Journal of Deaf Studies and Deaf Education, 2026, 1–13
https://doi.org/10.1093/jdsade/enag050
Published: 24 August 2026
Empirical Manuscript

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Analyzing the influence of deafness on serial position function for letters

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Abstract

Previous research has shown that letter and digit identification typically follows a W-shaped serial position function, whereas symbol identification exhibits an inverted U-shaped pattern. Given that reading outcomes vary widely among deaf populations, the present study investigated whether deaf adults display serial position functions similar to hearing adults. Using the Target-in-String Identification paradigm, we compared letter, digit, and symbol recognition across five target positions in matched groups of deaf and hearing participants. Both groups demonstrated a pronounced first-letter advantage, consistent with specialized position-tuned letter detectors. However, only the hearing group showed the canonical W-shaped function for letters. Deaf participants exhibited a more linear and quadratic profile, with reduced accuracy at central positions, which may be consistent with a potentially greater influence of visual crowding, even within foveal vision. No reliable position effects emerged for symbols, and both groups displayed similar linear position effects for digits. These findings indicate that while initial-letter prioritization is preserved in deaf readers, spatial tuning for other positions may be influenced, partially supporting the MRF theory and underscoring the need for models that account for variability in orthographic processing across populations.

Public significance statements

Reading begins with the ability to recognize individual letters, even when they appear in crowded strings. For people who are deaf, this skill may develop differently because they rely more heavily on vision than on sound. In our study, we asked deaf and hearing adults to identify letters, digits, and symbols presented in random strings. We found that deaf readers showed a particularly strong advantage for recognizing the first letter in a string, but more difficulty identifying letters in the middle, where crowding from neighboring characters is strongest. This pattern invites a closer look at existing scientific ideas suggesting that deaf readers may process visual information more broadly due to their greater reliance on vision, ideas that, while supported by some evidence, have largely been studied in peripheral vision or during whole-word recognition tasks rather than in tasks requiring identification of individual letters within crowded strings. Our findings suggest that any such advantage may not extend uniformly across all letter positions, and that efficiency may instead be concentrated at the initial position of a string. This pattern challenges existing scientific ideas that assume deaf readers process all letters more efficiently because of their broader visual attention. By showing that efficiency is uneven across positions, our findings suggest that educational and technological approaches to reading support should consider ways of reducing visual crowding, which could make text easier for deaf readers to process.

Introduction

During reading, letters within a word are first recognized, then combined and mapped onto meaning and sound. This makes letter recognition the earliest reading-specific process and a crucial foundation for word-level processing (Grainger, 2018). Consequently, extensive research has investigated fundamental mechanisms, such as the encoding of letter identities and positions. While there is a broad agreement that letters are processed simultaneously during reading (e.g., Adelman, 2011; Perry et al., 2010), it is also widely acknowledged that the efficiency of letter processing varies depending on each letter's position within the string (e.g., Grainger & van Heuven, 2003). For example, when identifying a specific character presented in a briefly displayed five-letter string (e.g., FGTHM), performance typically follows a W-shaped function. Accuracy is consistently higher for letters at fixation, as well as those in the first and last positions, compared to neighboring second and fourth positions. Visual acuity at

Received: January 13, 2026. **Revised:** June 19, 2026. **Accepted:** July 7, 2026
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the center and reduced crowding at the edges of the string are thought to contribute to these effects (e.g., Levi, 2008; Pelli & Tillman, 2008; Stevens & Grainger, 2003; Tydgat & Grainger, 2009). Interestingly, a processing advantage for the middle item also emerged for digits and symbols, but first- and last-position advantages occurred only for letters and digits, not for symbols. As a result, serial position functions are W-shaped for letters and digits but inverted U-shaped for symbols. Also, crowding effects are more spatially restricted for letters than for symbols: a single flanking item is sufficient to produce maximal interference for symbols, but not for letters. This reduced crowding for letters may explain the superior performance at outer positions in letter strings (Tydgat & Grainger, 2009).

The modified receptive field (MRF) hypothesis has been proposed to account for letter-position effects in typical reading. It argues that learning to read induces adaptive changes in the visual system to optimize orthographic processing under crowding (Chanceaux & Grainger, 2012; Grainger et al., 2010, 2016; Tydgat & Grainger, 2009). In alphabetic scripts, this involves the development of gaze-centered, location-specific letter detectors whose receptive fields become progressively more finely tuned with reading experience (Grainger & van Heuven, 2003). For example, when fixating on the letter b in the word table, the system simultaneously detects "a" to the left and "t" further left. These detectors adapt in size and shape to reduce interference from neighboring letters. Specifically, receptive fields in the left visual field become elongated leftward, enhancing processing of initial letters. This mechanism accounts for the prioritization of first and last letters in left-to-right languages and predicts the typical W-shaped serial position function observed in hearing readers. To date, however, the MRF framework has only been applied to hearing readers, and it remains an open question whether the same adaptive tuning mechanisms develop in deaf readers.

While reading outcomes among deaf individuals show significant variability, those with limited or no access to the phonology of the spoken language they read often face persistent literacy challenges (Goldin-Meadow & Mayberry, 2001; Mayberry et al., 2011; Ormel et al., 2010). However, most of the existing research trying to understand the origins of these difficulties have limited their research focus to the word recognition level (Fariña et al., 2017; Costello et al., 2021; Daigle & Berthiaume, 2021; Gutierrez-Sigut et al., 2022; Winsler et al., 2023). In contrast, while letter recognition underpins the acquisition and development of orthographic knowledge, only a few studies have examined the nature of letter representations in deaf people. Those studies have moreover reached inconsistent conclusions, some suggesting that letter recognition is not impacted by deafness (Sehyr et al., 2020; Sehyr et al., 2023), others reaching the exact opposite conclusion (Guldenoglu et al., 2014; Kamble et al., 2024; Kamble et al., 2026). In the former study, Event-Related Potential (ERPs) were recorded while deaf and hearing adults performed a letter (probe) detection task (i.e., press a button when the letter Y appeared either as a prime or as a target). Results demonstrated that the timing of visual letter recognition was not impacted by deafness or signing experience. Both deaf and hearing participants indeed activated an abstract letter representation at similar stages of the processing time course (i.e., similar letter-to-letter priming effects during the early 120–180 ms time epoch and during the latter 300–500 ms epochs) (Sehyr et al., 2023). Another study (Kamble et al., 2024), which aimed to examine whether crowding affects letters and symbols differently in deaf and hearing adults, however, reached a different conclusion. In this study, letters and symbols were presented in isolation or in a string of three or five characters, on the left or on the right of a fixation cross. Deaf and hearing participants had to identify, by pressing one of two response keys, which character (among two) was presented at the string's middle position. Results first demonstrated that letter identification was more accurate than symbol identification. Characters (letters and symbols) were also processed more efficiently when presented in isolation than when presented in a string of three or five characters. This pattern of results was observed in both groups, thus suggesting that deafness does not prevent the development of specialized letter-string processing. However, deaf participants only processed letters faster than symbols when presented in isolation but not when flanked by 4 other characters (see Hung et al., 1981 for similar results; see Guldenoglu et al., 2014 for the observation of letter identification difficulties in a same-different judgment task, in Arab and Turkish participants but not in Hebrew, English and German participants). This result therefore suggests that deafness might slow down letter identification when letters are presented in the periphery and in a crowded condition (as already reported for dyslexic patients; Bouma & Legein, 1977; Pel et al., 2019; for more on crowding Bouma, 1970).

