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BRIEF REPORT

How time shapes letter position flexibility: Testing positional uncertainty and open bigram accounts

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Abstract
One of the critical benchmarks for understanding orthographic processing during word recognition and reading is the transposed-letter effect (e.g., in lexical decision, *CHOLOCATE* [created by transposing two letters from *CHOCOLATE*] produces slower and more error responses than *CHOTONATE*). Two main theoretical frameworks explain this phenomenon: positional uncertainty models, which attribute the effect to uncertainty in letter position encoding that diminishes over time, and open bigram models, which propose a level of ordered pairs of letters between the letter and word levels that may be more resilient to decay. We designed two delayed lexical decision experiments to test whether the transposed-letter effect vanishes or persists at two time delays (750 ms and 1,500 ms). In Experiment 1, a robust transposed-letter effect in accuracy emerged at 750 ms (9.6%) but diminished to a small (2.9%) yet reliable effect at 1,500 ms. Experiment 2 replicated this pattern with a contrast manipulation on the critical letters (e.g., *CHOLOCATE* vs *CHOTONATE*), yielding a slightly smaller transposed-letter effect (2.0%) at 1,500 ms. These findings demonstrate that positional uncertainty diminishes over time, yet residual orthographic overlap persists, particularly for a subset of participants, supporting hybrid accounts that combine bottom-up perceptual refinement with top-down contributions from shared sublexical codes (e.g., open bigrams).

Keywords Word recognition · Lexical access · Letter position coding

Most readers can effortlessly understand sentences like "The jugde enjoyed a piece of cholocate", even when judge and chocolate are misspelled with transposed letters. In fact, it may take a moment to realize that jugde is not actually a word—unlike jupte, which feels less wordlike. This remarkable ability demonstrates the flexibility of the visual system in encoding letter positions, allowing readers to tolerate minor disruptions while still recognizing the intended words (see Mirault & Grainger, 2021, for a recent review). This tolerance—known as the transposed-letter effect—is one of the most robust findings in word recognition and reading research (Grainger, 2018).

Notably, similar phenomena occur in other domains, such as the transposed-phoneme effect in auditory word recognition (e.g., perceiving /tæk/ as /kæt/ [cat]; Dufour et al., 2021; Toscano et al., 2013), the transposed-letter effect when reading in a tactile modality, braille (e.g., perceiving [*jugde*] as [*judge*]; Baciero et al., 2022), and the transposed-word effect during sentence reading (e.g., "you that read wrong" being interpreted as "you read that wrong"; Mirault et al., 2018). All these phenomena reveal the capacity of the cognitive system for flexibility in processing serial order (see Logan, 2021).

Over the past few decades, the transposed-letter effect has become central to understanding the mechanisms underlying orthographic processing, encouraging new models of word recognition and reading (see Grainger, 2024). A classic demonstration of this effect occurs in the lexical decision task, where pseudowords formed by transposing two letters in real words (e.g., the transposed-letter pseudoword

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jugde; the base word is judge) produce longer RTs and more errors than replacement-letter controls like jupte (e.g., Perea & Lupker, 2004). Furthermore, in ERP lexical decision experiments, transposed-letter pseudowords elicit different neural responses than replacement-letter pseudowords even at late epochs (around 600 ms; see Labusch et al., 2024; Vergara-Martínez et al., 2013), suggesting that flexibility in letter position coding persists beyond the early processing stages. These findings raise a fundamental question: how does this flexibility in letter position coding evolve over time? Although readers tolerate positional disruptions early on (e.g., with masked primes; Forster et al., 1987), it remains an open issue whether this tolerance is transient or enduring.

To address this question, we turn to two theoretical frameworks that offer contrasting explanations for the temporal dynamics of letter position coding, with the transposed-letter effect serving as a key benchmark. On the one hand, positional uncertainty models (e.g., overlap model, Gomez et al., 2008; noisy Bayesian reader, Norris et al., 2010; spatial coding model, Davis, 2010) propose that letter-position coding—or, more generally, the location of visual objects in space in the context of models of visual attention (see Logan, 1996)—is imprecise in the early stages of processing, allowing letters to activate adjacent positional slots to some degree. For instance, in jugde, the letters d and g would activate nearby slots, partially triggering the lexical representation of *judge*. Critically, these models predict that positional uncertainty diminishes over time, leading to a more precise encoding of letter position (Davis, 2010, p. 718; Gomez et al., 2008, p. 580; Norris et al., 2010, p. 524), as illustrated in Fig. 1.

