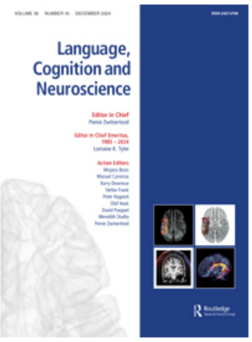

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A stringent test of visuospatial position uncertainty accounts of letter position coding

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ABSTRACT
The encoding of letter position appears to be relatively flexible. Transposed-letter pseudowords (e.g. *CHOLOCATE*) are more often misidentified as their base words (*CHOCOLATE*) compared to replacement-letter pseudowords (*CHOTONATE*) – transposed-letter effect. One plausible explanation for this effect is that it arises from visuospatial position uncertainty in letter position encoding. To test this account, we conducted two lexical decision experiments. Pseudowords were presented syllable-by-syllable in vertical and zigzag formats, making the position of the critical transposed or replaced letters more noticeable. In Experiment 1, we found a transposed-letter effect in both formats, which was sizeable in the error rates. Experiment 2 introduced a delayed 900-ms response cue to assess whether the transposed-letter effect fully vanishes in the absence of immediate time pressure. Results again showed a transposed-letter effect. Thus, while visuospatial uncertainty contributes to letter position flexibility during word recognition, an additional non-visual component is necessary to fully explain this phenomenon.

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Transposed-letter effect; position uncertainty; orthographic processing; visual word recognition; lexical decision

Whether assembling furniture, learning a music piece, recalling a phone number, or conducting data analyses, encoding order information is a common and critical element. This process is essential for performing everyday tasks, intertwining with perception, memory, and action (see Logan, 2021, for review). Notably, in the context of reading, the cognitive processes that encode order information manifest some flexibility, both for words within a sentence (e.g. "*you that read wrong*" being read as "*you read that wrong*"; Mirault et al., 2018) and letters within a word (e.g. *jugde* being read as *judge*; Perea & Lupker, 2004). This latter phenomenon, first described by Bruner and O'Dowd (1958), is the focus of the present paper.

Pseudowords like *MOHTER* and *CHOLOCATE,* created by transposing two internal letters from a given word, either adjacent or non-adjacent, produce a substantial activation of their base words (see Chambers, 1979; O'Connor & Forster, 1981, for early evidence; see Mirault & Grainger, 2021; Perea et al., 2023, for recent reviews). The greater wordlikeness of transposed-letter pseudowords (e.g. *MOHTER*) relative to their replacement-letter controls (e.g. *MONFER*) strongly suggests that information about a word's letter order is subject to some flexibility (see Meade et al., 2022; Vergara-Martínez et al., 2013, for electrophysiological evidence).

The robustness of the transposed-letter similarity effect across tasks (e.g. lexical decision, perceptual identification, sentence reading, among others) led theorists to refine the orthographic front-end (i.e. the interface between the visual input and the orthographic representations [letter identities and positions]; see Grainger, 2018) in the family of interactive activation models. For these models, each letter identity in a printed word is immediately assigned to a position (e.g. McClelland & Rumelhart, 1981; see also Coltheart et al., 2001; Grainger & Jacobs, 1996, for other models of visual word recognition that kept this same orthographic front-end). These models would wrongly predict that the transposed-letter pseudowords *MOHTER* and its replacement-letter *MONFER* are equally similar to their base word *MOTHER* (i.e. they have four letters in common). As discussed below, this phenomenon created the need to a number of newer models that accounted for letter position coding during word recognition (e.g. LTRS: Adelman, 2011; spatial coding model: Davis, 2010; local combination detector model: Dehaene

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et al., 2005; overlap model: Gomez et al., 2008; open bigram model: Grainger & van Heuven, 2004; noisy Bayesian reader model, Norris et al., 2010; SERIOL model: Whitney, 2001).

In fairness to McClelland and Rumelhart, their goal was not to model letter position coding, and they acknowledged the possibility that "information presented in one location might activate detectors in a range of locations, rather than just simply in one fixed position" (p. 89; Rumelhart & McClelland, 1982), capturing the greater wordlikeness of the pseudoword *MOHTER* compared to *MONFER*. Rumelhart and McClelland's (1982) notion that the transposition errors relate to "a region of uncertainty associated with each feature and with each letter" (p. 89) was at the heart of Gomez et al.'s (2008) overlap model. This model assumed, following parallel ideas from models of visual attention (e.g. Logan, 1996), that there is initial uncertainty regarding the relative positioning of objects in space, in this case, letters in a word, which is "reduced over time" (p. 580; Gomez et al., 2008). As illustrated by Gomez et al.'s (2008) Figure 1, each letter in the overlap model initially activates its own position and, to some level, surrounding positions. As a result, the pseudoword *MOHTER* would activate *MOTHER* to a greater degree than the pseudoword MONFER (i.e. the position of the letters *H* and *T* in *MOHTER* is not perfectly encoded).

Notably, the uncertainty regarding letter order is smaller for the initial letter (Gomez et al., 2008) – note that the initial letter is the most important during word recognition ("first-letter advantage"; see Scaltritti & Balota, 2013; Tydgat & Grainger, 2009). Thus, the overlap model can readily capture the reduced transposed-letter effects when the transposition involves the initial letter (e.g. the pseudoword OMTHER is less confusable with MOTHER than the pseudoword MTOHER; Perea et al., 2015; Rayner et al., 2006). A visuospatial position uncertainty account can also provide a comprehensive explanation for transposition effects observed in various domains. Transposition effects have been reported with strings of numbers (e.g. García-Orza et al., 2010), symbols (Duñabeitia et al., 2013), letters from artificial scripts (Fernández-López, Marcet, et al., 2021), geometric shapes (García-Orza et al., 2011), and musical notes (Perea et al., 2013). Furthermore, these effects have also been reported in preliterate children (Fernández-López, Gómez, et al., 2021) and baboons (Ziegler et al., 2013). This wide-ranging applicability suggests that these phenomena extend beyond mere orthographic processes, indicating broader characteristics of cognitive processing (see Logan, 2021, for review).