In addition, deaf readers are known to differ from hearing readers in their distribution of visual attention. They exhibit a wider perceptual span and more efficient extraction of linguistic information per fixation (Bélanger et al., 2012, 2018; Schotter et al., 2024). This broader perceptual span may be an adaptation to their reliance on visual information, which has been found to influence recognition of random strings of letters (Kamble et al., 2024; Kamble et al., 2026; Sehyr et al., 2023). According to the Word Processing Efficiency (WPE) hypothesis (proposed by Bélanger & Rayner, 2015, deaf readers are more efficient at extracting linguistic information from visual input within one fixational pause. This increased efficiency leads skilled deaf readers to read faster by skipping words more often and making shorter fixations, fewer regressions, and longer forward saccades (Bélanger et al., 2012; Rayner, K. 1998; Traxler et al., 2021), which are characteristics of skilled readers. According to the hypothesis (Bélanger & Rayner, 2015), these adaptations should enhance visual uptake and could predict preserved or even superior letter recognition under crowded conditions. This prediction stands in contrast to the MRF framework, which would suggest that if adaptive receptive field tuning does not generalize to deaf readers, crowding effects should be stronger and the canonical W-shape weaker or absent.

The present study aimed to investigate how deaf readers process letter position information within letter strings and to determine whether their performance reflects patterns predicted by existing models of visual word recognition. Specifically, competing hypotheses derived from the MRF framework and from accounts of enhanced visual processing in deaf individuals were tested. If deaf readers exhibit the same adaptive tuning assumed by the MRF framework for hearing readers, they should show the canonical W-shaped serial position function for letters. By contrast, if their broader perceptual span enables more efficient parallel uptake of visual information, they may show preserved or even enhanced W-shaped functions. Alternatively, if crowding disproportionately affects deaf readers, particularly at central positions, the W-shape should be weakened relative to hearing readers. To test these predictions, the Target-in-String Identification (TSI) paradigm (Tydgat & Grainger, 2009) was employed. In this task, a string of unrelated elements (random consonant strings, digit strings, or symbol strings) was briefly and centrally presented on a computer screen, followed by a pattern mask and a post-cue indicating one position in the string. Participants were required to report the identity of

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the element at the cued location. Digits and symbols served as control conditions to clarify whether any observed differences between deaf and hearing participants are specific to orthographic processing or reflect general visuo-spatial mechanisms.

Methods

Participants

Twenty-three deaf adults (10 females; 2 left-handed; $M = 35.4$, $SD = 12.87$) and twenty-three hearing participants (10 females, 1 left-handed; $M = 34.9$, $SD = 12.25$) were initially recruited. Eight participants from each group were removed from the analyses because they performed below chance, leaving 15 deaf adults (7 females; 1 left-handed; age- $M = 36.53$, $SD = 12.32$) and 15 hearing participants (6 females, 1 left-handed; age- $M = 32.27$, $SD = 12.60$). Deaf participants presented bilateral profound to complete deafness and had French or LSFB (i.e., "Langue des Signes Francophone de Belgique", the sign language used in the French-speaking part of Belgium) as mother tongue. Twelve participants had hearing aids or cochlear implants. None reported additional disabilities or neurological conditions (see Table A1 for a detailed description of the deaf participants and see Table B1 for information on their hearing device). Hearing participants were matched to the deaf participants in terms of age ($t(28) = 0.93$, $p > .3$), educational level ($t(28) = 0$, $p > .9$), gender ($\times^2$ (1, 30) = 0, $p > .9$), handedness ($\times^2$ (1, 30) = 0, $p > .9$), and nonverbal IQ tested using the Raven Progressive Matrices (Raven & Raven, 2003) ($t(28) = 0.60$, $p > .5$). Reading components were also assessed for both groups (see the methods and results sections for more details). Participants received compensation of 10 euros for their participation. All participants reported having normal or corrected-to-normal vision. Written informed consent to participate and use of data for publication were signed by all participants. The study was approved by "Comité d'Ethique Hospitalo-Facultaire Saint-Luc-UCLouvain" (2019/13JUI/256) and the procedures were in line with the Declaration of Helsinki.

Transparency and openness

We report all data exclusions (if any), all manipulations, and all measures in the study, and we follow JARS recommendations (Appelbaum et al., 2018). All analyses were performed using R Statistical Software (version 4.3.0; R Core Team, 2021). The study was not preregistered. Data and materials are available in a repository and will be made accessible upon publication.

Reading components assessment

Sentence comprehension was evaluated using a computer-adapted version of the ECOSSE task from the BALE (Jacquier-Roux et al., 2010). Four images numbered from 1 to 4 were presented on a computer screen, along with a sentence in the middle of the screen. Participants had to choose the image that corresponded to the written sentence by clicking the corresponding number on the numeric keypad. The sentence and the pictures stayed on the screen until participants responded. A total of 12 sentences, which increased in syntactic complexity, were presented.

A spelling decision task was designed to assess spelling skills. The participants saw words appear one by one in the center of the screen. They had to indicate whether the word was spelled correctly (by selecting the number 1 on the numeric keypad) or misspelled (by selecting the number 2 on the numeric keypad). Stimuli consisted of 20 frequent and regular words, 20 frequent and irregular words, 20 rare and regular words, and 20 rare and irregular words (see Table C1 for the list of items used). Words remained visible until participants responded.

The phoneme judgment task developed by Hirshorn et al. (2015) was adapted into French to evaluate phonological knowledge. In this "odd-man-out" task, participants were shown three pictures on a computer screen and were instructed to identify which item produced a different sound. The task was divided into two blocks. In the first block, the odd-man-out was located at the first consonant sound. In the second block, the odd-man-out was located at the first vowel sound. Orthographic transparency was moreover manipulated in each block, which included two shallow and two deep conditions. In a first shallow condition called shallow 1, the two similar-sounding items shared the same orthography, whereas the odd-man-out had a different orthography (e.g., chat/*singe*/chaise[1]). In a second shallow condition called shallow 2, the three presented pictures corresponded to words with different orthographies. Correct responses required flexible letter-to-sound knowledge, such as recognizing that "k" and "c" can represent the same sound in French (e.g., *pâtes*/kiwi/craie). In the first deep condition called deep 1, all words shared the same letter. Correct responses required knowledge of idiosyncratic mappings in French (e.g., goutte/gare/*génie*). In the second deep condition called deep 2, the odd-man-out shared orthography with one of the two similar-sounding items (e.g., cerf/singe/*cape*). In total, the task comprised 40 stimuli. Participants had to answer by pressing the number on the keyboard for the correct response (see Table D1 for the list of items used).

Although not all deaf individuals rely on phonological processing during reading, previous research has shown that phonological awareness can still vary widely among deaf readers and may be influenced by factors such as access to auditory input and language experience (e.g., Colin et al., 2007; Harris & Beech, 1998; Hirshorn et al., 2015). Importantly, the deaf participants in the present study had partial access to auditory input through hearing aids ($n = 3$) or cochlear implants ($n = 10$), which may support the development of some phonological representations. Including this measure therefore allowed us to characterize the phonological skills of our participants and compare them with hearing controls. More broadly, assessing phonological knowledge situates the linguistic profiles of both groups. Comparing deaf and hearing participants on this task thus provides a useful reference point for understanding potential differences in reading-related processes.

