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The processing of multiple letters and multiple words in deaf adults

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Abstract

Readers utilize both foveal and parafoveal information to recognize letters and words effectively. In the fovea, the ability to identify letters is maximized, resulting in greater accuracy for letters that are directly fixated upon. Conversely, the accuracy of letter identification diminishes in the parafovea. Notably, letters at the beginning and end of words are often recognized more accurately than those in the middle, which yields a W-shaped function in identification accuracy and an M-shaped function in response times. Building upon these observations, word identification rates are higher for strings presented in the foveal area. Due to an attentional bias toward reading direction, there exists a greater ability to identify words in the right parafovea compared to the left. Given that deaf readers display a distinct distribution of visual attention, the present study aims to investigate, using a Rapid Parallel Visual Presentation paradigm, whether deaf readers differ in their ability to identify letters and words. Participants were presented with three-letter nonword and word sequences at foveal and parafoveal positions and instructed to identify post-cued letter and word targets. While both groups demonstrated the W-shaped accuracy function for letter identification, response times for deaf readers were characterized by a distinct M-shaped pattern, particularly for letters in the right visual field (RVF). Hearing participants exhibited a RVF advantage in word identification; however, deaf participants displayed a reduced RVF advantage, suggesting a more bilateral distribution of visual attention during reading. These results indicate that deafness leads to subtle yet significant differences in letter and word identification processes.

Keywords Deafness · Word identification · Letter identification · Visual attention · Parafoveal processing · RPVP

Introduction

When reading texts from left to right, the eyes fixate on a single word before moving to the next. Despite primarily focusing on processing the fixated words within foveal vision (i.e., the retinal area up to 2° of visual angle), readers also utilize information from parafoveal vision, which extends up to 5° of visual angle around the foveal region (e.g., McConkie & Rayner, 1975; Snell & Grainger, 2018, for computational models of reading). The extent of valuable preview information within these regions is known as the perceptual span and typically extends from three to four letters to the left and up to 15 letters to the right of fixation (Rayner, 1998; Reichle et al., 2009). The visibility of letters and words within this span is influenced by various visual factors (Bouma, 1970; Grainger et al., 2016), such as visual acuity, crowding, and visuo-spatial attention. When recognizing letters within a five-letter string, for example, individuals consistently demonstrate superior letter recognition performance for letters positioned at the far left of the array (first position), at the medial position (third position), and at the far right of the array (fifth position), compared with their neighboring letters occurring in the second and fourth positions (Tydgat & Garinger, 2009). In this context, visual acuity for the central letter and reduced crowding for the first and last letters contribute to efficient letter identification. This produces a W-shaped function in recognition

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accuracy (Tydgat & Grainger, 2009; Ziegler et al., 2010) and an M-shaped function in recognition times (Hammond et al., 1982; Pitchford et al., 2008).

The combined effects of visual acuity, crowding, and visuo-spatial attention also influence the simultaneous processing of multiple letter strings. In this context, letter visibility as a function of position within the string is examined using the Rapid Parallel Visual Presentation (RPVP) paradigm. An extended W-shaped pattern is reported when three three-letter strings are presented simultaneously at the fovea and parafovea, with peak letter identification performance observed at the three central positions as well as the first and last letters of the entire sequence of nine letters (Scaltritti et al., 2021). The central string benefits from high visual acuity, while the first and last letters of the entire sequence benefit from reduced crowding, facilitating processing compared to interior letters. Expanding on these observations, findings from the RPVP paradigm have shown that participants exhibit higher word identification rates for strings presented in the foveal area. Furthermore, there is a greater ability to identify words in the right parafovea compared to the left parafovea (Scaltritti et al., 2021). This advantage in the right visual field (RVF) is believed to reflect an inherent attentional bias toward reading direction (Ducrot & Grainger, 2007; Snell & Grainger, 2019) or the emergence of a highly organized cortical system that integrates the processing of visuo-orthographic, phonological, and lexico-semantic features of words (Landi et al., 2013; Pugh et al., 2000), particularly within the left hemisphere, which is associated with connections to the speech-based language system (Borowsky et al., 2006; Canário et al., 2020; Cohen & Dehaene, 2004).

Considering that deafness profoundly impacts the cognitive and neural bases of language, and visual processing (Goldin-Meadow & Mayberry, 2001), reading difficulties are more frequently observed among the deaf compared with the general population (Herman et al., 2017; Wagner et al., 2020). Neuroimaging work, for example, has shown that the neural organization for reading in deaf adults diverges from the one of hearing readers. Whereas hearing readers typically show a strong left-lateralized network for orthographic and phonological processing, deaf readers often display more bilateral activation patterns during word recognition (e.g., Emmorey, 2020; Glezer et al., 2018; Corina et al., 2013; Neville et al., 1998). For example, studies report bilateral recruitment of occipito-temporal regions for orthographic selectivity (Emmorey et al., 2017) and reduced left-hemisphere dominance for language processing (Costello et al., 2021). Such findings suggest that deafness is associated with altered hemispheric specialization and neural reorganization of the reading system, likely reflecting both reduced phonological tuning and enhanced reliance on visual/orthographic mechanisms.