The assumption of position uncertainty within the visual system when encoding letter position is not unique to the overlap model; it is also a key component in other models of visual word recognition (e.g. spatial coding model, Davis, 2010; overlap open bigram model, Grainger, Granier, et al., 2006; Grainger, Kiyonaga, et al., 2006; start-end position coding model, Houghton, 2018; positional-noisy version of Bayesian reader model, Norris et al., 2010). While these models capture many findings in the literature with word and pseudoword stimuli, purely visuospatial accounts of letter position coding would predict comparable transposition effects for visual objects that appear in the same contexts, such as letters, digits, or symbols. However, several experiments using the same-different matching task (e.g. Duñabeitia et al., 2013; Massol & Grainger, 2022) have shown that the size of transposition effects is greater for strings of letters (e.g. *FKRP-FRKP* vs. *FSCP-FRKP*) than for strings of digits (e.g. *5938-5398* vs. *5248-5398*). This latter finding has been taken to suggest that the transposed-letter effect during visual word recognition has an orthographic locus. Indeed, several models of visual word recognition propose that the bulk of the transposed-letter effect occurs at an abstract, orthographic level via an intermediate layer of (open) bigram detectors level between the letter and word levels (Dehaene et al., 2005; Grainger & van Heuven, 2004; Whitney, 2001; e.g. *MOHTER* would activate the same open bigrams as *MOTHER* [MO, MH, MT …] except for the bigram *TH*). Furthermore, recent research has reported transposed-letter effects in a non-visual modality, with congenitally blind individuals reading in braille (Baciero et al., 2022). Taken together, these findings suggest that there may be several loci of the transposed-letter effect (see Marcet et al., 2019; Massol & Grainger, 2022, for discussion): a generic mechanism of position order for all visual objects, and an orthographic mechanism specific to letter strings.

	Format	
	Syllabic vertical format	Syllabic zigzag format

Transposed-Letter Pseudoword	CHO
	LO
	CA
	TE
		CHO
		    LO
		CA
		  TE

Replacement-Letter Pseudoword	CHO
	TO
	NA
	TE
		CHO
		    TO
		NA
		  TE

Figure 1. Depiction of the transposed-letter pseudoword CHOLOCATE and the replacement-letter pseudoword CHOTONATE in the syllabic vertical and zigzag formats.

Evidence against a purely visuospatial account of letter position coding, which is a direct precursor of this work, comes from a recent paper (Perea et al., 2023) that introduced a multiple-line presentation format to examine whether letter transposition effects could occur when the critical letters were far in space (i.e. a visuospatial element). Specifically, the letter transposition (or replacements) were in different lines (e.g. L/C from the transposed-letter pseudoword *CHOLOCATE* and T/N from the replacement-letter control *CHOTONATE*). For instance, in Experiment 1, *CHOLO* – would be in the first line, whereas *CATE* would be in the second line. The transposed-letter effect was measured as the difference in response times (or error rates) between the transposed-letter and the replacement-letter pseudowords, the logic being that the more word-like the pseudoword was, the longer the correct lexical decision times and the higher the probability of an incorrect "yes" response (e.g. see Marcet et al., 2019; O'Connor & Forster, 1981; Perea & Lupker, 2004, for a similar argument). Although the latency data showed a reduced transposed-letter effect relative to the horizontal format, the transposed-letter effect in the error rates was sizable in all vertical formats (above 10%). Perea et al. (2023) argued that these transposition effects could not be fully captured in terms of a visuospatial explanation based on the position uncertainty of letters in space. However, the visuospatial manipulation employed in these experiments still allowed some overlap across the critical letters, thus potentially capturing a small transposed-letter effect (see Perea et al., 2023 for fits of the overlap model).

The goal of the present lexical decision experiments, using the same materials as Perea et al. (2023), was to provide a more stringent test of visuospatial accounts of letter position coding by presenting each stimulus in a syllable-by-syllable zigzag vertical format – note that all non-adjacent letter transposition would occur in the initial consonant of syllables. For example, the transposed-letter pseudoword "*CHOLOCATE*" was displayed as "CHO" in one row, "*LO*" in the third position of the following row, "CA" at the beginning of the third row, and "TE" in the third position of the final row (see Figure 1). This arrangement – occasionally used in billboards and advertisements (see Figure A4 in the Appendix) – ensured not just more spatial distance between the transposed letters, but also that all the critical manipulations involved the first positions in each line. As a result, there would be a minimal overlap in visuospatial terms, as shown in the updated version of the overlap model designed to account for the present experiments (see Appendix A). For comparison, we employed a purely vertical syllable-by-syllable format like Perea et al.'s (2023) Experiment 3, for which we would expect to observe a transposed-letter effect, particularly for the error data, replicating their results – indeed, as shown in Appendix A, the updated overlap model predicts some transposed-letter effect in the vertical format.

In Experiment 1, we used the typical setup of the lexical decision task, whereas, in Experiment 2, we employed a delayed variant of the lexical decision task aiming to separate lexical access per se from those elements related to the decision and response (see López Zunini et al., 2020). The rationale for Experiment 2 becomes apparent in the context of the results from Experiment 1 and hence is spelled out when discussing such results.

The predictions are clear: a visuospatial model of letter position coding would predict a vanishing transposed-letter effect for the pseudowords in the zigzag format, but not in the vertical format (see Appendix A) – keep in mind that in the zigzag format not only would the position of the initial letters from the consonant-vowel syllables be more salient, but also the letter transpositions would be farther, reducing the uncertainty when assigning letters to positions. Critically, the existence of a sizable transposed-letter effect in both the zigzag format and the purely vertical format would indicate that letter position coding in visual word recognition tasks involves a component related to the organisation of a word's letter representations during orthographic processing that is not particularly responsive to visuospatial elements.

Experiment 1 (standard lexical decision task)

Methods

Participants

Forty Spanish-speaking adults (24 females and 16 males) aged 20 to 39 years (M = 26.9, SD = 4.5) participated in the experiment. This sample size ensures 2,000 observations in each pseudoword condition, aligning with the recommendations for small-sized effects (see Brysbaert & Stevens, 2018). The participants were recruited via the Prolific online platform (https://www.prolific.com/) with self-reported normal or corrected vision and no self-reported history of reading difficulties. They signed an informed consent form before the experiment. The experiments reported in this paper were approved by the Experimental Research Committee of the Universitat de València and followed the requirements of the declaration of Helsinki.

