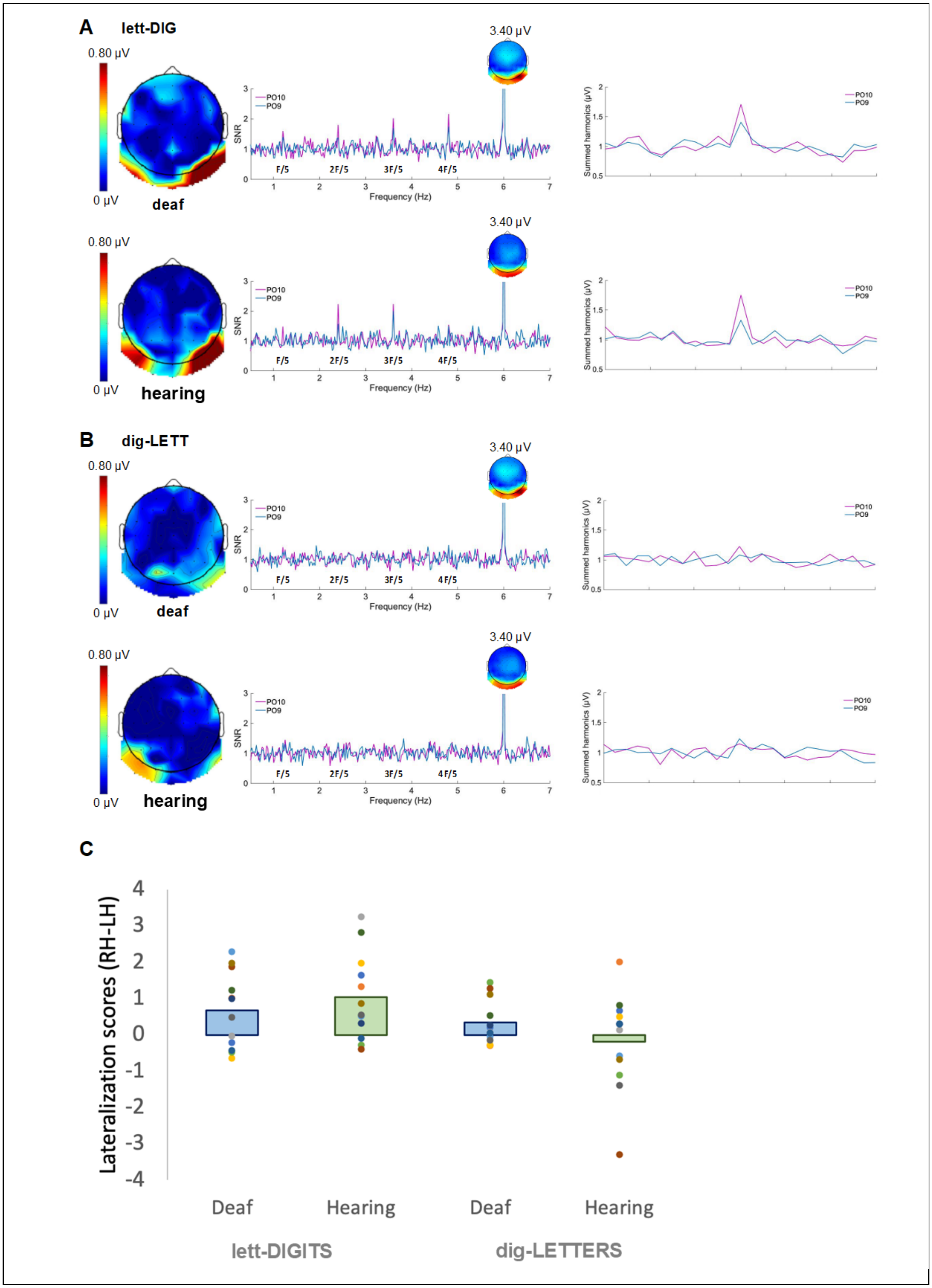
Responses at the base rate were significant up to 6 consecutive harmonics, from 6Hz to 36Hz, on medial occipital electrodes (Figure 2 A, B). For the purpose of replicating analyses of Lochy & Schiltz, (2019), we selected the same medial electrodes (O1 O2 I1 I2 Oz Iz) and we ran an ANOVA with 2 *Conditions* (dig-LETT and lett-DIG) x 2 *Groups* (deaf vs. hearing children) on the sum of harmonics amplitudes. There was no main effect of *Condition* ($F<1$), no effect of *Group* ($F<1$) and no interaction, $F(1,22)=1.180$, $p=.289$. Given that the ranking of the first 6 electrodes gave rise to a slightly more right-lateralized region in the current data by comparison to Lochy & Schiltz (2019), including PO8 but excluding I1, we also analyzed the data with this slightly different ROI, but the results were the same: no main effect of Condition ($F<1$), no effect of Group ($F(1,22)<1$) and no interaction ($F<1$).