TSI task

Stimuli and design

The TSI paradigm of Tydgat and Grainger (2009) was used to assess the serial position function of letters, digits, and symbols. In this task, participants saw strings of five characters in the center of a computer screen and had to indicate which character was presented at a post-cued position. Nine uppercase consonant letters (B, D, F, G, K, N, L, S, and T), nine digits (1 to 9), and nine symbols (%, /, ?, @, }, <, £, §, and μ) were used as stimuli. Each target character was presented 40 times at a non-target position and two times at each of the five target positions, giving a total of 270 stimuli (i.e., 3 characters' categories × 9 characters × 5 positions × 2 presentations). The task was divided in

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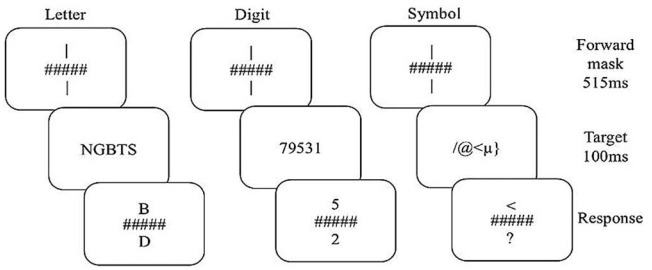


Figure 1 *Note.* Schematic illustration of the experimental procedure for the TSI task. The examples shown use "B" as the letter target, "5" as the digit target, and "<" as the symbol target.

three blocks of 90 stimuli of the same category (one block of letters' strings, one block of digits' strings and one block of symbols' strings). The presentation order of the blocks was counterbalanced among participants.

Procedure

The experiment was run with E-Prime software (Psychology Software Tools, Inc., 2016). Participants were seated in front of a computer screen at a viewing distance of approximately 60 cm. At that distance, target stimuli in the five different positions were located at 1.2°, 0.6°, 0°, 0.6°, and 1.2° of visual angle from the central fixation point. Each character subtended on average 0.44° of visual angle. Stimuli were displayed in white on a black background and were presented in 18-point Courier New font. Each trial began with the 515 ms presentation of two vertical bars placed above and below the center of a forward mask composed of five hash marks. The characters' string was then presented during 100 ms followed by a backward mask, which was composed of five hash marks and two characters placed above and below one of the five possible positions. One of the character corresponded to the target, the other character corresponded to an incorrect alternative. The correct alternative appeared once above the backward mask (with the incorrect alternative below) and once below the backward mask (with the incorrect alternative above) for each target position. Each target character was always presented with the same alternative character at each of the five positions. The incorrect alternative was moreover never present in the characters' string. Participants had to decide, as accurately and as fast as possible, which one of these two characters was present in the corresponding position of the preceding string. To give their responses, they had to press the upward response button of a response box to select the character presented above the hash mark and press the downward response button to select the character presented below the hash mark. The next trial began 515 ms after the participant had given a response. To familiarize with the task, participants performed 81 trials before starting the experimental blocks. Participants were instructed to perform the task as quickly and accurately as possible (see Figure 1).

Results

All analyses were performed using R Statistical Software (version 4.3.0; R Core Team, 2021). Accuracy and response times were assessed using either mixed-effects models or Mann–Whitney *U* Test tests, implemented with the lmerTest package (version 3.1–3; Kuznetsova et al., 2017). Fixed effects were considered significant when their inclusion improved model fit, as determined by likelihood ratio tests, with statistical significance set at $p < .05$. Random-effects structures included only by-participant random intercepts, as random slopes were excluded to avoid overparameterization (Matuschek et al., 2017). Pairwise comparisons were performed on the models' estimated marginal means (via the emmeans package; Lenth, 2021), with Bonferroni adjustments applied to control for multiple comparisons. We report estimates, standard errors (SEs), *t* values, and *p* values for all tests.

Sentence comprehension

For sentence comprehension, the results were not normally distributed. Non-parametric Mann–Whitney *U* tests (with continuity correction) were therefore used to compare group differences. The results revealed no significant differences between groups in either response accuracy ($U = 121.5$, $p > .70$) or response time ($U = 149$, $p > .10$).

Spelling decision task

A mixed effects model was first fitted to predict accuracy with group, frequency, and regularity (formula: accuracy ~ group × frequency × regularity). This model incorporated by-participants as random intercepts (formula: ~ (1 | subject)). The results indicated a significant main effect of group, $F(1, 28) = 7.12$, $p < .01$, $\eta^2_p = .20$, 95% CI [0.03, 1.00], with the deaf group demonstrating superior performance relative to the hearing group (estimate = 0.05, $SE = 0.02$, $t = 2.66$, $p < .01$). Additionally, a significant main effect of frequency was observed, $F(1, 84) = 73.46$, $p < .001$, $\eta^2_p = .47$, 95% CI [0.34, 1.00], revealing that words with higher frequency were identified more accurately than those with lower frequency (estimate = 0.05, $SE = 0.02$, $t = 2.66$, $p < .01$). A similar significant effect was found for regularity, $F(1, 84) = 21.91$, $p < .001$, $\eta^2_p = .21$, 95% CI [0.09, 1.00], indicating that regular words were recognized more effectively than irregular words (estimate = 0.04, $SE = 0.01$, $t = 4.68$, $p < .0001$). The interaction between group and regularity was also significant, $F(1, 84) = 3.78$, $p < .05$, $\eta^2_p = .04$, 95% CI [0, 1.00], suggesting that for regular words, the deaf group outperformed the hearing group (estimate = 0.07, $SE = 0.02$, $t = 3.24$, $p < .05$), whereas no significant difference between groups was noted for irregular words (estimate = 0.03, $SE = 0.02$, $t = 1.56$, $p < .5$). Furthermore, the interaction between frequency and regularity was significant, $F(1, 84) = 6.35$, $p < .01$, $\eta^2_p = .07$, 95% CI [0.01, 1.00], with higher frequency words recognized more promptly than lower frequency words for both regular (estimate = 0.06, $SE = 0.01$, $t = 4.27$, $p < .0001$) and irregular categories (estimate = 0.11, $SE = 0.01$, $t = 7.84$, $p < .0001$).

Subsequently, the mixed effects model was applied to log-transformed reaction time, utilizing group, frequency, and regularity as predictors (formula: log (reaction time) ~ group × frequency × regularity). A main effect of frequency was identified, $F(1, 84) = 81.72$, $p < .0001$, $\eta^2_p = .49$, 95% CI [0.37, 1.00], indicating that high frequency words were recognized more quickly than low frequency words (estimate = −0.37, $SE = 0.04$, $t = -9.04$, $p < .0001$). Lastly, the interaction between frequency and regularity was significant, $F(1, 84) = 8.43$, $p < .004$, $\eta^2_p = .09$, 95% CI [0.02, 1.00], reaffirming that for both regular and irregular words, higher-frequency words were recognized at a faster rate than lower-frequency words (estimate = −0.25, $SE = 0.05$, $t = -4.33$, $p < .0001$), (estimate = −0.49, $SE = 0.05$, $t = -8.44$, $p < .0001$) respectively.