However, while research over the past 2 decades has predominantly emphasized the role of phonology in reading acquisition among deaf individuals (Trezek & Mayer, 2019), relatively few studies have investigated the visual and orthographic mechanisms that support reading in this population. Two eye-movement studies have shown that deaf readers exhibit a wider perceptual span compared with hearing readers—up to 18 letters to the right of fixation (Bélanger et al., 2012) and 10 letters to the left (Stringer et al., 2024). This suggests that deaf readers are capable of extracting more visual information within a single fixation, potentially indicating a broader attentional window. However, it remains unclear whether this broader span facilitates or hinders efficient word recognition. Although wider visual attention may enhance parafoveal processing, it could also increase the risk of perceptual interference or diminish attentional focus on the target (Dye et al., 2008; Lu & Guoli, 2018). To further probe visual and orthographic mechanisms, a recent study investigated visual crowding in deaf and hearing readers (Kamble et al., 2024). Participants were shown letters or symbols either in isolation or embedded within strings of three or five characters and asked to identify the central character. While hearing participants consistently processed letters more efficiently than symbols across all conditions, deaf participants exhibited this advantage only when stimuli were presented in isolation. This suggests that as visual complexity increases, letter processing in deaf readers may become more susceptible to interference from surrounding characters, indicating subtle differences in visual letter processing strategies.

The present study aims to investigate whether deafness also influences the parallel processing of multiple letters and multiple words. To achieve this, the RPVP design employed by Scaltritti and colleagues (2021) was utilized and presented to early deaf signers and hearing controls. This design first examined the accuracy of word identification by simultaneously presenting three three-letter words, with one word positioned at the fovea and the other two located in the left and right parafovea. Based on prior findings suggesting a more symmetrical attentional spread and reduced lateralization in deaf readers, it was hypothesized that the typical right visual field (RVF) advantage observed in hearing readers would be diminished or absent in the deaf group. The RPVP design then assessed the accuracy in identifying the individual letters of these words when presented at the same location within a context of three three-letter nonword sequences. Given deaf readers' enhanced sensitivity to orthographic structure, it was hypothesized that their letter identification performance would either demonstrate a less pronounced W-shaped or M-shaped pattern due to crowding effects or adhere to the typical pattern reflecting refined letter position coding mechanisms, with optimal letter identification performances expected at the first, last, and central positions of the entire sequence.

Methods

Participants

Twenty deaf (six men, two left-handed, M_{age} = 31.05 years, *SD* = 9.17) and 20 hearing controls (six men, four left-handed, M_{age} = 30.65 years, *SD* = 10) were tested and compensated with 10 € for their participation. Deaf participants were recruited if they (a) presented congenital or early deafness, (b) reported severe to profound hearing loss, and (c) used sign language as their daily means of communication. None of the deaf participants were diagnosed with additional disabilities. Fourteen reported congenital deafness, two prelingual deafness (before 9 months), and four postlingual deafness (between 2 and 6 years of age). The hearing participants were matched with the deaf participants in terms of age, $t(38) = -0.131$, $p = .89$, educational level, $t(38) = 0$, $p = 1$, gender, $\chi^2(1, 40) = .000$, $p = 1.00$, and handedness, $\chi^2(1, 40) = 0.19$, $p = .65$ (see Table 1 for a detailed description of the participants).

Preliminary assessments

Before performing the experimental task, participants completed a battery of assessments. Instructions in Langue des Signes Francophone de Belgique (LSFB) and written format were provided prior to each task. These tasks measured sentence comprehension, phonological skills, visuo-spatial span, and nonverbal reasoning.

Sentence comprehension was assessed utilizing a computer-adapted version of the ECOSSE task (Jacquier-Roux et al., 2010). Each trial featured four distinct images arranged in each quadrant, illustrating a specific situation, with a sentence presented in the center. The participant's objective was to select the image that accurately corresponded to the meaning of the sentence. The sentences varied in syntactic complexity, and the task comprised 12 trials.

The phoneme judgment task, originally developed by Hirshorn et al. (2015), was adapted into French to evaluate phonological knowledge. In this "odd-man-out" task, participants were presented with three images on a computer screen and instructed to identify which item produced a distinct sound. The task was divided into two blocks: in the first block, the odd-man-out was determined by the first consonant sound, while in the second block, it was determined by the first vowel sound. Additionally, orthographic transparency was manipulated in each block,

Table 1 Characteristics of deaf participants

Sub	Age	Sex	Handedness	Education (in years)	Deafness onset	Etiology	Deafness level
1	28	F	R	14	2 y	Meningitis	Severe and profound
2	25	F	R	13	Birth	Genetic	Severe and profound
3	23	F	R	10	Birth	Unknown	Profound
4	25	M	R	6	Birth	Genetic	Severe and profound
5	19	M	R	6	Birth	Auditory nerve damage	Profound
6	32	M	R	10	6 y	Mumps disease	Severe and profound
7	19	F	R	8	Birth	Genetic	Profound
8	22	F	R	9	Birth	CMV	Profound
9	24	M	R	15	5 y	Meningitis	Profound
10	34	F	L	7	4 y	Meningitis	Complete
11	46	F	R	14	Birth	Unknown	Profound
12	48	M	R	6	Birth	Rubella	Complete
13	31	F	R	10	Birth	Pendred syndrome	Complete
14	33	F	R	16	Birth	CMV	Complete
15	21	F	R	11	Birth	Usher syndrome type 1	Complete
16	30	M	R	13	1 month	Meningitis	Severe and profound
17	42	F	R	9	Birth	Genetic	Profound
18	36	F	L	9	Birth	Malformation	Severe and profound
19	37	F	R	12	Birth	Genetic	Profound
20	46	F	R	11	8 months	Severe ear infection	Profound 3rd degree

R Right-handed, *L* Left-handed, *F* Female, *M* Male, *y* Years which included two shallow and two deep conditions. In the first shallow condition, the two similar-sounding items shared the same orthography, while the odd-man-out had a different orthography (e.g., chat/*singe*/chaise). In the second shallow condition, the three presented images corresponded to words with differing orthographies. Correct responses necessitated 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, all words shared the same letter, and correct responses required knowledge of idiosyncratic mappings in French (e.g., goutte/gare/*génie*). In the second deep condition, the odd-man-out shared orthography with one of the two similar-sounding items (e.g., cerf/singe/*cape*). In total, the task consisted of 40 stimuli, with participants responding by pressing the corresponding number on the keyboard.