*Categorical response*

Across groups and conditions, averaged Z-scores were significant ($z > 3.1$, $p < .001$) for discrimination responses on 6 consecutive harmonics, from 1.2Hz up to 7.2Hz (excluding the base rate at 6Hz). Scalp topographies of the sum of harmonics show large posterior selective response in both left (LH) and right hemispheres (RH) (Figure 2), as in the previous study using this paradigm (Lochy & Schiltz, 2019). For the purpose of replication, we selected *a priori* the same electrodes as in Lochy & Schiltz (2019), i.e., PO9 for the LH and the contralateral PO10 for the RH.

The sum of baseline corrected amplitudes for the six significant harmonics on the electrodes PO9 and PO10 was analyzed with a 2 (*Groups*: deaf vs hearing children) x 2 (*Conditions*: dig-LETT vs lett-DIG) x 2 (*Hemispheres*: left vs right) ANOVA with repeated measures on the last two factors. Results showed a main effect of *Condition*, $F(1, 22) = 16.49$, $p < .001$, $\eta^2_p = .43$, observed power = .97, with responses being stronger when digits were presented as deviant (lett-DIG: $M = 1.26\mu V$, $SE = .21\ \mu V$) than when letters were presented as deviant (dig-LETT: $M = .411\ \mu V$, $SE = .13\ \mu V$). There was also a main effect of *Hemisphere*, $F(1, 22) = 6.13$, $p = .02$, $\eta^2_p = .22$, observed power = .66, with overall stronger responses in the right hemisphere ($M = 1.10\ \mu V$, $SE = .20$) than in the left hemisphere ($M = .601\ \mu V$, $SE = .128$). There was no effect of *Group*, $F(1, 21) = .27$, $p = .61$, and no interaction of this factor with *Condition* or *Hemisphere* (both $F < 1$). There was however a significant interaction between *Condition* and *Hemisphere*, $F(1,22) = 11.285$, $p = .003$, $\eta^2_p = .34$, observed power = .89, and a trend for a triple interaction between *Condition*, *Hemisphere* and *Group*, $F(1, 22) = 3.85$, $p = .06$, $\eta^2_p = .15$, observed power = .47.

Because of our a-priori hypotheses, we decided to decompose the marginally significant triple interaction by computing a lateralization score (LS) for each child in each condition (Right Hemisphere – Left Hemisphere; positive values indicating right-lateralized responses, negative values indicating left-lateralized responses). These new measures were then submitted to paired-sample t-tests. In the hearing group, the LS of the digit and letter's conditions were different from each other, $t(11) = 3.58$, $p = .004$, the LS being positive in the digit condition ($M = 1.04\ \mu V$, $SE = .32$) and negative in the letter condition ($M = -.19\ \mu V$, $SE = .30$). In the deaf group, the LS were similar and positive in both conditions ($M = .67\ \mu V$, $SE = .32$ in the digit condition; $M = .35\ \mu V$, $SE = .30$ in the letter condition), $t(11) = 1.04$, $p = .32$. As the variability of the data was higher in the hearing group than in the deaf group (see figure 2C), non-parametric Wilcoxon signed-rank tests were also conducted, leading to the same conclusions ($Z = -2.67$, $p = .008$ in the hearing group; $Z = -1.41$, $p = .16$ in the deaf group).