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Phoneme judgment task

The mixed effects model was initially fitted to predict accuracy based on group, condition, and transparency (formula: accuracy ~ group × condition × transparency). This model included random intercepts for participants (formula: ~ (1 | subject)). A significant main effect of group was observed, $F(1, 28) = 6.57$, $p < .01$, $\eta^2_p = .19$, 95% CI [0.02, 1.00], indicating that hearing participants outperformed the deaf group (estimate = 0.10, $SE = 0.04$, $t = 2.56$, $p < .01$). Additionally, a main effect of condition was found, $F(1, 196) = 4.62$, $p < .03$, $\eta^2_p = .02$, 95% CI [0, 1.00], revealing that all participants exhibited greater accuracy for consonants compared to vowels (estimate = 0.05, $SE = 0.02$, $t = 2.15$, $p < .03$). Furthermore, a significant main effect of transparency was identified, $F(3, 196) = 29.20$, $p < .0001$, $\eta^2_p = .31$, 95% CI [0.22, 1.00]. The shallow 1 condition was associated with higher accuracy than the shallow 2 (estimate = 0.15, $SE = 0.03$, $t = 4.76$, $p < .0001$), deep 1 (estimate = 0.17, $SE = 0.03$, $t = 5.37$, $p < .0001$), and deep 2 (estimate = 0.30, $SE = 0.03$, $t = 9.32$, $p < .0001$). The shallow 2 condition was easier than the deep 2 condition (estimate = 0.15, $SE = 0.03$, $t = 4.56$, $p < .0001$). Deep 1 was also easier than deep 2 (estimate = 0.13, $SE = 0.03$, $t = 3.95$, $p < .0001$). Regarding interactions, the group × transparency interaction was significant, $F(3, 196) = 2.91$, $p < .03$, $\eta^2_p = .04$, 95% CI [0, 1.00], with hearing participants performing better than the deaf group in the most challenging orthographic transparency condition, deep 2 (estimate = 0.21, $SE = 0.05$, $t = 3.68$, $p < .006$). The condition × transparency interaction was also significant, $F(3, 196) = 3.01$, $p < .03$, $\eta^2_p = .04$, 95% CI [0., 1.00], indicating that participants were more accurate for consonants than vowels only in the most difficult condition, deep 2 (estimate = 0.14, $SE = 0.04$, $t = 3.15$, $p < .02$). Lastly, the group x condition interaction approached significance, $F(1, 196) = 3.47$, $p = 0.06$, $\eta^2_p = .02$, 95% CI [0, 1.00], suggesting that for consonants, hearing participants tended to demonstrate greater accuracy than the deaf group (estimate = 0.15, $SE = 0.04$, $t = 3.14$, $p < .01$).

Subsequently, the mixed effects model was applied to log-transformed reaction time, incorporating group, condition, and transparency as predictors (formula: log(reaction time) ~ group × condition × transparency). This model also included random intercepts for participants (formula: ~ (1 | subject)). It revealed a marginally significant effect of group, $F(1, 28) = 3.83$, $p = 0.06$, $\eta^2_p = .12$, 95% CI [0, 1.00], indicating that hearing participants tended to be faster than the deaf group (estimate = −0.26, $SE = 0.13$, $t = -1.95$, $p = .06$). A significant main effect of transparency was identified, $F(3, 196) = 20.10$, $p < .0001$, $\eta^2_p = .24$, 95% CI [0.15, 1.00]. The shallow 1 condition yielded faster reaction times than the shallow 2 (estimate = −0.47, $SE = 0.06$, $t = -7.75$, $p < .0001$), deep 1 (estimate = −0.24, $SE = 0.06$, $t = -4.02$, $p < .0005$), and deep 2 conditions (estimate = −0.26, $SE = 0.06$, $t = -4.24$, $p < .0002$). The shallow 2 condition was also faster than the deep 1 (estimate = 0.22, $SE = 0.06$, $t = 3.72$, $p < .001$) and deep 4 conditions (estimate = 0.21, $SE = 0.06$, $t = 3.51$, $p < .003$).

TSI task

The mixed effects model was initially fitted to predict accuracy based on group, position, and character (formula: accuracy ~ group × position × character). This model included random intercepts for participants (formula: ~ (1 | subject)). A significant main effect of position was observed, $F(4, 392) = 16.42$, $p < .001$, $\eta^2_p = .14$, 95% CI [0.09, 1.00]. Overall, performance at position 1 was significantly greater than at position 2 (estimate = 0.06, $SE = 0.01$, $t = 3.68$, $p < .002$), position 3 (estimate = 0.08, $SE = 0.01$, $t = 4.55$, $p < .0001$), position 4 (estimate = 0.11, $SE = 0.01$, $t = 6.21$, $p < .0001$), and position 5 (estimate = 0.13, SE = 0.01, $t = 7.50$, $p < .0001$). Furthermore, performances at positions 2 and 3 were superior to that at position 5 (estimate = 0.06, $SE = 0.01$, $t = 3.82$, $p < .001$; estimate = 0.05, SE = 0.01, $t = 2.95$, $p < .03$, respectively). A significant main effect of character was also identified, $F(2, 392) = 4.94$, $p < .007$, $\eta^2_p = .02$, 95% CI [0.00, 1.00]. Performance was significantly better for letters than for symbols (estimate = 0.03, $SE = 0.01$, $t = 2.34$, $p < .05$), and better for digits than for symbols (estimate = 0.04, $SE = 0.01$, $t = 2.98$, $p < .009$). However, no significant difference was found between letters and digits (estimate = −0.008, $SE = 0.01$, $t = -0.64$, $p > 1$). Regarding interactions, the position x character interaction was significant, $F(8, 392) = 3.34$, $p < .001$, $\eta^2_p = .06$, 95% CI [0.02, 1.00]. For letters, accuracy at position 1 was significantly better than at all other positions: position 2 (estimate = 0.14, $SE = 0.03$, $t = 4.81$, $p < .0001$), position 3 (estimate = 0.14, $SE = 0.03$, $t = 4.63$, $p < .0002$), position 4 (estimate = 0.15, $SE = 0.03$, $t = 5.11$, $p < .0001$), and position 5 (estimate = 0.15, $SE = 0.03$, $t = 5.17$, $p < .0001$). For digits, accuracy at position 1 was significantly higher than at position 3 (estimate = 0.11, $SE = 0.03$, $t = 3.67$, $p < .01$), position 4 (estimate = 0.14, $SE = 0.03$, $t = 4.57$, $p < .0003$), and position 5 (estimate = 0.18, $SE = 0.03$, $t = 6.07$, $p < .0001$). Accuracy at position 2 was also higher than at position 5 (estimate = 0.13, $SE = 0.03$, $t = 4.51$, $p < .0004$). No significant differences were reported for symbols. Finally, the group × position interaction approached significance, $F(4, 392) = 2.26$, $p > .06$, $\eta^2_p = .02$, 95% CI [0.00, 1.00]. For the deaf group, accuracy was significantly higher at position 1 compared to positions 2 (estimate = 0.08, $SE = 0.02$, $t = 3.48$, $p < .01$), 3 (estimate = 0.12, $SE = 0.02$, $t = 5.06$, $p < .0001$), 4 (estimate = 0.12, $SE = 0.02$, $t = 4.86$, $p < .0001$), and 5 (estimate = 0.17, $SE = 0.02$, $t = 6.83$, $p < .0001$). Additionally, performance at position 2 was better than at position 5 (estimate = 0.08, $SE = 0.02$, $t = 3.34$, $p < .02$). For the hearing group, accuracy was significantly higher at position 1 than at positions 4 (estimate = 0.09, $SE = 0.02$, $t = 3.93$, $p < .002$) and 5 (estimate = 0.09, $SE = 0.02$, $t = 3.78$, $p < .004$). A post hoc power analysis, based on the observed parameters and assuming a minimum detectable difference of 0.05 in accuracy, revealed that statistical power was high for all tested effects: position (power = 1.00), character (power = 0.78), group × position (power = 0.48), and position × character (power = 0.27) (see Figure 2).