Materials

The set of 200 words and 200 pseudowords was the same as in the experiments conducted by Perea et al.

(2023). These pseudowords had been created from a set of 200 base words not used in the experiment (Zipf frequency: M = 3.8 [range 1.24–5.31], number of letters: M = 8.9 [range 7–11], orthographic neighbourhood [OLD20]: M = 2.5 [range 1.40–3.65]). Each base word was used to create two pseudowords: a transposed-letter pseudoword and a replacement-letter pseudoword, both matched in bigram frequency (see Perea et al., 2023 for further details). The transposition and replacement always involved the initial consonant of two internal syllables (e.g. *CHOLOCATE* vs. *CHOTONATE*) since each pseudoword could be presented in the syllabic vertical (each syllable in a line) or the syllabic zigzag (each syllable in a line in zigzag format), we had four types of pseudowords: (1) a transposed-letter pseudoword in syllabic vertical format, (2) a transposed-letter pseudoword in syllabic zigzag format; (3) a replacement letter pseudoword in syllabic vertical format, and (4) a replacement letter pseudoword in syllabic zigzag format (see Table 1). The set of 200 Spanish words, also taken from Perea et al. (2023), had a mean Zipf frequency of 3.8 (range 0.6–5.0), a mean number of letters of 9.0 (range 7–11), and a mean OLD20 of 2.5 (range 1.6–4.3). We created four counterbalanced lists, each containing 200 pseudowords (50 stimuli in the four pseudoword conditions) and 200 words (half in vertical format and half in zigzag format), and 25% of the participants were assigned to each list.

Procedure

The experiment script was written in PsychoPy (Peirce et al., 2022), and the session was hosted on the Pavlovia platform (https://www.pavlovia.org). Since the experiment took place online, all participants were asked to remain in a distraction-free location for the duration of the experiment. Participants were informed with written illustrations that, on each trial, they would be presented with letter strings in a vertical format (either purely vertical or in zigzag) that could be either a word or a nonword in Spanish. Their task was to press "m" for words or "z" for nonwords as fast and as accurately as possible. Each trial had a 500-ms fixation point (+) preceding the stimuli. The stimulus item, in 18pt Courier New, was on the screen until the participant's response or a 2000ms deadline. There were short breaks every 100 trials. The presentation order of trials was fully randomised for each participant. Before the experimental blocks, there was a brief 16-trial practice block to familiarise participants with the task – in the practice phase, there was also feedback on the response (whether accurate or not and whether the response was too slow in case of reaching the deadline). The experiment was done in 20–30 min.

Table 1. Mean correct lexical times (in ms) and error rates (in percentage) for the stimuli in vertical and zigzag format in Experiment 1.

	Word	Transposed-Letter Pseudoword	Replacement-Letter Pseudoword	Transposed-Letter effect
Format				
Vertical	1028 (8.7)	1222 (20.4)	1199 (4.8)	23 (15.6)
Zigzag	977 (7.2)	1183 (16.8)	1153 (4.1)	30 (12.7)

Results and discussion

Error responses (11.5% for pseudowords, 7.9% for words) and correct response times faster than 250 ms (less than 0.01%) were excluded from the latency analyses – as indicated above, trials that reached the deadline of 2000ms were counted as errors. Our focus was on the pseudoword data (i.e. the stimuli containing transposed or replaced letter items), but we also reported the analyses of the word data. Table 1 displays the mean RTs and error rates for each condition in the experiment.

We employed Bayesian linear mixed-effects models with the *brms* package (see Bürkner, 2017) in R (R Core Team, 2023) to analyze the latency and accuracy of the data. We chose this package as it allowed us to fit the models with the maximal random effect structure without convergence issues (see Barr, 2013, for arguments in favour of maximal models). We employed the default priors of the *brms* package for each parameter. Each model was run with four chains of 10.000 Markov chain Monte Carlo iteration. For each chain, there was a 1000-iteration warmup. The output of these models provides estimates of each effect (the coefficient *b*, which is the mean of the posterior distribution), its estimation error (the standard deviation of the posterior distribution), and its 95% credible interval (CrI). We inferred that there was evidence of an effect when its 95% CrI did not include zero.

For the pseudoword data, the fixed factors in the models were the Type of pseudoword (replaced-letter vs. transposed-letter pseudowords; coded as −0.5 and 0.5) and Format (vertical vs. zigzag; −0.5 and 0.5). We modelled the latency data with the ex-Gaussian distribution to capture the positive asymmetry of the response time data. For the accuracy analyses, we used the Bernoulli distribution (where 1 and 0 corresponded to correct and error responses, respectively). For both dependent variables, we fitted the maximal model in terms of random-factor structure:

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Dependent variable: RT or Accuracy ~ Type_pseudoword * Format + (1 + Type_pseudoword * Format | subject) +1 + Type_pseudoword * Format | item)
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For the word data, the analyses were similar, except that the only fixed factor was Format. All models converged effectively, and the values of *R-hat* were 1.00 for all parameters. In addition, to complement the inferential linear mixed-effects models, we also employed, for the pseudoword data, conditional accuracy functions that will be explained below.

Pseudoword data

Response time analyses. We found faster response times in the zigzag format than in the vertical format ($b = 39.31$, Estim.Error = 6.71, 95% CrI[26.16, 52.50]) and faster response times for replacement-letter pseudowords than for transposed-letter pseudowords ($b = 26.54$, Estim.Error = 9.85, 95% CrI[7.02, 45.83]). As shown in Figure 2, there was no evidence of an interaction between these effects ($b = -1.87$, Estim.Error = 11.06, 95% CrI[−23.60, 20.04]).

Accuracy analyses. We found more accurate responses to the pseudowords in zigzag format than in the vertical format ($b = -0.32$, Estim.Error = 0.11, 95% CrI[−0.54, −0.11]). We also found that replacement-letter pseudowords produced fewer errors than transposed-letter pseudowords ($b = -1.58$, Estim.Error = 0.16, 95% CrI [−1.91,−1.28]). Finally, as occurred in the latency data, the two effects combined additively (i.e. they did not interact, $b = 0.01$, Estim.Error = 0.21, 95% CrI[−0.40, 0.41]; see Figure 2).