Visuo-spatial span was evaluated using the Corsi Block-Tapping Test (Richardson, 2007). In this assessment, participants were presented with a series of nine blocks arranged in a specific pattern on a board. The experimenters tapped a sequence of blocks at a rate of one block per second, and the participant’s task was to replicate the sequence immediately after its presentation. The length of the sequences began with two blocks and gradually increased. The test continued until the participant could not accurately replicate two consecutive sequences of the same length.

Nonverbal reasoning skills were assessed using the Raven Progressive Matrices (Raven & Raven, 2003). This nonverbal assessment measures fluid intelligence, reasoning, and problem-solving abilities through a series of diagrammatic puzzles, each containing a missing piece. The participant’s task was to identify the missing piece from a set of options that best completes the pattern. The complexity of the puzzles increased as the test progressed. Raw scores were converted to age-normalized standard scores in accordance with the test manual.

As indicated in Table 2, the two groups did not exhibit significant differences in sentence comprehension, visuo-spatial memory, or nonverbal reasoning. However, deaf participants scored lower on phonological assessments compared to their hearing counterparts.

For deaf participants, the instructions were recorded in LSFB, the sign language utilized in the French-speaking region of Belgium. All participants reported normal or corrected-to-normal vision and provided written informed consent. The procedures were conducted in accordance with the Declaration of Helsinki and approved by the Research Ethics Boards of the Université Catholique de Louvain (“Comité d’Ethique Hospitalo-Facultaire Saint-Luc” (2019/13JUI/256)).

Table 2 Means and standard deviations (*SD*) for each measure for the deaf and hearing groups

Tests	Hearing		Deaf		*T* test *p* value
	M	*SD*	*M*	*SD*	
Sentence comprehension[a]	11.20	0.52	10.60	1.64	$p = .42$
Phonological skill[b]	34.80	3.30	28.65	6.38	$p = .001$*
Visuo-spatial span[c]	5.90	0.85	5.95	0.94	$p = .86$
Nonverbal reasoning[d]	107.95	14.73	110.95	14.27	$p = .51$

The last column displays the *p* value of an independent-sample *t* test (two-tailed) comparing deaf and hearing participants for each measure

[a] raw score, max = 12. [b] Raw score, max = 40. [c] raw score, max = 10. [d] NS

*$p = .001$

Procedure of the experimental task

Participants performed a word-identification and a letter-identification task in the context of the RPVP paradigm. They were instructed to identify one word from a set of three three-letter words (word-identification task) or one letter out of nine in a sequence of three three-letter nonwords (letter-identification task). All sequences were briefly and simultaneously presented in both the fovea and the left and right parafovea. The task was designed using E-Prime software (Psychology Software Tools, Pittsburgh, PA). Participants were seated approximately 60 cm from the computer screen. Stimuli were presented in black on a gray background using 16-pt Courier New lowercase font. Each string subtended 2.9° of visual angle. Instructions in LSFB and written format were provided prior to the task, followed by nine practice trials to familiarize participants with the procedure. Each trial commenced with a fixation display lasting 517 ms, consisting of two vertical bars positioned at the center of the screen, one above and one below fixation. Participants were instructed to concentrate their attention between the two bars. Subsequently, the target string appeared for 200 ms, followed by a backward mask composed of nine hash marks aligned with the previous letter positions. Two vertical bars served as postcues, indicating the targets to be identified. In the word identification task, cues appeared above and below the middle character of the target word. Conversely, in the letter identification task, two bars appeared, one above and one below the position of the letter to be reported. Participants were instructed to type their responses on the computer keyboard, with their typed responses displayed on the screen in uppercase beneath the string of hash marks serving as a backward mask. Editing and self-correction were permitted using the backspace key. The fixation display reappeared after the participants pressed the “enter” key, and the color of the vertical bars changed to provide feedback (green indicating a correct response, red indicating an error). Feedback remained on the screen for 517 ms, followed by a blank screen that served as the intertrial interval (see Fig. 1). There were 90 trials in the word identification task and 270 trials in the letter identification task for each participant. After every 45 trials, participants were permitted to take self-terminated breaks. The two tasks were administered to participants in a counterbalanced order, with the entire assessment taking approximately three hours to complete.

Stimuli and design

Ninety three-letter French words were selected from the Lexique3 (New & Pallier, 2020; New et al., 2004) database for the word identification task. Regarding their consonant (C) and vowel (V) structure, the majority exhibited a CVC (65.56%) or a CVV (18.89%) structure, while other structures were less common (CCV = 1.11%; VCC = 1.11%; VCV = 6.67%; VVC = 4.44%; VVV = 2.22%), reflecting their distribution in the French language. These words were randomly divided into three subsets, each containing 30 words. Subsequently, 30 triplets of words were created, with each word within a triplet belonging to one of the three subsets. Each participant viewed each triplet three times, with each position of the triplet being probed once per participant. Moreover, all words were probed only once within each participant. The word probed at each position within each triplet was counterbalanced across participants. The only manipulated experimental factor was therefore word position (1 = left parafovea, 2 = fovea, 3 = right parafovea), manipulated within participants and across items.