A
lett-DIG
0.80 μV
0 μV
deaf
3.40 μV
PO10
PO9
SNR
F/5
2F/5
3F/5
4F/5
Frequency (Hz)
Summed harmonics (μV)
hearing
B
dig-LETT
C
Lateralization scores (RH-LH)
Deaf
Hearing
lett-DIGITS
dig-LETTERS

**Figure 2.** *Categorical Response.* Responses elicited in the lett-DIG condition **(A)** and the dig-LETT condition **(B)** for deaf and hearing children. Topographies (on the left) display the sum of amplitude responses for the significant (Z > 1.64) harmonics (from 1.2 Hz to 7.2 Hz, excluding the 6-Hz base frequency). SNR response spectra (middle and right figures) show the electrodes of the ROIs for both conditions: PO9 and PO10. The frequencies of significant harmonics are marked as F/5 (1.2 Hz), 2F/5 (2.4 Hz), 3F/5 (3.6 Hz) and 4F/5 (4.8 Hz). The response at 6 Hz represents the response synchronized with the base stimulation frequency (topography above). On the right figure, the summed amplitudes (baseline corrected) of the significant harmonics (excluding the base) is represented centered with 10 surrounding bins on each side. **(C)** Bar plot showing the mean amplitudes and the individual data of deaf (in blue) and hearing children (in green) per condition (digit on the left, letter on the right).

## Discussion

Numbers and letters are culturally created symbols that become meaningful after extensive training (Dehaene & Cohen, 2007; Hamilton, Mirkin, & Polk, 2006), and then induce a major tuning of the brain. While the processing of letters and words elicits a left-lateralized brain response (McCandliss et al., 2003; Dehaene & Cohen, 2011; Schlaggar & McCandliss, 2007), it has been demonstrated that the processing of numbers preferentially elicits a right-lateralized brain response (Allison et al., 1994; Park et al., 2012; Roux et al., 2008; Shum et al., 2013). Despite extensive training, deaf children often struggle with learning to read and to calculate. While the origins of these difficulties have been extensively studied (lack of auditory access, language delay, etc., see Marcelino, Sousa, & Costa, 2019; Buyle, Marlair, & Crollen, 2021; Santos and Cordes, 2022 for reviews), the impact they may have on the letter-number hemispheric specialization is still unknown.

The present exploratory study aimed to tackle this question by using a FPVS-EEG approach (Lochy et al., 2019). Deaf and hearing children from 8 to 13 years old were presented with 2 different FPVS-EEG conditions. In the first one, digits were presented as base stimuli and LETTERS as oddball stimuli. In the second condition, letters were presented as base stimuli while DIGITS were periodically inserted as oddballs in the stream. Our results suggest a different pattern of lateralization between deaf and hearing children for letters and digits. We acknowledge that the triple interaction between Group, Hemisphere and Condition gave rise to a p-value slightly above the conventional threshold for significance (p=.06), but given the exploratory aim of our study, we computed a lateralization score for each child and condition, providing individual data that is convincing in suggesting a different pattern of lateralization between groups. Indeed, deaf individuals showed right lateralization that did not differ between letters and digits, while hearing children had a significant difference in lateralization with digits being right-lateralized and letters tending to be left lateralized. Thus, in both populations, responses to digits were right-lateralized and stronger than responses to letters. The current findings in hearing children replicate the response pattern for letters previously found in hearing first graders with the same paradigm and experiment (Lochy and Schiltz, 2019): a bilateral response with a non-significant trend for left lateralization. In deaf children, the neural response to letters was in contrast stronger in the right hemisphere than in the left hemisphere. These results are important and will be discussed theoretically here below. However, they must be taken cautiously, as a first exploratory step in the field, that can provide valuable insights for future studies, given the small sample size of our population. In that light, our results also provide essential information for conducting future a priori power analyses and sample size analyses (see supplementary material).