To further examine how accuracy evolved as a function of latency, we computed the conditional accuracy functions (CAFs; see Bonnet & Dresp, 1993) per format type (see Figure 3). To do this, we (1) divided the response time data into five bins based on the 0.1, 0.3, 0.5, 0.7, and 0.9 quantiles, including both correct and error responses; (2) calculated the mean accuracy and mean RT per quantile bin and condition across participants; and (3) plotted the means in a graph that shows the mean response time per quantile in the x-axis and the mean accuracy per quantile in the y-axis. The obtained graph describes a similar pattern of results for both formats: responses to replacement-letter pseudowords are quite accurate (all above .95) in both zigzag and vertical formats; however, responses to transposed-letter pseudowords are low in accuracy for short response latencies (.70 for zigzag and .65 for vertical formats), increasing rapidly as response times increase, but staying lower than the accuracy for responses to replacement-letter pseudowords across all response times.

Word data

Response times were faster in the zigzag format than in the vertical format ($b = 46.58$, Estim.Error = 5.99, 95% CrI [34.78, 58.35]). In addition, the differences in format in the accuracy data produced only a minimal advantage for the zigzag format ($b = 0.04$, Estim.Error = 0.15, 95% CrI[−0.33, 0.26]).

The present experiment showed a transposed-letter effect for the pseudowords regardless of format (purely vertical format versus zigzag). The transposed-letter effect was relatively small for response times

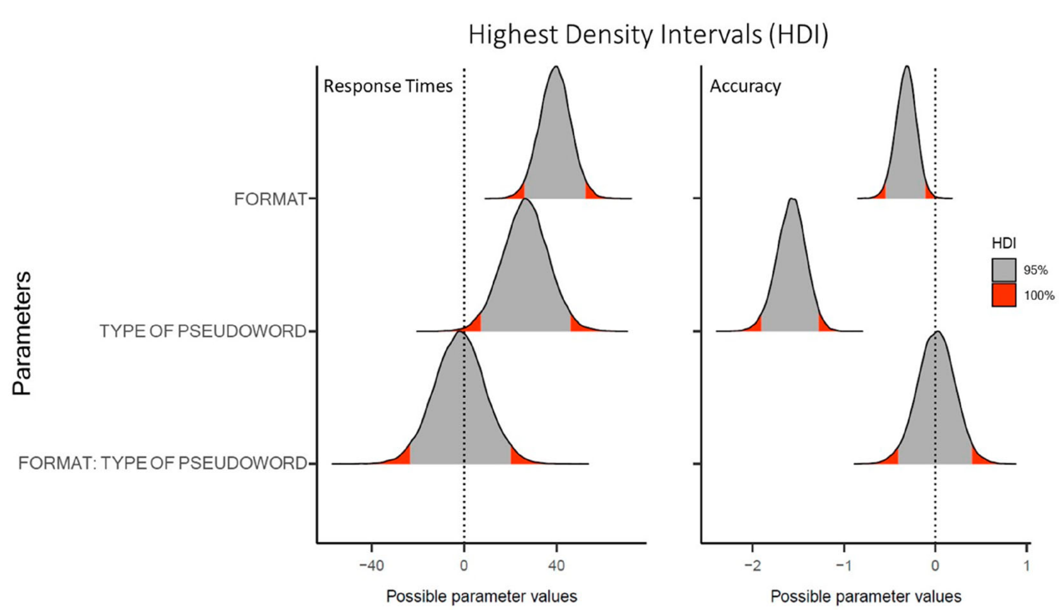

Figure 2. Posterior Distributions of the three estimates for the response time data (left panel) and the accuracy data (right panel) in Experiment 1. The estimates of the effects correspond to the means of these distributions. The red areas correspond to the values beyond the 95% credible intervals.

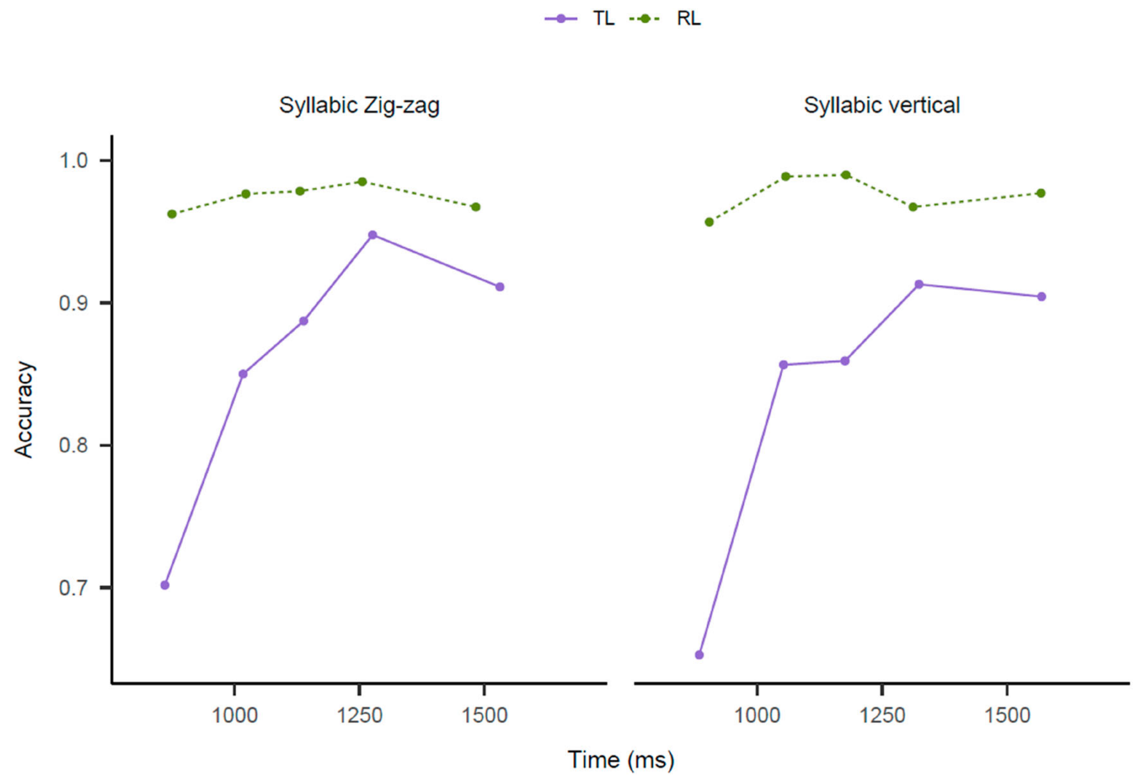

Figure 3. Conditional accuracy function plots for the zigzag format condition (right) and the vertical format condition (left) in Experiment 1. TL and RL stand for Transposed-Letter pseudowords and Replacement-Letter pseudowords, respectively.