Open bigram models (e.g., open bigram model, Grainger & van Heuven, 2004; SERIOL model, Whitney, 2001; OB1-reader, Snell et al., 2018; see also Dehaene et al., 2005) propose that flexibility in letter position encoding arises from an intermediate layer of representation composed of open bigrams. Open bigrams are ordered pairs of letters that preserve relative position within a word (e.g., *JU*, *JD*, *JG*, *JE*, *UD*, etc., for *JUDGE*), serving as a bridge between letter-level and whole-word representations. Because the open bigram layer feeds directly into the word level, a transposed-letter pseudoword like JUGDE (from JUDGE) activates many of the bigrams associated with the base word—sharing all but one (e.g., missing *DG),* resulting in false positives and slow correct responses in lexical decision tasks. In contrast, a replacement-letter control like JUPTE shares fewer bigrams, resulting in faster and more accurate responding. Furthermore, because this partial activation is driven by the intermediate open-bigram layer, the activation from transposed-letter pseudowords can persist over time due to shared sublexical representations shared with their base words.

To examine how tolerance to transpositions evolves over time, we employed a delayed lexical decision task. Unlike speeded lexical decisions—where responses are initiated once a decision threshold is reached, requiring participants to respond as quickly and accurately as possible after item presentation, delayed tasks allow for post-decision evidence accumulation and potential reevaluation (Resulaj et al., 2009; see also Forstmann et al., 2016, for a diffusion model account). Thus, the delayed lexical decision permits additional processing time before the response cue appears,

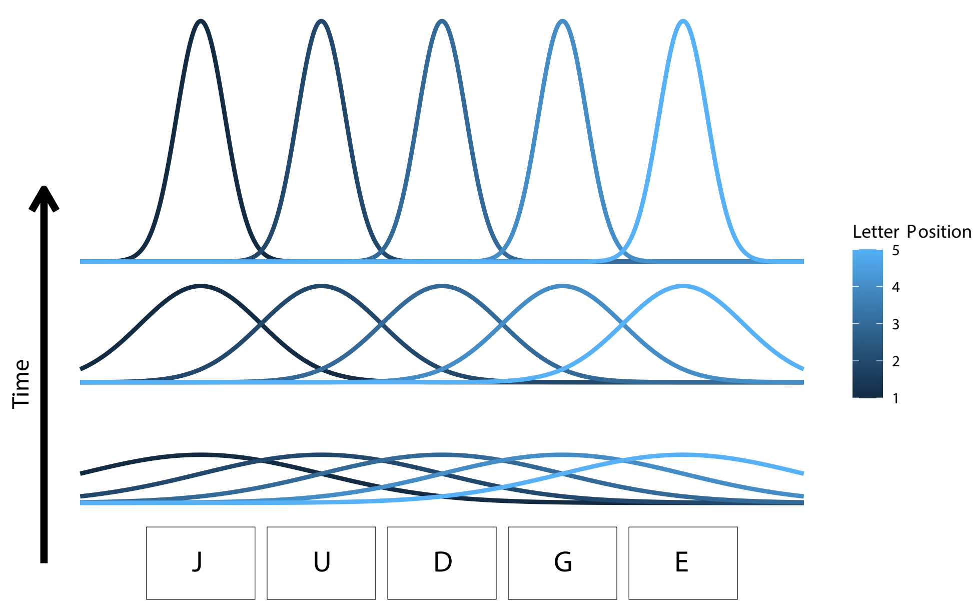

Fig. 1 Reduction of positional uncertainty over time for the pseudoword *JUGDE* from early (bottom panel) to late processing (top panel). (Color figure online)

offering a unique window into how orthographic evidence evolves beyond the initial stages of processing. This helps reduce premature "word" responses to transposed-letter pseudowords (e.g. *CHOLOCATE*), often confusable with their base words at early stages of processing. The idea is that transposed-letter pseudowords (e.g., *CHOLOCATE*) might initially trigger a "word" decision internally, which could later be revised to "nonword" as evidence accumulates.

Our choice of delays was guided by prior ERP and behavioral findings. As noted earlier, ERP studies have shown distinct neural responses to transposed- and replacement-letter pseudowords up to 600 ms—the latest time window examined in speeded tasks (Labusch et al., 2024; Vergara-Martínez et al., 2013). Meanwhile, Romero-Ortells et al. (2024) reported approximately 10% more errors for transposed-letter than for replacement-letter pseudowords in a 900-ms delayed lexical decision task. Based on this, we selected 750 ms as a point likely to retain noticeable transposed-letter effects, and 1,500 ms—twice that duration—to test whether the effect persists after extended processing. Crucially, this temporal manipulation allows us to test the predictions of the above-cited models about the time course of letter position coding.

