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ORIGINAL ARTICLE

Reading about a RELO-VUTION

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Abstract

Pseudowords created by transposing two letters of words (e.g., MOHTER; CHOLOCATE) are highly confusable with their base word; this is known as the transposed-letter similarity effect. In this work, we examined whether transposed-letter effects occur when words span more than one line (e.g., CHOLO- in one line and CATE in another line; note that the transposed letters L and C are in different lines). While this type of presentation is not the canonical format for reading in alphabetic languages, it is widely used in advertising, billboards, and street signs. Transposed-letter pseudowords and their replacement-letter controls were written in the standard one-line format versus a two-line format (Experiments 1–2) or a syllable-per-line format (Experiment 3). While results showed some decrease in the transposed-letter effect in the two-line and syllabic formats, the transposed-letter effect was still substantial in the accuracy of responses. These findings demonstrate that even when the letters being transposed are relatively far apart in space, the transposed-letter effect is still robust. Thus, a major component of letter position coding occurs at an abstract level.

Introduction

Reading involves multiple sensory, perceptual, and linguistic processes. Researchers enthusiastically debate the interaction and the boundaries of such processes (e.g., Grainger, 2018) because they have important consequences for our understanding of reading development and skilled reading alike. The present research deals with a manipulation that bridges the perceptual and orthographic aspects of reading words, thus constraining the front-end of models of word recognition and reading: words that span more than one line. This format has not been widely studied but is not unfamiliar to readers. Professionally printed books and newspapers often have hyphenation at the end of the line; furthermore, and multiple-line format is reasonably frequent in posters and advertisements (see Fig. 1). Critically, multiple-line presentations allow us to spatially separate letters that are close in the ordinal order of words. Consider the physical distance of the letters L and T in the word REVO**L**U**T**ION, which are only 2 letters apart. When the word is presented across two lines, they remain two ordinal positions apart, but they are spatially more distant than in the one-line presentation:

REVO**L**U-
TION

In the present research, dissociating spatial distance from ordinal distance allow us to explore an aspect of orthographic processing that has been the focus of considerable interest in the recent past: letter position coding. The transposed-letter (TL) similarity effect gives us a glimpse into the letter position coding: pseudowords created by transposing two letters of words (e.g., MOHTER; REVOTULION) are perceived as highly similar to their base word. We can describe this effect as evidence of flexibility in the system because it is not difficult to make sense of a word with a transposed-letter misspelling (e.g., the apocryphal Cambridge University email from the early 2000s); importantly,

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The raw data and code for all analyses are provided on the OSF website https://osf.io/zyab2/.

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Fig. 1 Examples of real-world text that uses multi-line format. The first picture on the left is a hotel in Valencia, Spain; the second picture is a business card for a restaurant that specializes in octopus (pulpo); the picture on the right is a poster for a film festival in Galena, MO, USA; and the last picture is an ad for the Galician tourism board (camina means "to walk" in the imperative, third person form)

this flexibility can also lead to errors (i.e., it is hard to find the misspelling in a string like JUGDE).

The first demonstration of the transposed-letter effect (Bruner & O'Dowd, 1958) involved reconstructing words from strings with letter transpositions asked to deduce the base word (AVITAION → AVIATION). More contemporary paradigms that explore this topic use single-presentation lexical decision tasks (the more word-like a pseudoword is [e.g., RELOVUTION], the longer the response times and the more false positives it will yield), masked priming tasks (the higher is similarity between prime and target, the stronger the priming effect), two-alternative force choice tasks (a probe is flashed and the two alternatives vary on their similarity), and parafoveal previews during reading (the higher is similarity between preview and target, the stronger the preview effect).

Transposition effects have been reported not only for letters, but also for other visual objects such as strings of digits (García-Orza et al., 2010), geometrical shapes (García-Orza et al., 2011), symbols (Massol et al., 2013), unfamiliar letters (Fernández-López et al., 2021), and notes in a staff (Perea et al., 2013). Furthermore, these effects have been found using letters with pre-readers (Perea et al., 2015, 2016) and non-human species (baboons: Ziegler et al., 2013; pigeons: Scarf et al., 2016). Given that the effect is present in non-orthographic contexts, it would be reasonable to assume that it has a strong visuo-spatial component. Indeed, a family of models of letter position coding assumes that transposition effects occur due to perceptual uncertainty when assigning objects to positions in the spirit of visual attention models (e.g., Logan, 1996)—one instance of these models of letter position is Gomez et al.'s (2008) overlap model. However, visual manipulations have typically proven almost ineffective at modulating the transposed-letter effect. For example, Marcet et al. (2019) used highlighted transposed/replaced letters (e.g., CHOLOCATE; CHOLOCATE) and Perea et al. (2021) used a varying graded gray intensity (e.g., JUDGE; JUDGE). Both studies found strong transposed-letter effects in both cases. Furthermore, transposed-letter effects are robust in the tactile modality, when reading braille (Baciero et al., 2022), which implies that the locus of the effect cannot only be due to visual uncertainty. In short, the transposed-letter effect might be one of the most robust effects in cognitive psychology and it may well be the case that it has multiple loci (e.g., spatial-specific and based of how words are represented, see Grainger, 2018; Marcet et al., 2019; Massol et al., 2013).