(around 25 ms) – this is substantially smaller than in the typical experiments with a horizontal format (greater than 80–100 ms; e.g. see Perea & Lupker, 2004; Perea et al., 2023). Nonetheless, the transposed-letter effect was still substantial in the error rates (around 13% more errors for the transposed-letter pseudowords), thus revealing that, regardless of format, a pseudoword like *CHO-LO-CA-TE* was still more wordlike than its control *CHO-TO-NA-TE* (see Table 1). While not the focus of the experiment, we found that words and pseudowords presented in the zigzag format had better performance than those presented in the vertical format, despite the latter being more visually familiar. This pattern suggests that the visual salience of the syllables in the string may help ensemble the letter strings, speeding up the responses. However, interestingly, this alleged salience did not reduce the size of the transposed-letter effects.

Overall, these findings offer evidence against an explanation of letter position coding as being only due to visuospatial position uncertainty. Had position uncertainty been a critical component in the present experiment, the transposed-letter effect would have been extremely reduced for the pseudowords in a zigzag format – note that in the zigzag disposition, all syllables were highly salient, and the transposed letters were far apart in space (see Figure 1). As shown in Appendix A, the overlap model, across various implementations of vertical noise, would predict a negligible transposed-letter effect in this format, whereas it can accommodate the transposed-letter effect for the vertical format.

One might argue that, due to the use of a non-canonical arrangement, the obtained transposed-letter effects could have occurred at a phonological level. Indeed, recent research with an auditory lexical decision task has reported transposed-phoneme effects. For instance, \ʃɔ.kɔ.la\ (*cholocat* in French; base word *chocolat*) produces slower response times than \ʃɔ.ʁɔ.pa\ [choropat] (see Dufour et al., 2021; Dufour & Grainger, 2022). However, we believe that this interpretation is unlikely: error rates to transposed-phoneme pseudowords and replacement-phoneme pseudowords were extremely low and similar in the two conditions (4–6% for the two types of pseudowords). Instead, the transposed-letter effect both in the present experiment and in previous research has been consistently large in the error data (e.g. see Perea et al., 2023). Furthermore, a number of experiments in the visual modality have also strongly suggested that the locus of the transposed-letter effect appears to be orthographic rather than phonological (see Grainger, Granier, et al., 2006; Grainger, Kiyonaga, et al., 2006; Perea & Carreiras, 2008; Perea & Pérez, 2008). For instance, using a Japanese syllabary, katakana, which disentangles form and sound, Perea and Pérez (2008) found that, for the target word アメリカ (a.me.ri.ka, in Romaji transliteration), a phonological prime created by transposing the two consonant sounds of the initial syllables (e.g. アレミカ; aremika) was not more effective than a control prime (e.g. アケヒカ; a.ke.hi.ka) – note that in the Roman script, *cholocate* is a very effective prime for *CHOLOCATE* (Perea & Lupker, 2004). Instead, a prime created by transposing the two internal syllables (アリメカ, a.ri.me.ka) was more effective than the replacement-control prime (アカホカ, a.ka.ho.ka), favouring that it is the transposition of orthographic characters rather than the phonological sounds that drives the effects. Similarly, Perea and Carreiras (2008) found similar transposed-letter priming effects regardless of whether the letter transposition involved a change in sound or not (e.g. as in racidal [base word, radical] vs mecidine [base word, medicine]) and Grainger, Granier, et al. (2006) and Grainger, Kiyonaga, et al. (2006) found that transposed-letter priming effects (e.g. barin-BRAIN) and phonological priming effects (e.g. brane-BRAIN) had different timing and topographical distributions topographical distributions and different timing.

Before examining the implications of these findings for how the brain encodes the order of letters in words, it is important to consider another alternative explanation for the observed effects based on the characteristics of the standard setup of the lexical decision task. One might argue that the increased number of "yes" responses for transposed-letter pseudowords over the replacement-letter pseudoword (see Figure 3) could have been due to the instructions in a standard lexical decision task. Early in processing, transposed-letter pseudowords produce similar ERP waves as their base words (Meade et al., 2022; Vergara-Martínez et al., 2013), which means that transposed-letter pseudowords are highly wordlike. As a result, in a number of instances, the activation elicited by the transposed-letter pseudowords could have reached the criterion for "yes" responses, thus producing an error response (see the conditional accuracy functions of Figure 3). Indeed, later in time, once the response is made, participants often notice the actual misspelling in the item (i.e. we ultimately notice that *CHOLOCATE* does *not* correspond to a real word, see Gomez et al., 2008).

To separate the processes that that are related to making an explicit "yes" or "no" response from those that are due to lexical access (i.e. lexical activation upon the presentation of a stimulus), Experiment 2 used a delayed lexical decision task (e.g. see Hintzman & Curran, 1997; López Zunini et al., 2020, 2022, for

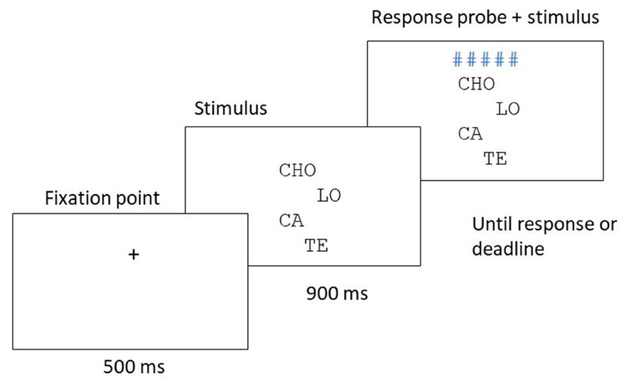

Figure 4. Illustration of a given trial in Experiment 2.

previous research with this variant of the lexical decision task). In Experiment 2, using the same materials as in Experiment 1, participants were asked to make the lexical decision response after 900 ms post-stimulus onset, which is when a when a response probe appeared (see Figure 4). We chose 900 ms as the signal to respond considering that the mean response time for correct responses in Experiment 1 was around 1200 ms – note that response times involve a motor component after deciding "yes" vs. "no" – and that longer intervals could induce participants not to process the stimuli until the onset of the probe.