Following the Phonological Mapping Hypothesis, a left dominance in the response for letters would be expected, at least in hearing children (Maurer & McCandliss, 2008). Indeed, learning these visual shapes in relationship to their spoken counterpart should drive the fast specialization of the left VOTC because of rapid connections established between anterior phonological regions and posterior visual regions. This view is also shared by theoretical perspectives assuming that language regions in general, and speech sounds in particular, induce top-down constraints to the left VOTC or VWFA (Price and Delvin, 2011). Such a left dominance was indeed disclosed in 5- to 8-year-old children, using the same FPVS-EEG paradigm but displaying pseudofonts as base stimuli, and letter-strings as deviant stimuli (Lochy et al., 2016; van de Walle de Ghelcke, Rossion, Schiltz, & Lochy, 2020; van de Walle de Ghelcke et al., 2021). Here, although the lateralization scores values (RH-LH) are negative in hearing children and differ from those for digits, the main analysis could not firmly confirm a left lateralization for letters. This finding strikingly replicates what was found in 6-year-old children with the same paradigm (Lochy & Schitlz, 2019). The discrepancy between the current (replicated) findings and previous ones could be due to at least two factors. First, we presented single characters and not letter-strings, considering that letter-strings trigger orthographic and combinatorial processes more strongly than single-letters (Nara, Raza, Carreiras, & Molinaro, 2023; James, James, Jobard, Wong, & Gauthier, 2005). The neural impact of recognizing single characters vs. strings of characters deserves to be further investigated in future studies designed for that objective. Second, the contrast level between base and deviant stimuli that was used here involved two familiar categories of visual shapes, letters and digits, thus leading to a more fine-grained contrast than letters against non-existing false font shapes. This is important to consider as the paradigm does not measure an *absolute* response to letters, but a differential response between base stimuli and deviant stimuli. It thus represents the periodic response to the deviant category, over and above the common processes related to the processing of these two categories. Finally, a last factor that may have driven the lack of left-lateralization observed at the group level lies in the greater variability in lateralization for letters in hearing children by comparison to deaf children, which is very clear on Figure 2C.

Crucially, in contrast to hearing children, deaf participants seemed to demonstrate a right-lateralized response to letters as reflected by the positive lateralization scores and a quite homogeneous distribution of individual data points despite the small sample size (see Figure 2C). This exploratory result supports previous studies suggesting that reading relies on distinct patterns of neural activation and lateralization in deaf individuals (Neville, Bavelier, Corina, Rauschecker, Karni, Lalwani, Braun, Clark, Jezzard, & Turner, 1998). It has for example been demonstrated that phonological processing elicited increased neural activity in deaf individuals, relative to hearing readers, in the left precentral gyrus and in the bilateral parietal cortex, suggesting greater reliance on articulatory phonological codes and increased phonological processing effort (Emmorey et al. 2013). In ERP studies of deaf readers, an increased amplitude of the N170 for words in the right hemisphere was found to be associated with better reading ability (Emmorey et al., 2017), which was interpreted as a difference in the contribution of left-lateralized phonological representations in deaf participants compared to hearing individuals. Similarly, selectivity of the VWFA to orthography in deaf readers was found over both the left but also the right VWFA with fMRI (Glezer, Weisberg, O'Grady Farnady, McCullough, Midgley, Holcomb, & Emmorey, 2018). The present results might thus be interpreted as pointing to representations of letters that are supported by alternative neural strategies in deaf compared to hearing children, relying less on an overall weaker phonological coding (Mayberry, del Giudice, & Lieberman, 2011). This possibility should however be investigated more in depth and larger samples in future studies (see supplementary material).

Consistent with a growing body of evidence emphasizing the importance of fingerspelling in the literacy development of deaf individuals (Stone et al., 2015; Sehyr & Emmorey, 2022), the deaf children tested in this study frequently used fingerspelling, a manual representation of orthographic code (Sutton-Spence and Woll, 1999), during the letter naming tasks. Fingerspelling may therefore serve as a bridge between sign language and written language. Since fingerspelling involves recognizing specific handshapes, which requires spatial and configural processing, the brain may engage areas typically associated with object recognition to process these configurations (Sehyr et al., 2023). For deaf children, this could, in turn, influence the neural representation of alphabetic letters and written language in general (Emmorey et al., 2017; Lee & Secora, 2022). Specifically, because fingerspelling relies on spatial processing, letter recognition might become more right-lateralized, as the right hemisphere is typically more involved in spatial and configural tasks. This could lead to letters being processed not only as abstract symbols but also through the spatial mechanisms engaged during object recognition, potentially altering the typical left-lateralized pattern observed in hearing individuals. This hypothesis would deserve full investigation in future studies with larger sample size.