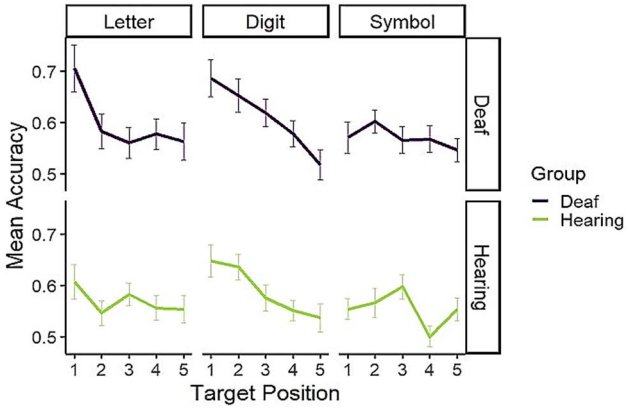


Figure 2 *Note.* Mean accuracy for identifying letters, digits, and symbols across five target positions for deaf and hearing participants. Error bars represent standard error of the mean.

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Subsequently, the mixed effects model was applied to log-transformed reaction time, incorporating group, position, and character as predictors (formula: log (reaction time) ~ group × position × character). This model also included random intercepts for participants (formula: ~ (1 | subject)). A significant main effect of position was observed, $F(4, 392) = 8.44$, $p < .0001$, $\eta^2_p = .08$, 95% CI [0.04, 1.00]. Performance at position 1 was significantly faster than at position 2 (estimate = −0.15, $SE = 0.04$, $t = -3.65$, $p < .003$), position 3 (estimate = −0.15, $SE = 0.04$, $t = -3.82$, $p < .001$), position 4 (estimate = −0.21, $SE = 0.04$, $t = -5.25$, $p < .0001$), and position 5 (estimate = −0.19, $SE = 0.04$, $t = -4.70$, $p < .0001$). A significant main effect of character was also identified, $F(2, 392) = 6.94$, $p < .001$, $\eta^2_p = .03$, 95% CI [0.01, 1.00]. Specifically, performance for letters was significantly faster than for symbols (estimate = −0.11, $SE = 0.03$, $t = -3.50$, $p < .001$), and performance for digits also surpassed that of symbols (estimate = −0.09, $SE = 0.03$, $t = -2.85$, $p < .01$), while no significant difference was detected between letters and digits (estimate = −0.02, $SE = 0.03$, $t = -0.65$, $p > 1$). Furthermore, the interaction between position and character was significant, $F(8, 392) = 4.67$, $p < .0001$, $\eta^2_p = .09$, 95% CI [0.03, 1.00]. For letters, reaction time at position 1 was significantly superior to that at all other positions: position 2 (estimate = −0.28, $SE = 0.07$, $t = -4.02$, $p < .003$), position 3 (estimate = −0.27, $SE = 0.07$, $t = -3.87$, $p < .005$), and position 4 (estimate = −0.34, $SE = 0.07$, $t = -4.76$, $p < .0001$). For digits, reaction time at position 1 was significantly higher than at position 3 (estimate = −0.28, SE = 0.07, $t = -3.91$, $p < .004$), position 4 (estimate = −0.39, $SE = 0.07$, $t = -5.48$, $p < .0001$), and position 5 (estimate = −0.37, $SE = 0.07$, $t = -5.23$, $p < .0001$). No significant differences were reported for symbols. Additionally, the interaction between group and character was significant, $F(2, 392) = 3.42$, $p < .03$, $\eta^2_p = .02$, 95% CI [0.00, 1.00]. Although no difference between groups was observed, within-group variations were evident. The deaf group did not exhibit any differences, whereas the hearing group demonstrated faster performance for letters and digits compared to symbols (estimate = −0.19, $SE = 0.04$, $t = -4.32$, $p < .0002$; estimate = −0.13, $SE = 0.04$, $t = -2.98$, $p < .02$, respectively). A post hoc power analysis, based on the observed parameters and assuming a minimum detectable difference of 3.9, which corresponds to a log-transformed difference of approximately 50 ms in raw RT values, revealed that statistical power was high for all tested effects: position (power = 1.00), character (power = 0.99), group × character (power = 1.00).

Following the work of Tydgat and Grainger (2009), we conducted trend analyses using generalized linear mixed models with polynomials (GLMMs) on accuracy measures to assess the optimal serial position functions for each stimulus type across the groups. In the hearing group, both linear ($z = -1.82$, $p < .06$) and quartic ($z = 1.94$, $p < .05$) trends for letter stimuli approached significance. Variance decomposition indicated that these components accounted for a substantial proportion of the observed variance, with 42% attributable to the quartic component (which reflects a W-shaped pattern) and 34% to the linear component. For digit stimuli, we observed a significant linear effect ($z = -3.41$, $p < .0006$), explaining 96% of the variance. In contrast, no significant effects were found for symbol stimuli. In the deaf group, letter stimuli exhibited significant linear ($z = -5.55$, $p < .0001$), quadratic ($z = 4.13$, $p < .0001$), and cubic effects ($z = -2.58$, $p < .0001$). These effects accounted for the observed variance, with 51% attributable to the linear function, 34% to the quadratic function, and 15% to the cubic function. For digit characters, a significant linear effect was also noted ($z = -5.53$, $p < .0001$), explaining 99% of the variance. Again, no significant effects were observed for symbol stimuli.

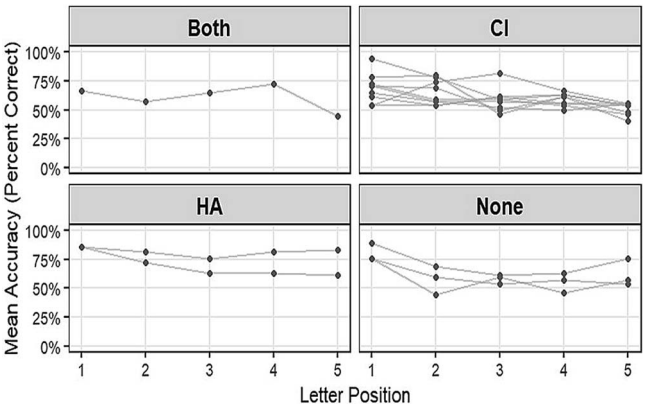


Figure 3 *Note.* Individual serial-position curves showing mean accuracy across five letter positions for participants in the deaf group, grouped by primary auditory device: cochlear implant and hearing aid (CI + HA), cochlear implant (CI), hearing aid (HA), and no device. Each curve represents an individual participant.

To visualize individual variability within our sample, we mapped the serial position curves of each participant categorized by their primary auditory device (hearing aid [HA], cochlear implants [CI], None, or both [HA and CI]). While there is expected natural variation in overall baseline accuracy among individuals, the trajectory of the curves seems uniform across all subgroups (see Figure 3).

Sensitivity analysis

To evaluate the impact of the exclusion criteria, we conducted a sensitivity analysis by comparing the ANOVA results of our primary mixed-effects model across the full dataset ($N = 46$) and the final included sample ($N = 30$). As shown in the comparative analysis, the core statistical findings remained robust. Specifically, the main effects of position and character, as well as the critical position and character interaction, remained highly significant ($p < .01$) in both models.

While the inclusion of participants performing below chance increased the overall noise, leading to slightly attenuated f-statistics for certain terms, the consistency of the significant interactions across both datasets confirms that our reported effects are representative of the broader sample and are not an artifact of the participant selection process (see Table E1 for more details).

We tested whether the errors made by these participants were concentrated on specific positions or specific letters. Chi-Square Goodness-of-Fit tests demonstrated that errors were randomly distributed across all five serial positions (X^2 (1,4) = 1.70, $p = .79$) and across all target identities of letters (X^2 (1,8) = 5.14, $p = .74$). The lack of systematicity in the error patterns suggests that these participants were not struggling with a specific aspect of the task or instruction. Instead, their performance may be affected by lapses in sustained attention or a perceptual threshold that was exceeded by the rapid presentation rates of the stimuli.