Under positional uncertainty models, a 750-ms delay may capture a stage at which letter order may remain ambiguous—In contrast, a 1,500-ms delay should reflect more precise encoding, with positional uncertainty essentially resolved (see Fig. 1; see also Supplemental Materials). Accordingly, these models predict a sizable transposed-letter effect at the 750-ms delay, but a negligible effect at 1,500 ms.

Open bigram models, in turn, predict that the transposed-letter effect may persist across both delays, as shared bigrams continue to provide input to the word level and help sustain lexical processing (see Grainger & van Heuven, 2004). While the details are not specified in word recognition tasks, one could assume that partially matching bigrams contribute less strongly to word-level activation as time passes, either due to passive decay or to a strategic shift in attention away from the stimulus. Indeed, in the context of sentence reading, OB1-reader—the only implemented and publicly available version of the open bigram framework—includes a decay parameter in the bigram layer, originally introduced to account for saccadic suppression (Snell et al., 2018). As such, the transposed-letter effect is expected to diminish over time but not fully disappear by the 1,500-ms delay, consistent with continued input from partially matching sublexical representations (see Supplemental Materials for simulations of overlap and open-bigram models).

To examine these predictions, we focused on nonadjacent transpositions (e.g., the transposed-letter pseudoword *CHOLOCATE* and its replacement-letter control *CHOTONATE*). Greater distance between the transposed letters facilitates disambiguation and reduces orthographic similarity, thereby providing a stronger test case—especially for positional uncertainty models, which rely on perceptual confusability. Despite its theoretical importance, little is known about the temporal persistence of transposed-letter effects during word recognition. As noted above, one exception is the study by Romero-Ortells et al. (2024), who employed a 900-ms delayed lexical decision task with vertical, syllable-by-syllable presentation and reported approximately 10% more errors for transposed-letter pseudowords (e.g., *CHOLOCATE*) than for replacement-letter pseudowords (e.g., *CHOTONATE*). However, because their design used a vertical format and only a single delay, its generalizability is limited and provides only a narrow window into the time course of orthographic processing.

In sum, the present experiments compared transposed-letter pseudowords (e.g., *CHOLOCATE*) with replacement-letter pseudowords (e.g., *CHOTONATE*) at two delays (750 ms and 1,500 ms), providing a test of how tolerance to letter transpositions evolves over time. Experiments 1 and 2 shared the same design, except that in Experiment 2 the critical letters were shown in bold (e.g., *CHOLOCATE*) to increase visual salience (Marcet et al., 2019). Accuracy served as the primary dependent variable, given its greater diagnostic value than response times in delayed-response tasks (Hintzman & Curran, 1997; López Zunini et al., 2022; Romero-Ortells et al., 2024). In these paradigms, the response window is fixed, limiting RT variability and making accuracy a more sensitive measure of orthographic processing dynamics.

Experiment 1

Method

The experiment was pre-registered at OSF (https://osf.io/bt5aj/?view_only=0c52c7b2996d496a9a6153373ea3b5a0). The materials, data, code, and output of the experiment are available at https://osf.io/6y4p9/?view_only=da2304c58ca143fb81f3c3969a2c1fb7

Participants

Forty Spanish-speaking adults (21 women, 19 men) ages 21 to 40 years ($M = 29.5$, $SD = 5.4$) participated in the experiment. This sample size provided 2,000 observations for each type of pseudoword and delay, following Brysbaert and Stevens' (2018) recommendations for detecting small effects. Participants were recruited via the Prolific online platform (https://www.prolific.com/) and reported normal/corrected-to-normal vision with no history of reading difficulties. All participants provided informed consent before the experiment. The experiments were approved by the Ethics Committee of the Universitat de València.

Materials

We employed a set of 200 words and 200 pseudowords from the experiments conducted by Perea et al. (2023). The 200 Spanish words, each containing 7 to 11 letters ($M = 8.9$; Zipf frequency: $M = 3.8$, range: 1.24–5.31; orthographic neighborhood [OLD20]: M = 2.5, range 1.40–3.65) from the subtitled-based EsPal dataset (Duchon et al., 2013), were used to create two types of pseudowords: transposed-letter pseudowords, where two internal nonadjacent consonants were transposed (e.g., *CHOLOCATE*), and replacement-letter pseudowords (e.g., *CHOTONATE*), matched for bigram frequency. These words were also drawn from Perea et al. (2023), with comparable characteristics: a mean Zipf frequency of 3.8 (range: 0.6–5.0), a mean length of 9.0 letters (range 7–11), and a mean OLD20 of 2.5 (range: 1.6–4.3).