Regarding numbers, a right-lateralized brain response was revealed in our study, in hearing as well as in deaf individuals. These data are well in line with previous data in hearing children showing that numbers elicit increased EEG (Lochy & Schiltz, 2019; Park et al., 2014) or ERP (Carreiras, Monahan, Lizarazu, Duñabeitia, & Molinaro, 2015) responses compared to letters on right hemispheric electrodes. Strikingly, responses to digits were three times greater than responses to letters (over both hemispheres, 1.26µV vs. .41µV). In the previous study using the same experiment with younger children (mean age = 6.12, Lochy & Schiltz, 2019), there was no main effect of condition, and the maximal response for digits over the right hemisphere was .61µV, while responses to letters lay in the same range of amplitudes as we found here (.49µV in the left hemisphere). This result points to a neural selectivity for digits that seems to dramatically evolves between 6 and 10 years old, far more than that for letters. This interpretation is further reinforced by the lack of difference in the amplitude responses at the base rate, which point to a selective effect on digits, rather than a general effect of age or attention. We speculate that this finding could reflect the fact that single digits have a meaning by themselves, as they relate directly to a numerosity, and the relationship between the visual shape and its semantic representation might be reinforced with age and the increased manipulation of numbers (for instance, during arithmetic learning at school). Letters, on the other hand, are the building blocks of words, have no meaning in themselves, and this status does not change over time.

The lack of difference between deaf and hearing children for digits is also in line with recent studies showing that deafness and the use of sign language does not influence the brain network underlying arithmetic processing (Andin et al., 2023; Berteletti et al., 2022; but see Andin et al., 2019). Arabic digits denote numerosities that can be represented in several other formats, using fingers or dots for instance, contrary to letters that relate to phonological representations only. Therefore, deaf children may develop precise semantic representations for single digits even if their verbal representations for number words are weaker. Cognitive plasticity may, however, be observed when number signs are involved (instead of Arabic digits). A stronger neural response to number signs was indeed recently revealed in deaf signers (Buyle et al., 2023) compared to hearing non-signers. Given this, it could be interesting to compare the brain correlates underlying fingerspelled and alphabetic letters in deaf individuals.

### Limitations and conclusions

This study has several limitations. First, to understand the development of letter knowledge and its impact on brain lateralization in deafness, a longitudinal study assessing changes at the behavioral and neural levels would be necessary. To do so, future studies should thoroughly assess the reading and math abilities of the children tested and should also aim to achieve better IQ matching between the hearing and deaf groups. Second, a larger sample would be recommended (see Supp.Mat 2; Brysbaert, 2019) although the current sample was representative of the population (i.e., we recruited all deaf children that could be included in the study; Luxembourg being a very small country). While the small sample size is a limitation of the present study, its exploratory nature allows us to generate new hypotheses and provide preliminary data to inform future research. Additionally, the high sensitivity and strong signal-to-noise ratio (SNR) of the FPVS approach, combined with the replication of previous findings with (younger) hearing children, lend some support to our results. Finally, the individual data showing a consistent right-lateralized profile for letters in deaf individuals further corroborates our observations, though these findings should be interpreted with caution and require validation in larger samples.

To conclude, our exploratory study suggests that deafness and the use of sign language shapes the hemispheric lateralization of letters while it does not seem to shape the hemispheric lateralization of Arabic digit processing. To better understand whether the distinct lateralization of letter processing in deaf children underlies a true reading difficulty, a mere reading delay or the use of different processing mechanisms, longitudinal studies are needed. These studies should thoroughly assess the children's reading and math abilities, compare brain processing of fingerspelled and alphabetic letters, and examine whether behavioral and brain performance are related.

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