We moreover conducted a sensitivity power analysis for our final sample ($N = 15$ per group) using the pwr package in R. At an alpha level of 0.05 and a standard power threshold of 0.80, our

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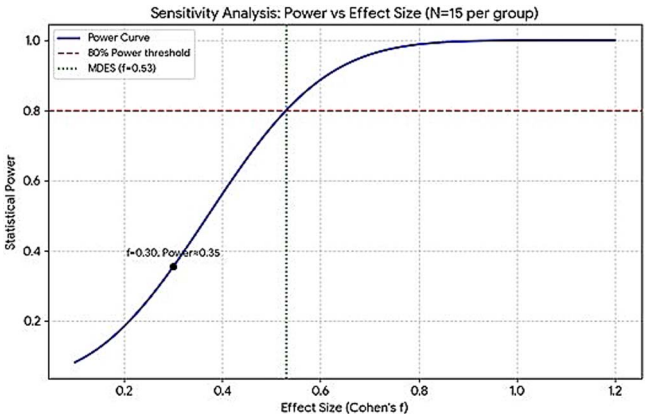


Figure 4 *Note.* Statistical power curve illustrating the relationship between effect size and statistical power for the final sample (N = 15 per group; total N = 30) at $\alpha = .05$. The minimum detectable effect size at 80% power is f = 0.53.

study is sensitive to large effect sizes ($f = 0.53$). We acknowledge that for moderate effect sizes (e.g., $f = 0.30$), the power is lower. However, the primary effects reported in this study, such as the main effect of position ($\eta^2_p = 0.14$) and the position × character interaction ($\eta^2_p = 0.09$), represent robust phenomena that are reliably captured by this design, especially given the high number of trials per participant (270 stimuli), which maximizes internal reliability (see Figure 4).

Discussion

This study aimed to compare the serial position effects for letters, digits, and symbols to determine whether deaf individuals exhibit distinct visual processing strategies in letter recognition, and whether their performance differs from that of hearing individuals, using the TSI paradigm of Tydgat and Grainger (2009).

Overall, letter identification accuracy was found to be highest at the initial position of the string relative to all other positions (Marzouki & Grainger, 2014; Merikle et al., 1971; Tydgat & Grainger, 2009). Like their hearing counterparts, deaf participants thus more accurately identified the first letter of a string compared to letters in other positions (Scaltritti et al., 2018; Scaltritti & Balota, 2013). This robust first-letter advantage is consistent with the predictions of the MRF hypothesis for hearing readers, and the present results extend this finding to deaf readers, showing that initial-position prioritization is preserved, and possibly even amplified, in populations with limited access to phonology. According to MRF, reading acquisition prompts adaptive modifications in the visual system to optimize orthographic processing within the crowded environment of printed text. These changes include the development of gaze-centered, location-specific letter detectors whose receptive fields become increasingly refined with reading proficiency. This refinement involves changes in both size and shape, including a leftward elongation of receptive fields in the left visual field, which reduces interference from rightward flanking letters. Consequently, the processing of the initial letter becomes more efficient, which is critical for fluent reading and word recognition (Grainger, 2020).

In digit identification, the first two digits were processed more accurately than those in other positions (Tydgat & Grainger, 2009; Ziegler et al., 2010). These findings suggest that digits may be processed by a similar, though possibly less specialized, visual processing mechanism compared to letters (Grainger et al., 2016). This pattern may result from the frequent and structured use of digits in daily tasks, though not to the same extent as letters in reading. In contrast, symbol identification showed no significant position effects, suggesting that this process is not shaped by reading acquisition.

Our trend analyses confirmed the presence of distinct serial position functions for different stimulus types (e.g., Tydgat & Grainger, 2009) but also revealed important differences across groups. In the hearing group, letter strings exhibited a marginally significant linear trend alongside a significant quartic trend, resulting in a W-shaped performance pattern. This is in line with earlier studies showing enhanced recognition at fixation and at the outer positions, likely reflecting a combination of central visual acuity and reduced crowding at string boundaries (e.g., Pelli & Tillman, 2008; Stevens & Grainger, 2003). The predominance of the quartic component (42% of explained variance) further supports the interpretation of a W-shaped serial position function as a robust signature of letter-specific visual processing in this group.

By contrast, letter stimuli elicited a more complex serial position profile in the deaf group, characterized by significant linear, quadratic, and cubic trends, with 51% of the variance explained by the linear component and 34% by the quadratic component. The absence of a prominent quartic component in this group suggests that the canonical W-shape observed in hearing participants may not generalize to deaf readers. Three major differences emerged between the deaf and the hearing groups. First, the first-letter advantage appeared to be particularly pronounced in the deaf group, indicating an even stronger prioritization of initial-position information. Second, the central-position peak was reduced in deaf readers, suggesting that visual crowding may potentially have a greater impact on their orthographic processing, even within foveal vision. It should be noted, however, that inter-letter spacing was not directly manipulated in the present study; as such, any interpretation linking reduced central-position accuracy to heightened crowding remains inferential rather than a direct empirical finding. Lastly, the deaf group did not identify letters any faster than the other types of stimuli, a pattern consistent with another study (Kamble et al., 2024), who also reported that deaf participants' letter processing speed was not superior to symbol processing speed under crowded conditions. Interestingly, while the above-mentioned study observed this effect in peripheral vision, the present results may suggest that a similar pattern could also extend to foveal vision. Taken together, these findings may indicate that in deaf readers, crowding effects are more pervasive across the visual field. While the mechanism of first-letter prioritization is intact or even enlarged, the tuning of receptive fields for other positions, especially central ones, may differ in deaf readers. In this sense, our data partially support the MRF hypothesis but also indicate its limits: the expected tuning mechanisms do not appear to mitigate crowding at medial positions in the same way for deaf readers as they do for hearing readers.

Interestingly, efficient first-letter processing plays a crucial role in linking novel orthographic stimuli to familiar phonological representations (Share, 1995; Ziegler et al., 2013). This adaptive mechanism develops during childhood and underpins the ability to recognize words quickly and accurately (Dandurand et al., 2011; Grainger & Jacobs, 1993; Hand et al., 2012). The initial letter is assumed to carry

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greater lexical and semantic information compared to medial or final letters. The initial letter therefore helps in quickly narrowing down lexical candidates, thereby facilitating efficient word recognition (see the interactive activation model of McClelland & Rumelhart, 1981; Blais et al., 2009; Aschenbrenner et al., 2017). The observation of a larger first-letter advantage in deaf readers aligns with evidence that deaf individuals may rely more heavily on orthographic sensitivity than phonological mediation when accessing word meaning (Beech & Harris, 1997; Transler & Reitsma, 2005; Miller & Clark, 2011; Bélanger et al., 2013; Peleg et al., 2020; Sehyr & Emmorey, 2022). In this context, the first letter of a word may serve as a particularly salient visual cue, helping to compensate for weaker phonological activation. The observation may have also contributed to possible ceiling effects in ECOSSE task and may reflect an adaptive orthographic strategy that supports efficient word recognition, potentially contributing to comparable performance at the sentence comprehension level in the present sample.

An alternative interpretation of the present findings is that the modified serial position function observed in the deaf group reflects a shift toward a more serial, position-by-position processing strategy for letters, as opposed to the more parallel processing typically reported in hearing readers (Kamble et al., 2026). In the hearing group, the canonical W-shaped curve suggests that multiple letter positions are processed simultaneously, supported by finely tuned position-specific detectors that mitigate crowding effects at both outer and central positions. In contrast, the deaf group's accuracy profile was dominated by a strong linear component, with performance declining progressively from the first to later positions and lacking the central-position boost characteristic of parallel processing. This pattern, together with the pronounced first-letter advantage, suggests that deaf participants may rely more heavily on extracting information from the initial position and then proceeding sequentially through the string. Such a strategy would be consistent with a greater susceptibility to visual crowding in central positions and might arise from differences in spatial attention allocation or from reduced tuning of receptive fields for non-initial letters during reading acquisition. Future research specifically designed to disentangle serial and parallel processing strategies in deaf readers would be necessary to directly test this account.