The motivation behind Experiment 2 was to minimise the possibility of "yes" responses driven by the urge to respond quickly, which can lead to false alarms for transposed-letter pseudowords. As indicated above, transposed-letter pseudowords produce an electrophysiological response similar to their base words in the initial moments of processing. We expect small or no transposed-letter effects on response times because participants are instructed when to respond, creating a scenario parallel to signal-to-response experiments with a long delay. Critically, we believe that Experiment 2 pushes the visuospatial position explanation of transposed-letter effects to its limits: participants are given more time to reduce position uncertainty, while the saliency of the transposed letters is maintained.

In sum, if responding under time pressure upon presentation of the stimuli was the reason why participants produced a sizable transposed-letter effect in the error data of Experiment 1, one would expect the transposed-letter effect to be negligible in the setup of Experiment 2 (delayed lexical decision). Thus, Experiment 2 measures performance at a stage of processing where visuospatial position uncertainty should have been essentially resolved. As indicated earlier, a transposed-letter effect, especially in the zigzag format, cannot be captured by visuospatial accounts of letter position coding such as Gomez et al.'s overlap model (see Appendix A).

Experiment 2 (delayed lexical decision task)

Methods

Participants

We recruited a new sample of 40 participants (20 females, 20 males), aged between 20 and 40 years (M = 28.5, SD = 5.9), with the same characteristics as in Experiment 1.

Materials and procedure

They were the same as in Experiment 1, except that participants were asked to make their response only after a response probe appeared on the screen 900 ms after stimulus onset (see Figure 4). The instructions were slightly modified to inform the participants that responses should be made after the probe appeared.

Table 2. Mean correct lexical times (in ms) and error rates (in percentage) for the stimuli in vertical and zigzag format in Experiment 2.

	Word	Transposed-Letter Pseudoword	Replacement-Letter Pseudoword	Transposed-Letter effect
Format				
Vertical	1281 (5.4)	1387 (15.5)	1384 (4.1)	3 (11.4)
Zigzag	1261 (4.4)	1356 (11.2)	1359 (3.6)	−3 (7.6)

Results and discussion

All the analyses were parallel to Experiment 1, except that we excluded all trials made before the 900-ms signal (1.7% of the trials). Table 2 displays the mean RTs and error rates for each condition in the experiment. We found very good fits in all the models (*R-hat* = 1.00 for all parameters)

Pseudoword data

Response time analyses. As in Experiment 1, response times to pseudowords were faster in the zigzag than in the purely vertical format ($b = 26.67$, Estim.Error = 4.70, 95% CrI[17.36, 35.82]). Notably, we did not find any clear evidence of a transposed-letter effect ($b = 0.43$, Estim.Error = 7.53, 95% CrI[−14.35, 15.29]) or an interaction ($b = 10.47$, Estim.Error = 8.53, 95% CrI[−6.06, 27.48]) (see Figure 5 for the posterior distributions).

Accuracy analyses. Accuracy was lower for replacement-letter pseudowords than for transposed-letter pseudowords ($b = -1.42$, Estim.Error = 0.18, 95% CrI [−1.79, −1.06]). Accuracy was slightly lower for the zigzag format, but the 95% credible interval crossed zero ($b = -0.24$, Estim.Error = 0.13, 95% CrI[−0.49,

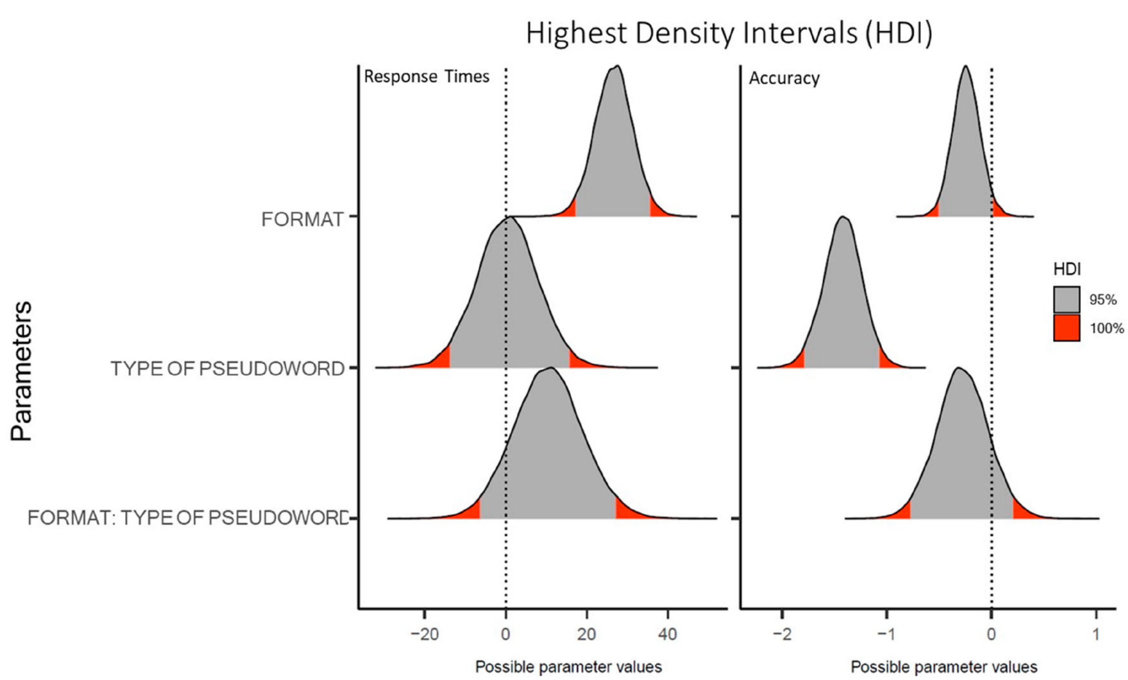

Figure 5. Posterior Distributions of the three estimates for the response time data (left panel) and the accuracy data (right panel) in Experiment 2. The effects estimates correspond to the means of these distributions. The red areas correspond to the values beyond the 95% credible intervals.