For the letter identification task, nine nonword variants were generated for each triplet of words by pseudorandomly scrambling the order of the nine letters contained within each word. In each scrambled variant, only one letter retained its original position from one of the words, which served as the target for the letter identification task. The remaining letters did not maintain their original positions within the triplet. During the task, participants encountered all nine scrambled variants corresponding to each word triplet observed in the word identification task. Measures were implemented to ensure that none of the nonwords overlapped with existing French words. This configuration involved two experimental factors: nonword position (1 = left parafovea, 2 = fovea, 3 = right parafovea) and three letter-in-nonword positions (first, second, and third letter). The distribution of consonant-vowel structures was relatively random across the various possibilities (CCC = 17.41%; CCV = 16.33%; CVC = 15.38%; CVV = 13.23%; VCC = 12.55%; VCV = 5.26%; VVC = 12.69%; VVV = 7.15%).

Results

All analyses were conducted using R Statistical Software (Version 4.3.0; R Core Team, 2021). Accuracy was evaluated through generalized linear mixed models utilizing the *lme4* package (Version 1.1–35.5.1.5), while response times for correct responses were analyzed with linear mixed-effects models via the *lmertest* package (Versions 3.1–3; Kuznetsova et al., 2017). Reaction times were not normally distributed. However, both models with and without outliers yielded consistent results. Consequently, no transformations were applied, and raw reaction times were analyzed. All potential interactions between predictors were examined. Fixed effects were deemed significant when their inclusion resulted in a substantial enhancement in goodness-of-fit, as indicated by likelihood ratio tests. Statistical significance was established at $p < .05$ for all computations. For the random effects, we included by-participants and by-items random intercepts. To avoid overparameterization

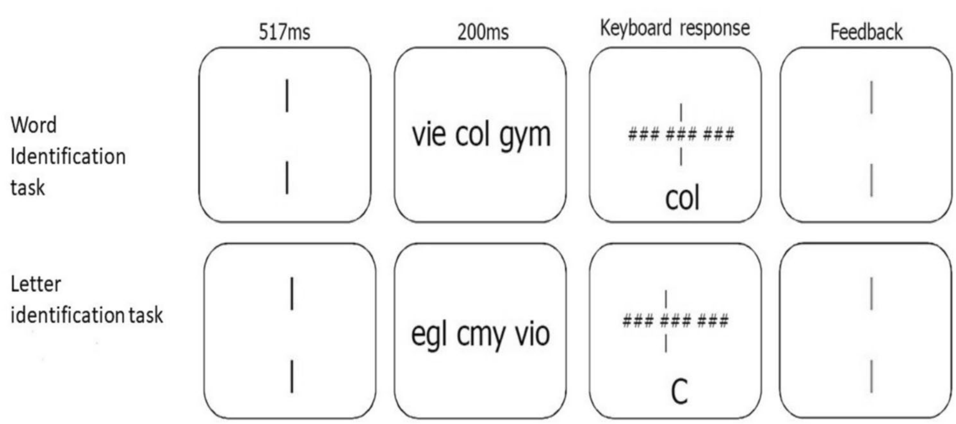

Fig. 1 Schematic illustration of the experimental procedure (not to scale). In this example, for the word identification task, the target stimulus was "col," presented at the fovea, and for the letter identification task it was "c," presented at the fovea (first letter of the second string)

(Matuschek et al., 2017), random slopes were not included in the model. Pairwise comparisons were conducted on the models' estimated marginal means (via the *emmeans* package (Lenth, 2024), and a Bonferroni adjustment of the *p* values was applied to control for multiple comparisons. Additional comparisons encompassed calculating differences in performance scores between fovea, left and right parafovea across word positions in the word identification task, and across nonword positions in the letter identification task. Estimates, standard errors (*SE*s), *z* (accuracy) or *t* (response time) values, along with *p* values, are reported.

Word identification task

A generalized linear mixed model was fitted to predict accuracy with word position (1 = left parafovea, 2 = fovea, 3 = right parafovea) and group (deaf, hearing controls [HC]) (formula: Accuracy ~ word position × group). The model included by-participants and by-items as random intercepts (formula: ~ (1 | subject) + (1| item)). Results highlighted a main effect of word position, $\chi^2(2) = 1261.48$, $p = .001$. Word identification was significantly higher in the fovea than in the left (*estimate* = 4.23, *SE* = 0.16, $z = 25.83$, $p = .0001$) and right parafovea (*estimate* = 2.98, *SE* = 0.15, $z = 19.32$, $p = .0001$). Additionally, accuracy was greater for words presented in the right parafovea than in the left parafovea (*estimate* = 1.25, *SE* = 0.09, $z = 12.70$, $p = .0001$). The interaction between word position and group was significant, $\chi^2(2) = 6.12$, $p = .047$, suggesting that the effect of word position varied across groups. Follow-up comparisons revealed that the difference in accuracy between the left and right words was smaller in the deaf group than in the hearing group (*estimate* = 0.11, *SE* = 0.04, $z = 2.55$, $p = .01$; see Fig. 2A).

A linear mixed-effect model was fitted to response time (RT) with word position and group (formula: RT ~ word position × group). This model also included by-participants and by-items as random intercepts (formula: ~ (1 | subject) + (1| item)). A main effect of word position was observed, $\chi^2(2) = 33.26$, $p = .001$, indicating that word identification was faster at the foveal position compared with words presented in the left (*estimate* = −207.7, *SE* = 39.3, $t = -5.28$, $p = .0001$) and right parafovea (*estimate* = −127.9, *SE* = 32.4, $t = -3.951$, $p = .0002$). The difference between words presented in the right parafovea and those presented in the left parafovea, however, did not reach significance (*estimate* = −79.8, *SE* = 42.1, $t = -1.89$, $p = 0.17$). The interaction between word position and group was also significant, $\chi^2(2) = 8.99$, $p = .01$. Further pairwise comparisons indicated that the difference in reaction times for left and central (foveal) words was greater for the deaf group compared to the hearing group (*estimate* = 197.40, *SE* = 78.5, $t = 2.51$, $p = .01$; see Fig. 2B). No other effects were significant.