We created four counterbalanced lists containing 200 pseudowords (100 transposed-letter pseudowords and 100 replacement-letter pseudowords) and 200 words. Each list was divided into two sublists, as the experiment consisted of two blocks: one with a 750-ms delay and the other with a 1,500-ms delay. The delays were presented in one of two orders: 750 ms followed by 1,500 ms, or 1,500 ms followed by 750 ms across the four lists. Each sublist contained 200 items: 100 pseudowords (50 with transposed letters and 50 with replaced letters) and 100 words.

Procedure

The experiment script was written in PsychoPy (Peirce et al., 2022) and hosted on the Pavlovia platform (https://www.pavlovia.org). Since the experiment was conducted online, participants were instructed to complete the task in a distraction-free location. Written instructions explained that, on each trial, participants would first be presented with a letter string that could either be a word or a nonword in Spanish. Shortly after, a signal-to-respond (a series of #s in blue) would appear. Participants were instructed to decide whether the letter strings were words or not by pressing the "M" key (for "word") or the "Z" key (for "nonword") on the keyboard using their index fingers. Responses were to be made when the signal-to-respond appeared above the letter string. Both speed and accuracy were emphasized in the instructions. Participants were informed that response delays would vary across blocks, although the exact duration of each delay was not disclosed to prevent strategic adjustments in processing.

Each trial of the lexical decision task began with a fixation mask displayed for 50 ms, followed by the word or pseudoword for up to 2,200 ms. The signal to respond ("#####", in blue) appeared after 750 ms in one block and 1,500 ms in the other. Each stimulus item, displayed in 24-point Courier New font, remained on the screen until a response was made or 2,200 ms elapsed. If participants failed to respond before the timeout, the trial was recorded as an error. Short breaks were provided every 50 trials. Participants received a random sequence of trials within each block, with block order (750 ms first or 1,500 ms first) counterbalanced across participants. For each block, the order of trials was fully randomized for each participant. Each block included 16 practice trials with the same delay manipulation: 16 practice trials for the first block and another set of 16 practice trials for the second block. The experimental session, including both blocks, lasted approximately 30 min.

Data analysis

We used Bayesian mixed-effects models implemented in *brms* (Bürkner, 2018) within the R environment (R Core Team, 2023). Accuracy data (1 = correct, 0 = error), the main dependent variable, were modeled with a Bernoulli distribution. The model included stimulus type (transposed-letter vs. replacement-letter pseudowords), encoded as −0.5 and 0.5, and time delay (750 ms vs. 1,500 ms), encoded as −0.5 and 0.5, as fixed factors, and employed a maximal random-effects structure: (1 + stimulus_type × time_delay | subject) + (1 + stimulus_type × time_delay | item). We employed the default non-informative priors from brms, and conducted 10,000 iterations (1,000 for warm-up) across four chains. In these Bayesian models, the output includes posterior estimates (*b*) for each effect—representing the medians of the posterior distributions and the standard errors of the posterior distributions, along with their 95% credible intervals (95% CrI). We considered that there was evidence for an effect when its 95% CrI did not cross zero. Credible intervals excluding zero are shown in bold. We employed *emmeans* (Lenth et al., 2018) to conduct simple effects analyses in case of evidence for an interaction between the two factors.

For completeness, we also conducted parallel Bayesian linear mixed-effects models on the correct response times to pseudowords, modeled using an ex-Gaussian distribution. Since the signal-to-respond times differed widely (750 and 1,500 ms), response times were calculated in the analyses from the signal-to-respond rather than the onset of the stimulus item.

Results and discussion

Trials with responses occurring before the signal-to-respond (2.77%) were excluded from the analyses. Table 1 presents the mean error rates (in percentage) and correct response times for transposed-letter and replacement-letter pseudowords at the two-time delays. The overall number

Table 1 Mean error rates (in percentage) and correct lexical decision times (in ms) for TL and RL pseudowords at 750-ms and 1,500-ms delays in Experiment 1

	Error rates (%)			Response times (ms)		
	TL	RL	TL Effect	TL	RL	TL Effect
Delay						
750 ms	6.7	1.1	9.6	1048	1018	30
1,500 ms	4.6	1.7	2.9	1818	1813	5

TL refers to transposed-letter pseudowords, and RL refers to replacement-letter pseudowords. For the "word" stimuli, the mean correct lexical decision times were 1,009 ms with an error rate of 2.1% at the 750-ms delay and 1803 ms with an error rate of 0.8% at the 1,500-ms delay

Note that the RTs are measured from the presentation of the string (not form the signal to respond)

of observations in the accuracy and correct RT analyses were 7817 and 7430, respectively.