For digit stimuli, both groups showed strong and consistent linear effects, with performance decreasing from the beginning to the end of the string. This pattern accounted for nearly all the observed variance in both groups (96% in hearing, 99% in deaf), indicating that digit recognition is primarily driven by a serial processing gradient, possibly reflecting attentional biases or left-to-right scanning strategies. A growing body of research suggests that visual processing during reading is shaped by habitual scanning directions associated with written language. Spatial processing biases vary as a function of reading direction, with left-to-right (LTR) and right-to-left (RTL) exhibiting corresponding attentional asymmetries (Holcombe et al., 2017; Jordan et al., 2014; Smigasiewicz et al., 2010). These findings can be interpreted within broader frameworks of attentional allocation and visual working memory. For example, spatial prioritization may reflect a learned strategy in which items are processed sequentially according to reading direction, with higher priority assigned to earlier positions (e.g., the left side in LTR languages such as French). This interpretation is also consistent with serial models of reading, such as the EZ Reader model (Reichle et al., 2003), which propose that words are processed sequentially in the order dictated by the writing system. Importantly, while such directionality effects are well established for linguistic stimuli (letters and words), their generalization to non-linguistic symbols is less straightforward. The alignment between attentional biases and reading direction may be strongest when stimuli are language-like or recruit orthographic processing mechanisms. In contrast, non-linguistic symbols may not engage learned scanning strategies to the same extent and thus may show weaker or different spatial biases.

Finally, no reliable position effects were observed for symbol strings in either group. This absence of structured position-dependent variation is consistent with prior work suggesting that unfamiliar or non-linguistic symbols are more susceptible to crowding and less likely to benefit from positional advantages observed for overlearned or meaningful stimuli (Tydgat & Grainger, 2009).

Our findings also challenge the WPE hypothesis. While it is evident that deaf readers may allocate visual attention more broadly, as indicated by prior studies, this broader attention span does not seem to mitigate the effects of crowding at central positions. Consequently, the efficiency of deaf readers appears to be asymmetrical: it is heavily dependent on strong initial-letter cues, while medial positions remain more susceptible to interference. This observation suggests that the WPE hypothesis necessitates refinement, as the efficiency of deaf readers is not uniformly distributed throughout the letter string. If neither MRF nor the WPE hypothesis fully accounts for the current data, an alternative consideration is that deaf readers may develop distinct visuo-cognitive strategies. These may include a greater reliance on serial position-by-position processing, variations in spatial attention allocation, or adaptations in the management of visual crowding. Such mechanisms may function in conjunction with, or even substitute for, the tuning processes posited by the MRF and the efficiency mechanisms suggested by the WPE.

It is important to acknowledge that both the WPE and MRF hypotheses were not originally developed or validated within the context of the present paradigm. The WPE hypothesis, in particular, was formulated to account for eye movement behavior during connected text reading, and the TSI task involving masked, isolated letter strings does not directly fulfill the procedural conditions under which its predictions were derived. Similarly, while the MRF hypothesis offers a compelling account of low-level orthographic tuning mechanisms, it was developed primarily from data on hearing populations, and its extension to the present paradigm and population should be understood as interpretively useful but inferential rather than as a direct empirical test of its core claims. Understanding how serial position functions in letter identification relate to broader models of orthographic processing requires examining whether mechanisms identified in hearing readers generalize to deaf readers, who acquire reading under markedly different sensory and linguistic conditions.

Importantly, the comparison is not motivated by a normative deficit framework (i.e., asking whether deaf readers are worse), but by a mechanistic question: Do deaf readers rely on the same spatial–perceptual computations as hearing readers during letter recognition, or do they engage distinct pathways that reflect different sensory and language experiences? Only by contrasting groups can we determine whether differences in serial position functions reflect

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(a) domain-general visual–attentional adaptations, (b) domain-specific orthographic tuning, or (c) individual variability independent of hearing status. Thus, the cross-group design directly tests theoretical models of visual word recognition rather than evaluating deaf readers against hearing norms. Recent work in deaf studies has rightly emphasized the need to avoid deficit framings in hearing–deaf comparisons and to foreground the linguistic, cultural, and cognitive diversity of deaf populations. From this perspective, differences between deaf and hearing readers are not interpreted as impairments but as adaptations that emerge from distinct sensory ecologies, language experiences, and educational trajectories. Our study aligns with this approach by (1) avoiding language about deficits or delays, (2) acknowledging sign languages as fully complex linguistic systems, and (3) interpreting group differences as alternative pathways to literacy rather than deviations from a hearing norm.

Conclusion

In conclusion, hearing participants exhibited the typical W-shaped serial position function for letter recognition, highlighting the combined effects of visual acuity and reduced crowding at string boundaries. Deaf participants, in contrast, displayed a more complex and asymmetric pattern, supporting the alternative prediction that deafness can influence letter recognition under crowded conditions, even in the fovea. These results suggest that while the core mechanisms supporting initial-letter processing are preserved, spatial tuning for other positions may be influenced in deaf readers. Our findings are thus partially consistent with the MRF hypothesis, and point to the need for models that accommodate variability in spatial attention and perceptual tuning among diverse reading populations.

Constraints on generality

The present findings are derived from a sample of adult participants, comprising either deaf signers or hearing readers. Consequently, the results may not be generalizable to individuals with varying degrees of hearing loss, or those with limited educational backgrounds. Additionally, our materials consisted of brief sequences of consonants, digits, and symbols, which were presented centrally under time-constrained conditions. It remains uncertain whether comparable position effects would manifest in connected text, under prolonged exposure times. The TSI paradigm utilized in this study isolates early visual-orthographic processing within a rigorously controlled environment; performance in natural reading contexts may also be influenced by higher-order lexical and semantic constraints.

Furthermore, spatial attentional biases are known to vary systematically across left-to-right (LTR), right-to-left (RTL), and top-to-bottom reading systems, reflecting learned strategies in which information is prioritized according to reading direction (Holcombe et al., 2017; Jordan et al., 2014). Accordingly, the left-to-right processing patterns observed in the present study, conducted in a French linguistic context, may not generalize to populations reading in other directions, where distinct attentional biases and processing strategies may emerge.

We anticipate that variations in the specific letter strings, digit sets, or symbol sets would not significantly impact the observed position functions. However, critical methodological attributes, namely brief central presentation, post-cueing, and masking, are essential for eliciting serial position effects and should remain consistent for purposes of replication.

Endnote

1. The odd-man-out is written in Italic.

Data availability

The study was not preregistered. Our data and codes are freely available at the OSF link –. https://osf.io/rbwgd/?view_only=0b0a5a46f5414180b10a365a7489d10b.

Author contributions

Veena Sameer Kamble (Conceptualization, Formal analysis, Writing—review & editing), Jennifer Leleux (Data curation, Formal analysis, Project administration), Marie Pirlot (Data curation, Formal analysis, Project administration), and Virginie Crollen (Conceptualization, Formal analysis, Funding acquisition, Supervision, Writing—original draft)

All authors contributed to the study and approved the final version of the manuscript.

Funding

This work was supported by “Projet De Recherche” (PDR, Grant no. T.0036.22) granted by the Fund for Scientific Research–National Fund for Scientific Research (FRS–FNRS, Belgium) to V.C.