In our multiple-line presentation stimuli, a novel manipulation, we can separate spatial distance from ordinal distance. For the nonwords in our experiments, letter transposition and replacements always involved letters in different lines. While there is some diagonal proximity between the transposed letters, we must keep in mind that all Roman-based orthographies are read from left to right, and there is very little information extracted from below the fixated line during sentence reading (see Pollatsek et al., 1993). For comparison purposes, the stimuli were also presented in a standard one-line format, and the size of the transposed-letter effect is calculated as the difference in RT and accuracy between the transposed-letter nonword condition and the replaced-letter nonword condition. Table 1 shows an overview of the three experiments, but the logic is the same across the three: we compare the transposed-letter effect in the multi-line presentation format to the same effect in the standard one-line presentation format.

Our manipulation has some resemblance to the one employed by Lee and Taft's (2009) Experiment 4. They termed their presentation "Hangulized" in reference to the Korean script, in which the letters are grouped based on the syllabic stricture of the word, as in the Korean writing system Hangul (see Fig. 2). In a lexical decision task, they presented English words in the standard and in a "Hangulized" format and found a much smaller percentage of errors for transposed-letter pseudowords like *widsom*

Table 1 Stimuli conditions in the experiment

	Format			
	One-line	Two-line (down)	Two-line (up)	Syllable-per-line
Words	REVOLUTION	REVO- LUTION	LUTION REVO-	RE VO LU TION
Pseudowords				
Replaced	RENOCUTION	RENO- CUTION	CUTION RENO-	RE NO CU TION
Transposed	RELOVUTION	RELO- VUTION	VUTION RELO-	RE LO VU TION

Fig. 2 The right panel presents an example of the stimuli in Lee and Taft's (2009) Experiment 4. They termed their presentation "Hangulized" in reference to the Korean script, in which the letters are grouped based on the syllabic stricture of the word, as in the Korean writing system Hangul

(baseword: wisdom) in Hangulized format (Experiment 4) than in a parallel experiment with the standard horizontal format (Experiment 1): 14.9% vs. 41.2%, respectively—the parallel averages for one-letter different nonwords (e.g., *widrom*) were 4.98% and 12.50%, respectively. While these findings offer some hints that the transposed-letter effect can be dramatically reduced with a visual-spatial manipulation, the latencies were dramatically higher in the extremely unfamiliar Hangulized stimuli than in the standard format (close to 1700 ms vs. less than 700 ms, respectively). Instead, our multiple-line manipulation is relatively familiar to all participants (see Fig. 1) and it may represent better the typical processes underlying rapid word recognition.

In sum, the main goal of the present article is to stablish whether the transposed-letter effect occurs across separate lines in the most employed word recognition task, lexical decision; hence its contribution is mostly empirical and to that end we complement the inferential analyses with exploratory data analyses aimed at shedding some light on the nature of the observed effects. Critically, it is important to point out that this work is motivated by our desire to find the limits of the perceptual uncertainty account as implemented by the overlap model (Gomez et al., 2008). Indeed, we present fits from a 2-D instantiation of the overlap model depicted in Fig. 3 (i.e., a visual-perceptual model of letter position coding); in Table 2 (see Appendix 1 for details), and we discuss the implications of the findings for models of letter position coding in "General discussion".

Experiment 1

Methods

Participants

Thirty-two undergraduate students (24 females and 8 males) from the University of Valencia participated in the experiment. This sample size ensured 1600 observations per condition for the pseudoword trials; hence, this experiment can detect relatively small-sized effects (see Brysbaert & Stevens, 2018)—note that the size of transposed-letter effects in Western languages is typically quite large. All participants were native speakers of Spanish with normal/corrected vision and no self-reported history of reading problems. They signed an informed consent form before the experiment.