Letter identification task

A generalized linear mixed model was fitted on accuracy with nonword position (1 = left parafovea, 2 = fovea, 3 = right parafovea), letter-in-nonword position (first, second, and third letter), and group (deaf, hearing controls (HC)) as

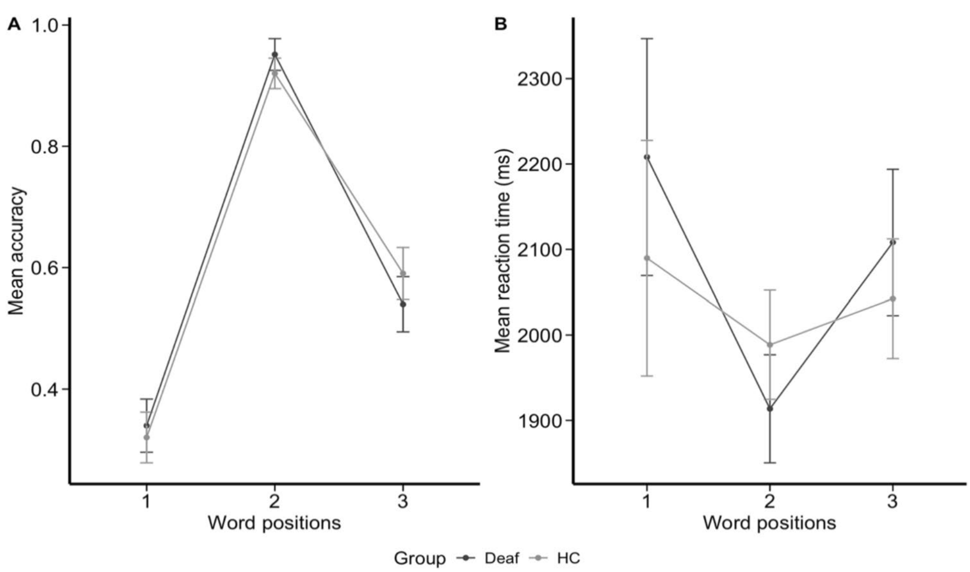

Fig. 2 Results of the word identification task in the deaf group (red) and in hearing controls (HC) (green). **A** Probability of correct response to word targets as a function of their position in the sequence. **B** Response time of correct responses to word targets as a function of their position in the sequence. (1 = left parafovea, 2 = fovea, 3 = right parafovea). Error bars represent 95% confidence intervals. (Color figure online)

fixed effects (formula: Accuracy ~ letter-in-nonword position × nonword position × group). The model included by-participants and by-items random intercepts (formula: ~ (1 | subject) + (1| item)). Results indicated a significant effect of nonword position, $\chi^2(2) = 5235.50$, $p = .001$. Letter identification accuracy was higher in foveal nonwords than in left parafoveal (*estimate* = 4.39, *SE* = 0.08, z = 50.34, *p* =.001) and right parafoveal nonwords (*estimate* = 3.711, *SE* = 0.08, *z* = 45.78, *p* =.001). Furthermore, accuracy was greater for letters in nonwords presented in the right parafovea compared with those presented in the left parafovea (*estimate* = 0.68, *SE* = 0.06, *z* = 10.65, *p* =.001). An effect of letter position was also observed, $\chi^2(2) = 16.90$, $p = .001$, alongside a significant nonword position × letter position interaction, $\chi^2(4) = 409.53$, $p = .001$. In the left parafovea, accuracy was highest at the first letter compared with both the second letter (*estimate* = 1.18, *SE* = 0.11, *z* = 10.02, *p* =.001) and the third letter (*estimate* = 1.90, *SE* = 0.12, *z* = 14.84, *p* =.001). Additionally, accuracy was higher at the second letter than at the third letter (*estimate = 0.71, SE* = 0.14, *z* = 5.09, *p* =.001). In the fovea, accuracy did not differ among the three letter positions. In the right parafovea, no difference in accuracy was found between the first and second letters (*estimate* = −0.19, *SE* = 0.11, *z* = −1.63, *p* =.911). However, accuracy was higher at the third letter than at both the second (*estimate* = 0.88, *SE* = 0.10, *z* = 8.35, *p* =.001) and the first letter (*estimate* = 1.07, *SE* = 0.10, *z* = 10.38, *p* =.001; see Fig. 3A). The interaction between nonword position and group was significant, $\chi^2(2) = 13.73$, $p = .001$. There were no significant differences between the deaf and hearing groups in the left parafovea (*estimate* = −0.25, *SE* = 0.32, *z* = 0.77, *p* = 1), in the fovea (*estimate* = 0.25, *SE* = 0.33, *z* = 0.76, *p* = 1), and the right parafovea (*estimate* = −0.32, *SE* = 0.32, *z* = −1.02, *p* =.915). Although none of the pairwise comparisons reached significance, visualization of the data (see Fig. 3A) suggests that deaf readers tended to be slightly more accurate at foveal positions, but slightly less accurate in the right parafovea, compared to hearing readers.