The analysis using linear mixed-effects effects models revealed higher accuracy at the 1,500-ms delay than at the 750-ms delay ($b = 0.80$, $SE = 0.22$, **95% CrI [0.40, 1.25]**) and higher accuracy for replacement-letter pseudowords than for transposed-letter pseudowords, reflecting a transposed-letter effect ($b = -1.60$, $SE = 0.31$, **95% CrI [−2.22, −1.02]**). Critically, we found evidence for an interaction between the two factors ($b = 1.19$, $SE = 0.48$, **95% CrI [0.26, 2.14]**): the transposed-letter effect was greater at the 750-ms delay (9.6%; $b = 2.183$, **95% CrI [1.479, 2.90]**) than at the 1,500-ms delay (2.9%; $b = 0.996$, **95% CrI [0.185, 1.79]**).

The analyses of the response times from the signal to respond also showed that the transposed-letter effect was modulated by the delay (interaction: $b = -20.95$, $SE = 5.46$, **95% CrI [−31.64, −10.23]**): simple effects analyses revealed a sizable transposed-letter effect at the 750-ms delay (30 ms; $b = -25.47$, **95% CrI [−32.5, −18.32]**) but not at the 1,500-ms delay (5 ms; $b = 4.44$, 95% CrI [−11.3, 1.99]) (see the OSF for the full analysis of response times).

Thus, this experiment showed higher accuracy for pseudowords at the 1,500-ms delay than the 750-ms delay, which was associated with greater transposed-letter effects at the 750-ms delay (9.6%) than at the 1,500-ms delay (2.9%). In addition, the response time data captured a transposed-letter effect at the 750-ms delay (30 ms) but not at the 1,500-ms delay (5 ms).

As suggested by a Reviewer, we also examined whether lexical processing was still ongoing at the time of the response. To that end, we computed the Pearson correlation between item-level Zipf frequency and response times for words at each delay. As expected, word frequency predicted response times at the 750-ms delay, $r = -.19$, $\boldsymbol{p = .008}$, but not at the 1,500-ms delay, $r = -.03$, $p = .64$. The absence of word-frequency effects at 1,500 ms contrasts with the persistence of a transposed-letter effect for pseudowords, indicating that residual orthographic activation still influences lexical decisions even when lexical variables no longer do.

While these findings strongly suggest that positional uncertainty decreases dramatically with increased processing time, the small but reliable transposed-letter effect at 1,500 ms may favor models that assume intermediate orthographic representations (e.g., open bigrams), with an influence on lexical activation that persists over time, albeit in a transient or diminishing form.

To further test the limits of the transposed-letter effect over time, we conducted Experiment 2, parallel in design to Experiment 1 but included a visual contrast manipulation on the two critical letters (e.g., *CHOLOCATE* vs. *CHOTONATE*). This manipulation has been shown to reduce the transposed-letter effect, as it enhances the salience of the transposed letters (see Marcet et al., 2019); for consistency, two letters were also marked for word stimuli.

In sum, in Experiment 2, we expected that increased visual contrast would reduce positional uncertainty over time, leading to a near-zero transposed-letter effect at the 1,500-ms delay (i.e., letter order would be fully encoded; see Fig. 1). However, according to open bigram models, the increased contrast might modulate the weighting of open bigrams; nonetheless, shared open bigrams could continue to drive lexical activation, suggesting a reduced but persistent transposed-letter effect at the critical 1,500-ms delay.

Experiment 2

Method

The experiment was pre-registered at OSF (https://osf.io/9qmue/?view_only=f61cdffdf37a45ad89dc6af62e84c1b9). The materials, data, code, and output of the experiment are available at https://osf.io/6y4p9/?view_only=da2304c58ca143fb81f3c3969a2c1fb7

Participants

We recruited a new sample of 40 participants (24 women, 16 men) age 21 to 40 years ($M = 28.7$, $SD = 5.46$) with the same characteristics as in Experiment 1.

Materials, procedure, and data analyses

They were the same as in Experiment 1. The only difference was that two contiguous consonants in the word stimuli and the transposed or replaced consonants in the pseudowords were marked in bold, following the Experiment 2 setting of Marcet et al. (2019). The instructions did not explicitly mention the function of contrast manipulation.

Results and discussion

Responses made before the signal-to-respond (3.00%) were excluded from the analyses. Table 2 summarizes the mean error rates and response times for transposed-letter and replacement-letter pseudowords across the two delays.