Materials

The word and pseudoword stimuli were extracted from Experiment 1 of Marcet et al. (2019). A table with the linguistic statistics as computed by the EsPal database (Duchon et al., 2013) is available in the OSF repository. The set was composed of 200 base words in Spanish (e.g., REVOLUCIÓN). The mean Zipf frequency was 3.8 (range 1.24–5.31), the mean number of letters of 8.9 (range 7–11), and the mean OLD20 was 2.5 (range 1.40–3.65). For each base word, we generated two pseudowords: a transposed-letter pseudoword and a replacement-letter pseudoword. The transposition/replacement always involved the initial consonant of two internal syllables (e.g., RELOVUCIÓN; RESOTUCIÓN). Since each pseudoword could be presented in the one-line

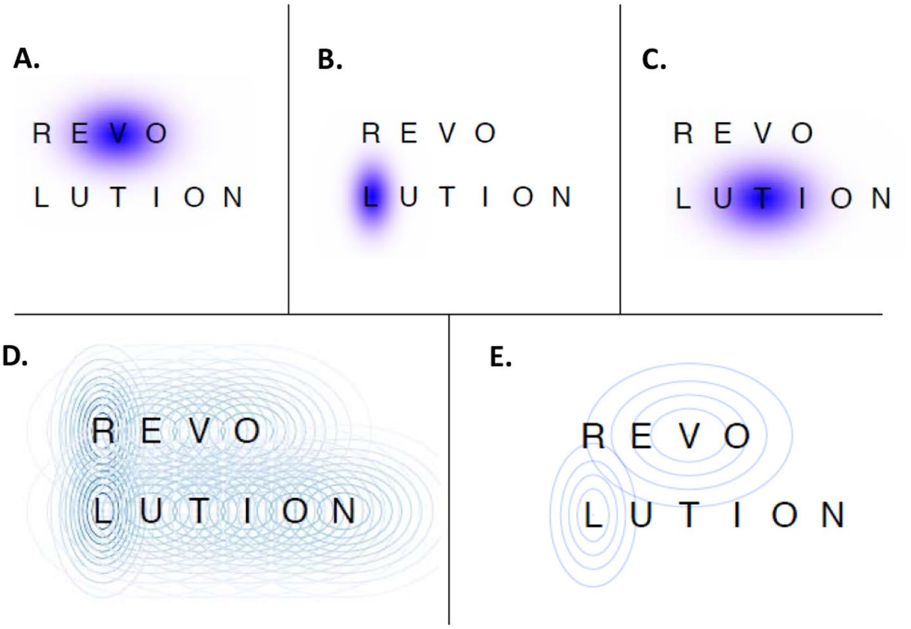


Fig. 3 Graphic representation of the 2-D overlap model. See the main text for an explanation of the panels

Table 2 Predicted effects in the 2-D overlap model in the experiments

Stimuli		Overlap		Model's TL effect		Exp 1 TL effect (accuracy)		Exp 2 TL effect (accuracy)	
1 line	2 lines	1 line	2 lines	1 line	2 lines	1 line	2 lines	1 line	2 lines
LI**R**E**T**ATURA	LI**R**E- **T**ATURA	0.863	0.762						
LI**N**E**B**ATURA	LI**N**E- **B**ATURA	0.807	0.755	0.0559	0.0069	0.24	0.15	0.10	0.12
PRI**V**A**M**ERA	PRI**V**A **M**ERA	0.885	0.768						
PRI**C**A**T**ERA	PRI**C**A- **T**ERA	0.822	0.766	0.0623	0.0017	0.28	0.15	0.13	0.14
OBLI**T**A**G**ORIO	OBLI**T**A- **G**ORIO	0.902	0.775						
OBLI**F**A**S**ORIO	OBLI**F**A- **S**ORIO	0.835	0.775	0.0670	0.0005	0.48	0.34	0.40	0.27

The conditions were based on a post hoc analysis of the number of letters in the first line. The overlap has a scale of 0 to 1, where 0 is no shared letters in any position, and 1 is the overlap for identical strings of letters. The stimuli examples are the transposed- and replaced-letter pseudowords originated from the Spanish words *literatura*, *primavera*, and *obligatorio* (literature, spring, and mandatory). The bold letters indicate the transposed/replaced letters. The two-line stimuli for Experiment 2 would have the second part of the screen on top of the first:

TATURA

LIRE-

format or split between two lines, we had four conditions: (1) a transposed-letter pseudoword in one line; (2) a transposed-letter pseudoword in two lines; (3) a replacement-letter pseudoword in one line; (4) a replacement-letter pseudoword in two lines (see Table 1). Note that the two sets of resulting nonwords were quite similar in terms of mean log bigram frequency (transposed letters-nw: 1.939, replacement letters-nw: 1.936) and neighborhood size (transposed letters-nw: 0.054; replacement letters-nw: 0.045). To comply with Spanish orthographic norms, the stimuli presented in two lines had a hyphen at the end of the initial line, and the hyphen only occurred at the boundary between syllables (in English, the rules of hyphenation are slightly more complex). For the lexical decision task (i.e., to act as the word fillers), we selected a separate set of 200 words from Marcet et al.'s (2019) Experiment 1. We created two versions for each word (i.e., one-line words; two-line words). Note that the comparisons of theoretical interests are among the nonword stimuli, and the total number of data points for each combination of format (one-line vs. two-line) and target type (transposed-letter vs. replacement-letter pseudoword) was 1600 (50 items per condition for 32 participants).