−0.03]). Finally, there were no apparent signs of an interaction between these two factors ($b = −0.28$, Estim.Error = 0.25, 95% CrI[−0.76, 0.22]).

Conditional accuracy functions (CAFs). Similar to the results in Experiment 1, both formats show a parallel pattern of responses regarding accuracy rates over time. Nonetheless, the shapes described in the CAF plots differ between the two experiments. As depicted in Figure 6, responses to replacement-letter pseudowords are highly accurate (all above .95) in both zigzag and vertical presentations. Nonetheless, the accuracy of transposed-letter pseudowords is constantly lower than for replacement-letter pseudowords across response times for both presentation formats.

Word data

Response times were faster in the zigzag format than in the vertical format ($b = 15.84$, Estim.Error = 3.86, 95% CrI [8.21, 23.44]). The accuracy data showed slightly higher accuracy in the zigzag format than in the vertical format, but the 95% credible interval crossed zero ($b = −0.27$, Estim.Error = 0.16, 95% CrI[−0.59, 0.03]).

Using a delayed lexical decision task, this experiment showed no signs of a transposed-letter effect (less than 5 ms) in the response time data. However, we still found a transposed-letter effect in the error data (around 7–11%) that was approximately similar in the two formats. Finally, as in Experiment 1, we found a processing advantage (for both words and pseudowords) of the zigzag format over the purely vertical format.

Thus, while the delayed lexical decision task reduced the transposed-letter effect in the latency data, the transposed-letter effect was still noticeable in the error data – note that this pattern occurred regardless of response latency (see the conditional accuracy function plots in Figure 6). We examine this dissociation in the next section.

General discussion

One leading explanation for the high degree of confusability of the pseudoword *CHOLOCATE* with its base word (*CHOCOLATE*) is that there is visuospatial position uncertainty when encoding letter order (e.g. Gomez et al., 2008; Norris et al., 2010). We conducted two lexical decision experiments to test the viability of this explanation. Transposed-letter pseudowords and their replacement-letter controls (e.g. *CHOLOCATE* vs. *CHOTONATE*) were presented in a syllable-by-syllable zigzag format that kept the syllables as visually salient elements and reduced the position uncertainty (see Figure 1): critically, the letter transposition/replacement

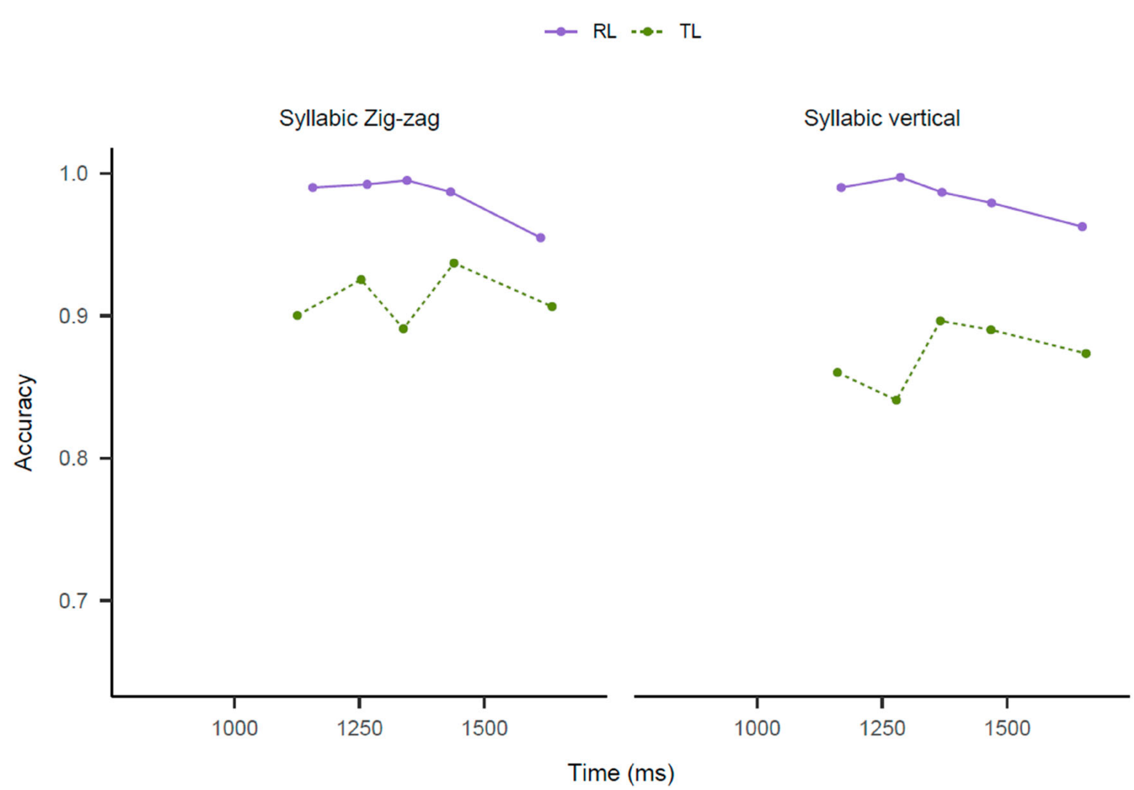

Figure 6. Conditional accuracy function plots for the zigzag format condition (right) and the vertical format condition (left) in Experiment 2. TL and RL stand for Transposed-Letter pseudowords and Replacement-Letter pseudowords, respectively.

not only involved separate syllables but were also spatially further apart – we included a purely vertical disposition of the syllables as a control.