The statistical analyses showed lower accuracy for the transposed-letter pseudowords than for the replacement-letter pseudowords ($b = -1.40$, $SE = 0.30$, **95% CrI [−2.00, −0.84]**), whereas the overall accuracy did not differ between the 750-ms and 1,500-ms delays ($b = 0.26$, $SE = 0.22$, 95% CrI [−0.17, 0.69]). More important, we found evidence of an interaction between the two factors ($b = 1.23$, $SE = 0.41$, **95% CrI [0.42, 2.05]**): the transposed-letter effect was sizable at the 750-ms delay (9.2%; $b = 2.00$, **95% CrI [1.29, 2.77]**), but it was much smaller at the 1,500-ms delay (2.0%; $b = 0.77$, **95% CrI [0.13, 1.48]**).

The analyses of the response times from the signal to respond also revealed an interaction between the two factors ($b = -19.29$, SE = 5.03, **95% CrI [−29.25, −9.48]**): we found a transposed-letter effect at the 750-ms delay (27 ms; $b = -18.97$, **95% CrI [−27.46, −10.52]**) but not at the 1,500-ms delay (−1 ms; $b = 0.30$, 95% CrI [−5.85, 6.49]).

Similar to Experiment 1, accuracy was higher for replacement- than for transposed-letter pseudowords. This difference was sizable at the 750-ms delay (9.2%; 26 ms) and largely diminished at the 1,500-ms delay (2.0%; −1 ms). Thus, the contrast manipulation barely affected the transposed-letter effect from Experiment 1 (9.8% and 2.9% at the 750-ms and 1,500-ms delays, respectively). Overall, this pattern is consistent with models incorporating intermediate representations (e.g., open bigrams), which may continue to support partial lexical activation even after lexical variables like word-frequency no longer exert an influence.

Furthermore, in line with Experiment 1, word frequency predicted response times at 750 ms ($r = -.32$, $\boldsymbol{p < .001}$) but not at 1,500 ms ($r = -.09$, $p = .21$). The absence of word-frequency effects at 1,500 ms, coupled with the continued presence of a transposed-letter effect, suggests that residual orthographic activation persists beyond early processing stages.

General discussion

The present experiments examined how letter position coding evolves by examining the transposed-letter effect in a delayed lexical decision task. In both experiments, participants saw nonadjacent transposed-letter pseudowords (e.g., *CHOLOCATE*) and their replacement-letter counterparts (e.g., *CHOTONATE*) under two signal-to-respond delays (750 ms vs. 1,500 ms). Our main goal was to test whether the transposed-letter effect would disappear with more extended processing (as predicted by positional uncertainty models) or persist to some extent (as proposed by open bigram accounts).

Experiment 1 showed a substantial transposed-letter effect at 750 ms (9.6% in accuracy and 30 ms in the RTs) that decreased but did not entirely vanish at 1,500 ms in the accuracy data (2.9% and 4 ms). Experiment 2 replicated this pattern, with a similarly robust effect at 750 ms (9.2% and 27 ms) and a minimal effect at 1,500 ms (2.0% and −1 ms), despite highlighting the critical letters in bold (e.g., *CHOLOCATE vs. CHOTONATE)*. The sizable transposed-letter effect at the 750-ms delay is consistent with previous ERP findings, suggesting positional uncertainty persists at late processing stages (see Labusch et al., 2024; Vergara-Martínez et al., 2013). Notably, the diminishing but persistent effect at 1,500 ms suggests that while positional uncertainty decreases, some residual orthographic overlap continues to influence lexical activation, increasing the likelihood of false positives (i.e., "word" responses to transposed-letter pseudowords).

Table 2 Mean error rates (in percentage) and correct lexical decision times (in ms) for TL and RL pseudowords at 750-ms and 1,500-ms delays in Experiment 2

	Error rates (%)			Response times (ms)		
	TL	RL	TL effect	TL	RL	TL effect
Delay						
750 ms	10.9	1.7	9.2	1053	1026	27
1,500 ms	4.4	2.4	2.0	1800	1801	−1

TL refers to transposed-letter pseudowords, and RL refers to replacement-letter pseudowords. For the "word" stimuli, the mean correct lexical decision times were 1,009 ms with an error rate of 1.9% at the 750-ms delay and 1785 ms with an error rate of 1.2% at the 1,500-ms delay