For response times, the model included letter-in-nonword position, nonword position, and group as fixed effects (formula: RT ~ letter-in-nonword position × nonword position × group). The model also included random intercepts for participants and items (formula: ~ (1 | subject) + (1 | item)). The analysis indicated a significant main effect of nonword position, $\chi^2(2) = 280.19$, $p = .001$, revealing that identification was faster in the foveal than in the left (*estimate* = −354.7, *SE* = 33.0, *t* = −10.73, *p* =.001) and right parafovea (*estimate* = −390.2, *SE* = 25.9, *t* = −15.06, *p* =.001). Response times for nonwords presented in the right parafovea did not significantly differ from those in the left parafovea (*estimate* = 35.6, *SE* = 37.6, *t* = 0.94, *p* = 1). Additionally, the interaction between nonword position and letter position was significant, $\chi^2(4) = 18.92$, $p = .0008$. In the left parafovea, response times were faster at the first letter compared with both the second letter (*estimate* = −211.62, *SE* = 63.1, *t* = −3.35, *p* =.007) and the third letter (*estimate* = −213.31, *SE* = 76.1, *t* = −2.80, *p* =.04). No significant difference in response times was observed between the second and the third letter (*estimate* = −1.69, *SE* = 84.6, *t* = −0.02, *p* = 1). In the fovea and right parafovea, there were no differences in response times across the three letter positions. Furthermore, the results indicated a significant interaction between letter position and group, $\chi^2(2) = 9.24$, $p = .01$, a significant interaction between nonword position and group, $\chi^2(2) = 23.52$,

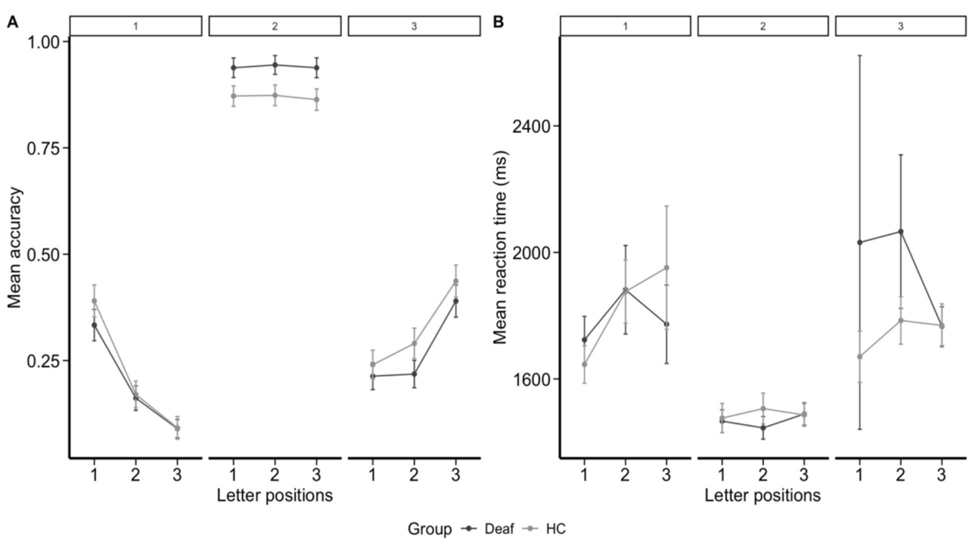

Fig. 3 Results of the letter identification task of deaf group (red) and hearing controls (HC) (green). **A** Accuracy performances of each letter position for each nonword. **B** Response time of correct response for each letter position. Error bars represent 95% confidence intervals. (Color figure online)

p =.0001, and a significant three-way interaction involving letter position, nonword position, and group, $\chi^2(4) = 14.19$, p =.005. Follow-up comparisons demonstrated that the difference in RTs between the left and right parafovea was greater in the deaf group compared to the hearing control group (*estimate* = −176.9, *SE* = 69.2, *t* = −2.55, *p* =.01). The difference between the fovea and the right parafovea was also larger in the deaf group than in the hearing control group (*estimate* = −212.6, *SE* = 50.7, *t* = −4.19, *p* =.0001). The three-way interaction suggested that letter identification performance in the left parafovea and in the fovea was comparable between deaf and hearing participants (see Fig. 3B). However, in the right parafovea, deaf participants exhibited slower identification of the first letter compared to hearing participants. Detailed pairwise comparisons are presented in Table 3.

Discussion

The main goal of this study was to examine the simultaneous processing of words and letters in deaf versus hearing readers using the Rapid Parallel Visual Presentation (RPVP) paradigm. In two independent tasks, participants were required to identify one word from a set of three three-letter words or one letter out of nine in a sequence of three three-letter nonwords. All sequences were briefly and simultaneously presented in both the fovea and the left and right parafovea. In line with our hypothesis and consistent with previous findings, the size of the right visual field (RVF) advantage for word identification was greater in the hearing group. This RVF benefit is typically attributed to left-hemisphere specialization for language (Brysbaert et al., 1996; Nettleton & Bradshaw, 1983; Knecht et al., 2000; Springer & Deutsch, 1998) and/or attentional biases aligned with reading direction (Maurer & McCandliss, 2008; Simola et al., 2009). According to the first hypothesis, the RVF advantage for word recognition is well-established and rooted in the left-lateralized reading network, wherein RVF input has direct access to the language-dominant left hemisphere. Anatomically, the RVF advantage is explained by contralateral projections from the retina to the brain, providing RVF stimuli with relatively direct access to the primary visual and language-processing areas of the left hemisphere, whereas left visual field (LVF) stimuli must traverse the corpus callosum (Banich, 2003; Bourne, 2006). The second hypothesis posits that attention is not evenly distributed across the median plane when individuals focus on a word (Kinsbourne, 1970). During linguistic tasks such as reading, the left hemisphere activates, exerting control over behavior and attention. This leads to an automatic allocation of more attentional resources to the right visual field (RVF), which corresponds to the left hemisphere, resulting in enhanced word identification in the RVF.