Using standard lexical decision instructions, Experiment 1 showed higher error rates for the transposed-letter pseudowords than for the replacement-letter pseudowords regardless of format (around 12–15%), which was accompanied by a small-sized transposed-letter effect in the latency data (around 23–30 ms). One possible explanation for this effect is that participants often responded "yes" on the basis of the early activation in the mental lexicon produced by the highly wordlike transposed-letter pseudowords – note that these pseudowords produce similar ERP signatures as their base words in early time windows (e.g. see Meade et al., 2022; Vergara-Martínez et al., 2013). To test this hypothesis, in Experiment 2, we used a delayed lexical decision task in which participants had to respond after a cue that appeared 900 ms after stimulus onset, preventing the urge to respond quickly. While the transposed-letter effect in Experiment 2 vanished in the latency data – not surprising since participants had to wait for the signal to respond, the error data showed a sizable transposed-letter effect in both formats (around 7–11%). Finally, although not the focus of our experiments, we found that the zigzag format produced faster responses than the purely vertical format times for both words and pseudowords – this suggests that despite being less visually familiar, the salience of the syllables in the zigzag format speeded up lexical access, perhaps related to the left-right arrangement of the initial two syllables (see Figure 1). We now discuss the implications of the present findings for models of letter position coding.

The main finding of the present experiments is that even in a physically non-canonical format (e.g. vertical format, zigzag format) and various timing conditions (e.g. standard and delayed lexical decision tasks), the transposed-letter effect was pervasive in the accuracy data. On the one hand, the manipulations of stimulus format in the present experiments dramatically reduced the size of the transposed-letter effect in the latency data compared to the canonical horizontal format. It was quite small with standard lexical decision instructions (around 25 ms) and negligible with delayed lexical decision instructions (around 3 ms) – in the Perea et al. (2023) experiments, these same items produced transposed-letter effects of around 80–92 ms in horizontal format. On the other hand, the transposed-letter effect in the present experiments was robust across formats (vertical vs. zigzag) and instructions (standard vs. delayed lexical decisions) in the error data. While the magnitude of the effect was smaller in the delayed than in the standard lexical decision task (around 8–11% vs. 12–15%), it was still statistically robust – again, the size of these effects was smaller than that reported when these stimuli were presented with the horizontal format (around 22–26%, see Perea et al., 2023).

Therefore, the transposed-letter effect, while influenced by a visuospatial component, cannot be fully explained by it. In Appendix 1, we document our efforts to expand a visuospatial account of letter position coding (overlap model, Gomez et al., 2008) into this presentation format. The basic conclusion across the various implementations of letter position coding in horizontal and vertical formats is that the visuospatial account is unlikely to explain the transposed-letter effect reported here. This is particularly the case in the zigzag format, for which the model predicts a negligible transposed-letter effect. Thus, while we have shown that the transposed-letter effect is reduced in scenarios where the visual format lessens position uncertainty (e.g. zigzag format), to comprehensively understand the pattern of findings, it is necessary to acknowledge an additional non-visual, orthographic component. This idea aligns with the dual-route model of word recognition proposed by Grainger and Ziegler (2011) and the overlap open-bigram model (Grainger, Granier, et al., 2006; Grainger, Kiyonaga, et al., 2006), which consider both visuospatial and orthographic components in letter position coding. These models could, in principle, capture the decrease in transposed-letter effects in the vertical and zigzag formats. This is because these formats would enhance the robustness of the open-bigram codes responsible for letter position information. In fact, in a recent paper by Massol and Grainger (2022), they argued that an increase of inter letter spacing leads to a more accurate encoding of open bigrams. Following this same logic, the open bigram model would predict greater robustness of the open bigram codes for letter order information when the critical letters are farther away, as in the zigzag format.

An issue that deserves some examination is that the transposed-letter effect in the present experiments quite robust, regardless of the format, in the error data, but not in the response time data. This dissociation is not new. In a rapid serial visual presentation (RSVP) experiment examining the transposed-word effect (e.g. you/that/read/wrong; see Mirault et al., 2018), Mirault et al. (2022) found a transposed-word effect in the error data, but not in the latency data. As Dufour et al. (2022) found sizeable transposed-word effects in both response and error rates in a parallel experiment with auditory stimuli, they argued that the lack of a transposed-word effect with RSVP was due to the atypical format of visual word presentation. Their reasoning is that this format might have disrupted normal reading behaviour, and made response times close to ceiling, thus making it difficult to find sizeable across-conditions differences. Using conditional accuracy functions, the present paper shows that while the effect in the error data occurred to a larger degree in the faster responses in Experiment 1 with the standard lexical decision task (see Figure 3), the effect occurred across the whole spectrum of response times. Remarkably, the stability of the transposed-letter effect in the error data across the range of response times was more pronounced in the delayed lexical decision task (see Figure 6), where response times must be close to ceiling and participants might have time to explicitly check for transposition misspellings.

In sum, the present experiments provide substantial insights into the visuospatial position uncertainty accounts of letter order encoding in visual word recognition models. While we focused on simulations with the overlap model (Gomez et al., 2008), the same arguments apply to the Bayesian reader model (Norris et al., 2010), as it uses the mechanisms of the overlap model for letter position coding. These accounts would predict a dramatic reduction in the transposed-letter effect in zigzag formats (see Appendix A). Contrary to these predictions, our experiments did not observe such a dramatic decrease. Instead, both experiments demonstrated a consistent transposed-letter effect in the error data. This outcome presents challenges to these models in their approach to encoding letter order during visual word recognition, suggesting that the effect of letter position coding might be related to the more general phenomenon of serial order encoding (e.g. see Logan, 2021, for a general framework of the encoding of serial order across several domains). Whether this latter component occurs at a phonological level, at a bigram level during word recognition (e.g. see Massol & Grainger, 2022; Snell, 2023) or during the encoding of order information in short-term memory (see Estes, 1975; Ratcliff, 1981) is an open issue for additional research in which those accounts are directly explored with targeted manipulations.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data, scripts, and output files are available at the following OSF link: https://osf.io/g5bh8/?view_only=2556b4f9bf2c4c7da7be2b83b0718c92

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