Figure 2 shows a raincloud plot from Experiment 2, illustrating transposed-letter effects across participants. (A similar plot for Experiment 1 is available in the OSF repository.) Accuracy for replacement-letter pseudowords remained high at both delays, suggesting limited lexical activation. In contrast, accuracy for transposed-letter pseudowords was markedly lower at 750 ms, consistent with early positional uncertainty. By 1,500 ms, nearly half of the participants (18/40; 45%) showed no transposed-letter effect, indicating that positional uncertainty had largely resolved. The remaining 22 participants (55%) showed a small effect at 1,500 ms. These individual differences echo earlier findings that highly skilled readers (e.g., Scrabble players) produce few errors on transposed-letter pseudowords (Gómez et al., 2021; Perea et al., 2016). This variability reflects an interplay between bottom-up refinement of letter-position information and top-down input from partially matching lexical representations.

Importantly, while both experiments revealed a sizable transposed-letter effect for pseudowords at the 750-ms delay, this effect was markedly reduced—but still present—at 1,500 ms. In contrast, word-frequency influenced response times to words at 750 ms, but not at 1500 ms. This dissociation suggests the transposed-letter effect reflects residual orthographic activation, rather than decisions made early and held until the response cue. These findings suggest the need for models incorporating intermediate representations in the word recognition system, beyond a mere decrease in perceptual uncertainty.

Taken together, these results support a hybrid account of letter position coding. Early in processing, positional uncertainty makes transposed-letter pseudowords more confusable with real words. Over time, letter positions are encoded more precisely, substantially reducing errors for transposed-letter pseudowords. However, the small transposed-letter effect in the false-positive rates at 1,500 ms (i.e.,