Table 3 Results of the pairwise comparisons for response time conducted across the three letter positions in a nonword (1, 2, 3)

Letter positions compared between groups (Deaf-HC)	Estimated difference	*SE*	*t*	*p*
Nonword position 1				
First letter	128.88	129.2	0.99	1
Second letter	57.70	148.4	0.38	1
Third letter	−113.89	174.4	−0.65	1
Nonword position 2				
First letter	28.78	117.5	0.24	1
Second letter	−20.70	117.4	−0.17	1
Third letter	43.02	117.5	0.36	1
Nonword position 3				
First letter	405.63	139.3	2.91	.06
Second letter	337.61	137	2.46	.23
Third letter	47.79	126.8	0.37	1

Thus, this attentional bias is influenced by left hemispheric control and, to some extent, scanning habits, including the primary direction of attention and eye movements relative to script orientation (Heron, 1957; Nicholls et al., 2001). In this context, RVF words may undergo automatic processing, while LVF words may require focused attention for identification. When words are presented in the parafovea, an endogenous attentional bias (i.e., voluntary orientation of attention based on behavioral goals) emerges in the direction of reading (Nicholls & Wood, 1998; Ducrot & Grainger, 2007), leading hearing participants to process words more effectively in the right parafovea than in the left parafovea.

The reduced size of right visual field (RVF) advantage observed in the deaf population compared to hearing population may indicate that reading processes in this population rely on atypical patterns of neural activation (Neville et al., 1998). Studies have shown that deaf readers often engage bilateral brain activation during word processing, possibly due to reduced phonological tuning and altered orthographic representations (Corina et al., 2013; Costello et al., 2021; Emmorey et al., 2017; Meade et al., 2019).

This may reflect not only neural reorganization but also an atypical deployment of visuo-spatial attention. Endogenous orienting of attention (top-down), characterized by voluntary shifts in the absence of salient events, typically predicts the location of upcoming targets with high probability, facilitating the processing of multiple targets. In contrast, exogenous attention (bottom-up), driven by salient external stimuli, is more beneficial for processing single targets (Guzman-Martinez et al., 2011). These findings imply that deaf individuals' visual attention is more readily captured by bottom-up stimuli and that top-down attentional shifts may require greater effort. In contrast, hearing individuals exhibit a greater reliance on endogenous cues, particularly in peripheral visual fields, reflecting a more top-down approach to attentional allocation (Li et al., 2022; Pavani & Bottari, 2012). Consequently, words presented in the LVF may receive comparable attention to those in the RVF, reducing the typical RVF advantage.

The letter identification task conducted in the present study revealed a similar RVF advantage as noted in the word identification task: participants demonstrated higher accuracy in identifying letters when presented in the right visual field compared to the left visual field. Additionally, when this advantage was compared for words versus nonwords, it was stronger for word stimuli (.2, 95% CI [.09,.30]) than for nonword stimuli (.07, 95% CI [.02,.13]) among deaf participants. Hearing participants showed a similar but more pronounced pattern (.27 for words, 95% CI [.15,.38];.10 for nonwords, 95% CI [.03,.17]).

For letters, accuracy was highest at the three central letter positions (attributed to visual acuity) and decreased with increasing distance from fixation, with exceptions noted for the first and last letters of the entire sequence (i.e., nonword Position 1, first letter, and nonword Position 3, third letter). In these instances, diminished visual acuity was counterbalanced by a reduction in crowding interference due to the decreased number of adjacent characters. Post hoc pairwise comparisons, collapsed across groups, between nonword in the left and right parafovea, based on letter-in-nonword eccentricity, revealed that letter identification in the RVF consistently surpassed that in the LVF. Indeed, accuracy for the first letter of the right parafovea nonword was significantly higher compared to the third letter of the left parafovea nonword (*estimate* = 1.13, *SE* = 0.13, z = 8.55, p <.001). Identification of the second letter of the right parafovea nonword was significantly better than the second letter of the left parafovea nonword (<.001). Furthermore, identification of the second letter of the right nonword was significantly better than that of the second letter of the left nonword (*estimate* = 0.60, *SE* = 0.10, z = 5.59, p <.001). Finally, accuracy for the third letter of the right nonword was slightly higher than for the first letter of the left nonword, with the difference approaching conventional significance (*estimate* = 0.30, *SE* = 0.09, z = 3.15, p =.05). These findings closely align with those reported by Scaltritti and colleagues (2021) and suggest that the letter identification performances of deaf readers adhere to the typical extended W-shaped function.

However, the M-shaped function characterizing response times was distinct in the deaf group, particularly when the letter closest to fixation was located in the right visual field. According to the Modified Receptive Field (MRF) hypothesis (Tydgat & Grainger, 2009), during the acquisition of reading skills, neurocognitive adjustments to the reading environment shape the receptive fields for letters, particularly in the left visual field (LVF), resulting in oval-shaped receptive fields with greater elongation toward the left and a more symmetrical shape in the right visual field, thus exhibiting reduced rightward extension. Consequently, initial letters viewed in the LVF are expected to experience less crowding, while subsequent letters may encounter more crowding compared to those in the RVF at comparable distances from the fixation point (Chanceaux et al., 2013; Grainger et al., 2010). This visual-field specificity of receptive field shape accounts for the systematic observation that the initial-position advantage (LVF) is consistently larger than the final-position advantage (RVF). For leftward initial letters, particularly in languages read from left to right, these receptive fields are further elongated to the left. This leftward elongation reduces interference from rightward flanking letters, enhancing the visibility of the first letter as a key access point for word recognition.