Conflicts of interest

None declared.

Acknowledgments

This research has benefitted from the statistical consultation with the Statistical Methodology and Computing Service, a technological platform at UCLouvain—SMCS/LIDAM, UCLouvain. We would like to thank all the individuals who participated in this study.

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Appendices

Appendix A

Table showing demographic characteristics of 15 deaf participants, including subject ID, age, sex, handedness, education level, age at diagnosis, deafness etiology, and level of deafness.

Table A1 Characteristics of the deaf participants.

Sub	Age	Sex	Handedness	Education	Age at diagnosis	Etiology	Deafness level
1	27	M	R	Secondary school	1 year	Congenital	Profound
2	47	F	R	Bachelor	2 years 6 months	Congenital	Complete
3	22	M	R	Bachelor (second year)	6 months	6 months	Profound
4	57	F	R	Secondary school	2 years 6 months	Congenital	Profound
5	45	M	R	Master	1 year 6 months	Congenital	Profound
6	41	M	R	Doctorate	2 years	Congenital	Profound
7	59	F	R	Fourth year of secondary school	1 year	1 year	Profound
8	35	F	R	Bachelor	8 months	Congenital	Profound
9	25	M	R	Master	1 year	Congenital	Profound
10	23	F	R	Bachelor (third year)	3 years	Congenital	Profound
11	25	F	R	Master	1 year	Congenital	Profound
12	26	M	R	Master	9 months	Congenital	Profound
13	45	M	L	Bachelor	10 months	10 months	Profound
14	41	F	R	Bachelor	/	Congenital	Profound
15	30	M	R	Bachelor	3 years	3 years	Profound

Note. F = females; M = males; L = left; R = right.

Appendix B

Table listing hearing device information for 15 deaf participants, including auditory device type, frequency of device use, estimated hearing level without and with device, frequency of LSFB use, and primary language.

Table B1 Information about hearing devices of the deaf participants.

Sub	Auditory devices	Use of hearing device	Hearing level estimate without hearing device	Hearing level estimate with hearing device	LSFB use	Primary language
1	HA (L & R)	Daily	Average	Good	Daily	LSFB
2	None	/	Profound deafness	/	Daily	French
3	CI (R)	Daily	Profound deafness	Good	Daily	French + LSFB
4	CI (R)	Daily	Profound deafness	Good	/	French
5	None	Never	Profound deafness	/	Daily	French
6	CI (L & R)	Daily	Profound deafness	Very good	/	French
7	CI (L) & HA (R)	Daily	Profound deafness	Good	Occasional	French
8	CI until 23 years	/	Profound deafness	/	Daily	French
9	CI (L)	Daily	Profound deafness	Good	/	LSFB
10	CI (L & R)	Daily	Profound deafness	Good	Daily	French + LSFB
11	CI (R)	Daily	Profound deafness	Average	Daily	LSFB
12	CI (L)	Daily	Profound deafness	Doesn't know	Daily	LSFB
13	HA (L & R)	Information unavailable	Profound deafness	/	/	French
14	None	/	Profound deafness	/	Daily	LSFB
15	CI (L)	Daily	Profound deafness	Good	Daily	French + LSFB

Note. CI = cochlear implant; HA = hearing aids; L = left; R = right.

Appendix C

Table containing the list of stimuli for the spelling task. Regular and irregular French words are grouped by high- and low-frequency conditions. Incorrect (misspelled) words are shown in italics.

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Table C1 List of spelling task stimuli. Regular words and irregular words used in the spelling task.

Conditions	Regular words	Irregular words
High frequency	Frère	Nuit
	École	*Vile*
	Tête	*Blan*
	Damme	Hiver
	Parmis	Six
	Livre	Huit
	Craime	*Vint*
	Tissu	Sang
	Règle	*Étans*
	Parque	*Cliant*
	Garre	Rang
	Maizon	Long
	Pâte	Fusil
	Piste	*Temp*
	Caffé	*Tront*
	Sucre	Banc
	Métal	Fils
	Pane	*Corp*
	Bocale	*Famme*
	Stylot	Hier
	Juppe	*Doig*
	Cadre	*Mile*
Low frequency	Nacre	Item
	Nèphle	Hélas
	Écrux	*Promt*
	Soja	*Emental*
	Narvale	Ajonc
	Tapire	Nerf
	Pâlir	*Gagere*
	Yétti	Flux
	Calle	Jonc
	Allée	*Chao*
	Flûtte	*Crucifi*
	Zèbre	Coing
	Rume	*Tacycardie*
	Lamme	Clerc
	Mâle	*Rassio*
	Mètre	*Fétus*
	Folie	*Meurs*
	Perle	*Moallon*
	Coala	Poster
	Larme	*Pic-ver*
	Cargot	Lys
	Sabre	Paon

Note. Incorrect words are written in italics.

Appendix D

Table showing word stimuli for the phoneme judgment task. Words are grouped into four conditions (Shallow 1, Shallow 2, Deep 1, Deep 2) and separated into consonant and vowel categories. Incorrect words appear in italics.

Table D1 List of phoneme judgment task stimuli. Consonants and vowels used in four conditions for the phoneme judgment task.

Conditions	Consonants	Vowels
Shallow 1	chat—*singe*—chaise	Rond—*point*—pont
	pâtes—poule—*faim*	*Sel*—route—poule
	mer—toile—toit	*Roue*—main—pain
	verre—vin—*pile*	Croix—*manche*—noix
	mouche—mur—*bol*	Riz—pile—*sel*
Shallow 2	ferme—phare—*bosse*	Beurre—*chaise*—cœur
	note—queue—cage	Melon—queue—*note*
	bulle—soupe—cerf	Vin—*loupe*—pain
	pelle—géant—jupe	Lait—*pipe*—tête
	kiwi—craie—*pâtes*	Manche—tente—*nez*
Deep 1	carte—coffre—*cirque*	*Melon*—persil—terre
	cirque—*croûte*—cerf	*Beurre*—jeux—bleu
	goutte—gare—*génie*	*Queue*—beurre—fleur
	phare—*plante*—photo	Pelle—*melon*—cerf
	poule—*phare*—plante	Lait—laine—*bain*
Deep 2	café—kiwi—*cerf*	*Têtard*—lait—tête
	queue—*cerf*—croix	Laine—pelle—*melon*
	jeux—*goutte*—génie	Melon—fleur—*queue*
	cerf—singe—*cape*	Banc—cane—dent
	plume—phare—froid	*Pomme*—pompier—bonbon

Note. Incorrect words are written in italics.

Appendix E

Table E1 Table showing results from two ANOVA models across two datasets: a full dataset (N = 46) and a current dataset (N = 30). Rows list predictors: Position, Character, Position × Character interaction, and Group × Position interaction.

Predictor	Full Dataset (*N* = 46) *F*(df)/*p*-value	Current Dataset (*N* = 30) *F*(df)/*p*-value
Position	$F(4,616) = 10.49$, $p < .001$	$F(4,392) = 16.42$, $p < .001$
Character	$F(2,616) = 5.57$, $p = .004$	$F(2,392) = 4.94$, $p = .008$
Position × character	$F(8,616) = 3.16$, $p = .002$	$F(8,392) = 3.34$, $p = .001$
Group × position	$p > .05$	$F(4,392) = 2.27$, $p = .062$

Note. Table comparing two ANOVA models on dataset with all participants versus participants that performed above chance level.

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Journal of Deaf Studies and Deaf Education, 2026, 1–13
https://doi.org/10.1093/jdsade/enag050
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