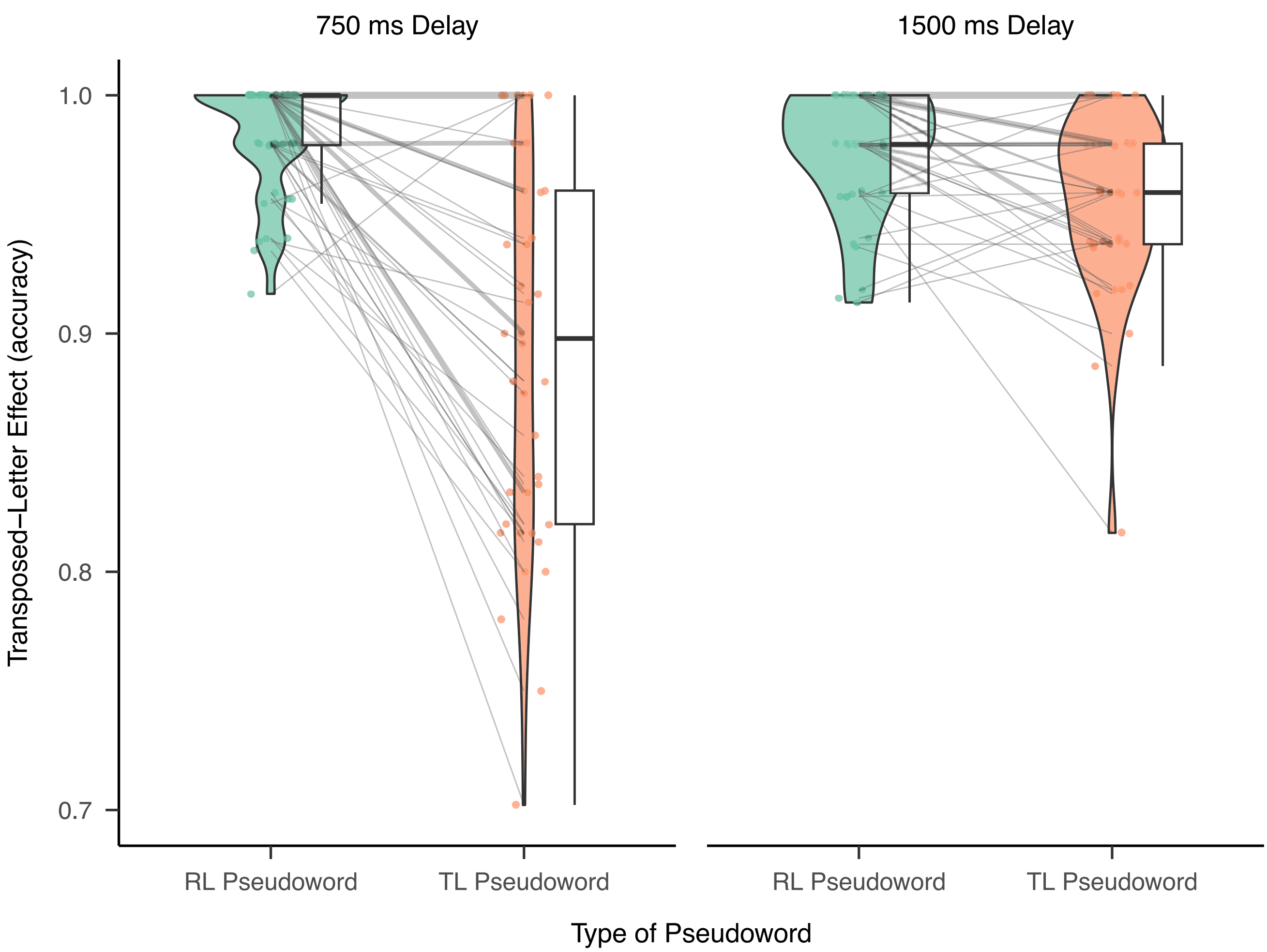

Fig. 2 Raincloud plot showing the accuracy of transposed-letter (TL) and replaced-letter (RL) pseudowords with violin and box plots by subjects in Experiment 2 (left panel: 750-ms delay; right panel: 1,500-ms delay). Gray lines connect the subject-level accuracies for RL and TL pseudowords, with line thickness indicating the number of participants sharing the same effect. (Color figure online)

"word" responses to *CHOLOCATE*), observed in both experiments, suggests that sublexical representations (e.g., open bigrams) continue to contribute lexical overlap, preventing the effect from disappearing entirely. These findings favor hybrid accounts of letter position coding (e.g., Adelman, 2011; Grainger & Ziegler, 2011; Marcet al., 2019; Massol & Grainger, 2022; Snell, 2025) over models relying on a single mechanism, and provide important constraints on how these models can accommodate individual differences. Notably, recent research on transposed-letter effects suggest that early stages of visual word recognition are relatively homogeneous across readers (see Gómez et al., 2025; Lee et al., 2024), implying that individual differences in letter position coding emerge at later stages of processing.

While simplified, the simulations of the two model families (see Supplemental Materials) illustrate how positional uncertainty and open bigram frameworks generate diverging predictions over time. Their purpose is not to offer full model implementations but to clarify the distinct temporal dynamics each account assumes. Importantly, the persistence of a transposed-letter effect at 1,500 ms—even when word frequency no longer influences responses—places clear constraints on models of visual word recognition: orthographic similarity continues to shape decisions beyond early processing stages. Full implementations will be needed to generate precise predictions under delayed-response conditions, but our findings help delineate the temporal window in which different mechanisms (i.e., perceptual uncertainty versus shared bigrams) modulate lexical activation. A remaining open question is whether the delay permits continued visual sampling or reflects a reevaluation of previously encoded input. We cannot disentangle these possibilities here, but future studies using brief presentation followed by post-stimulus masking (e.g., 500 ms) may help clarify the underlying dynamics.

To examine these temporal dynamics, future studies could employ electrophysiological measures with several signal-to-respond delays to help pinpoint when positional uncertainty resolves and when higher-level representations (e.g., open bigrams) begin to exert their influence, as well as how reader-specific factors (e.g., reading skill, orthographic knowledge) modulate this process (see Gómez et al., 2021, for behavioral evidence with young readers). In addition, applying similar paradigms to braille reading or speech perception may reveal domain-general principles of serial order processing across tasks (see Logan, 2021, for a similar approach).

In sum, the present findings demonstrate that letter position coding is flexible and increasingly precise over time: it remains imprecise early on, allowing robust transposed-letter effects even at 750 ms post-stimulus, yet is not fully "locked in" after considerable processing time (1,500 ms) for around half of the participants. Therefore, models of visual word recognition must consider the interplay of decreasing positional noise and on-going contribution of partially activated sublexical codes. Ultimately, our ability to read quickly while *toelrating* minor perceptual disruptions underscores the flexibility of the cognitive system in managing serial order.

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Declarations

Conflicts of interest The authors have no competing interests to declare relevant to this article's content.

Ethics approval This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of the University of València.

Consent to participate and publication Informed consent was obtained from all individual participants included in the study.

Open practices (Availability of data, materials and code) The two experiments were preregistered: https://osf.io/bt5aj/?view_only=0c52c7b2996d496a9a6153373ea3b5a0 (Exp. 1) and https://osf.io/9qmue/?view_only=f61cdffdf37a45ad89dc6af62e84c1b9 (Exp. 2). The materials, data, code, and output of the two experiments are available at https://osf.io/6y4p9/?view_only=da2304c58ca143fb81f3c3969a2c1fb7

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