For deaf individuals, the initial letter presented in the LVF does not exhibit significant impairment, thereby preserving its role in reading. However, innermost letters presented in the RVF demonstrate longer processing times. While Kamble et al. (2024) suggest that attention spread in the periphery slows down efficient processing of letters in crowded condition, our results also point to nuanced differences in response dynamics, possibly reflecting altered attentional strategies even within the parafoveal region. Since our strings were short (three letters) and presented parafoveally, it is unlikely that the effects are driven by spatial crowding, which are more pronounced in longer or more peripheral stimuli. Rather, our results point toward differences in strategic allocation of attention during early orthographic processing, possibly reflecting broader or less focused visual attention in deaf readers (Li et al., 2022).

One potential explanation for these findings is that deaf individuals compensate for the absence of auditory input by reallocating attentional resources to vision. At a descriptive level, the observed pattern appears to be inconsistent with the "division of labor" hypothesis, which posits that enhanced parafoveal processing in deaf individuals may occur at the expense of foveal efficiency (Dye & Bavelier, 2010; Proksch & Bavelier, 2002). Visual inspection of Fig. 3 indicates that deaf readers demonstrated slightly higher accuracy and marginally faster processing for foveal letters, while performance in the right parafovea was comparable across groups in terms of accuracy, while displaying marginally slower processing times in the deaf group for the two positions closest to fixation. This trend may suggest relatively efficient foveal processing among deaf readers, alongside subtle temporal costs in right-parafoveal processing. However, given that these patterns were not statistically reliable, they should be interpreted with caution and regarded as preliminary.

The present findings thus extend our understanding of reading by elucidating how phonological processing and visual attention collaboratively influence the efficiency of word recognition. For hearing readers, the pronounced RVF advantage observed in this study likely reflects the alignment of left-lateralized phonological networks with attentional biases favoring the right visual field. This indicates that phonological processing not only facilitates lexical access but also interacts with visual attention, thereby biasing the allocation of cognitive resources. Conversely, the diminished RVF advantage in deaf readers suggests an alternative balance between these mechanisms. With a reduced reliance on phonological representations, deaf readers appear to allocate attentional resources more symmetrically across visual fields, indicating a heightened dependence on visuo-spatial and orthographic strategies. This interpretation is consistent with previous evidence that deaf readers often rely less on phonological codes and may even demonstrate faster lexical decisions than hearing readers (Fariña et al., 2017; Meade et al., 2020; Lee et al., 2022). More broadly, these results emphasize that reading is not exclusively a linguistic activity but also a visuo-attentional one, dynamically tuned by the availability of phonological codes.

An important next step will be to broaden the comparison groups beyond deaf signers and hearing non-signers. In particular, French-speaking hearing-impaired readers represent a critical population: unlike deaf signers, they acquire spoken French as a first language, but reduced auditory access may limit the development of phonological representations. Depending on degree and onset of hearing loss, as well as amplification and language environment, their performance might either resemble that of deaf readers (if phonological constraints dominate) or align more closely with hearing controls (if spoken language access is preserved). In parallel, hearing signers provide a unique opportunity to disentangle the contributions of sensory deprivation and sign language experience. Unlike deaf signers, they share full auditory access with hearing non-signers, yet their everyday use of a visual–manual language engages attentional and neural mechanisms that may resemble those of deaf signers. Indeed, prior work has shown that sign language experience can redistribute visual attentional resources (Stoll & Dye, 2019). Taken together, testing both French-speaking hearing-impaired readers and hearing signers would provide critical leverage to disentangle the respective roles of auditory deprivation, sign language use, and bilingual (LSFB–French) status in shaping visual attention during reading.

In conclusion, this study investigated the simultaneous processing of words and letters in deaf readers utilizing the RPVP paradigm. Hearing readers demonstrated a pronounced RVF advantage for both words and letters, likely indicative of left-hemispheric language specialization and attentional biases associated with reading direction. Conversely, deaf readers exhibited a diminished RVF advantage, suggesting variations in neural organization and attentional allocation. While letter identification patterns were broadly similar across groups, the deaf group displayed subtle deviations, potentially linked to modified visuo-spatial attention strategies. These findings highlight nuanced differences in early visual processing influenced by sensory experience. While our sample size was necessarily limited by the demographics of the deaf community, our findings provide a valuable starting point for replication studies in other contexts. The present results yield concrete effect size estimates that can be used to conduct power analyses for future studies, allowing replication attempts to be properly powered. Such work across different countries and sign languages will not only test the robustness of our findings but also help to establish their cross-linguistic and cross-cultural generalizability.

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Author contributions V.K.: conceptualization, formal analysis, writing–original draft, data curation, investigation

M.S.: conceptualization, formal analysis, writing–review and editing, methodology

V.C.: conceptualization, writing–review and editing, funding acquisition, supervision.

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Data availability The study was not preregistered. Our data are freely available at the OSF link: https://osf.io/u6w82/?view_only=966349ca25504c3782446a695eefc343.

Code availability Our codes are freely available at the OSF link: https://osf.io/u6w82/?view_only=966349ca25504c3782446a695eefc343.

Declarations

Ethics approval 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.

Consent to participate Written informed consents to participate were signed by all participants.

Consent for publication Written consents for use of data for publication were signed by all participants.

Conflicts of interest The authors declare no conflict of interests.

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