Procedure

The experimental session took place in groups of up to seven participants in a quiet room. We employed DMDX (Forster & Forster, 2003) for stimulus presentation and response collection. Participants were told that, on each trial, they would be presented with a letter string in uppercase that could be a Spanish word. Their task was to press, as quickly and accurately as possible, either a green-colored button ("word") or a red-colored button ("nonword"). In each trial, a fixation point was presented for 500 ms, and this was followed by the stimulus until the participant's response—or a 2100-s deadline. Every 120 trials, there was a short break. There was a brief 16-trial practice block to familiarize participants with the task. The experiment lasted for around 15 to 17 min.

Results

Error responses and very fast correct responses (less than 250 ms) were excluded from the latency analyses—responses could not be longer than the 2100 ms deadline. Table 3 shows the mean response time and accuracy in each condition. Although our focus was on the pseudoword data (i.e., the stimuli containing transposed/replacement-letter items), we also report the analysis of the word data.

To analyze the latency and accuracy data, we employed Bayesian linear mixed-effects models with the brms package (see Bürkner, 2016) in R. This allowed us to fit models with the maximal random effect structure that other (generalized) linear mixed-effects functions typically fail to converge (see Barr et al., 2013, for arguments in favor 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 iterations. For each chain, there was a 1000-iteration warmup. Our statistical inferences are based on the posterior distributions, for which we obtained estimates of the mean (i.e., the coefficient *b*), its standard error, and its 95% credible interval (CrI). We interpreted an effect as significant when its corresponding 95% CrI did not cross zero.

Table 3 Mean correct lexical times (in ms) and error rates (in percentage) for one-line and two-line stimuli in Experiment 1

	Word	Transposed-letter pseudoword	Replacement-letter pseudoword	Transposed-letter effect
Format				
One-line	788 (2.6)	1032 (33.8)	940 (7.5)	92 (26.3)
Two-line	957 (8.1)	1173 (26.8)	1104 (10.9)	69 (15.9)

For the pseudoword data, the fixed factors in the models were Type of pseudoword (replacement-letter pseudoword vs. transposed-letter pseudoword; coded as − 0.5 and 0.5) and presentation Format (one line vs. two lines; − 0.5 and 0.5). We used the ex-Gaussian distribution for the latency analyses because of the positive skew of response time data (family = ex-Gaussian (identity = link)). In contrast, we employed the Bernoulli distribution for the accuracy analyses (family = Bernoulli). We fitted the maximal model in terms of random-factor structure:

$$\text{Dependent variable}: \text{RT or Accuracy} \sim \text{Format} * \text{Type} + (1 + \text{Format} * \text{Type} \mid \text{subject}) + (1 + \text{Format} * \text{Type} \mid \text{item})$$

where type could be transposed letters or replaced letter, and Format could be one or two-line presentation). The models converged successfully and the values of $\hat{R}$ were 1.00 for all parameters. For the word data, the only fixed factor was presentation Format, and the analysis plan was analogous to that for the pseudoword data.

Pseudoword data Regarding latency data, responses were slower for transposed-letter pseudowords than for replacement-letter pseudowords ($b = 69.22$, SE = 11.61, 95% CrI [4.59, 92.20]) and responses were slower for two-line pseudowords than for the one-line pseudowords ($b = 158.33$, SE = 15.17, 95% CrI [128.75, 188.51]). Furthermore, the magnitude of the transposed-letter effect was smaller in the two-line format than in the one-line format (92 vs. 69 ms; interaction: $b = -28.14$, SE = 12.90, 95% CrI [− 53.36, − 2.80]).

Regarding accuracy data, responses were, overall, more accurate for replacement-letter pseudowords than for transposed-letter pseudowords ($b = -2.12$, SE = 0.23, 95% CrI [− 2.59, − 1.67]) and responses were also more accurate for one-line pseudowords than for two-line pseudowords ($b = -0.58$, SE = 0.19, 95% CrI [− 0.96, − 0.24]). Finally, the size of the of the letter transposition effect was smaller in the two-line format than in the one-line format (error rates: 15.9 vs. 26.3%; interaction: $b = 0.91$, SE = 0.21, 95% CI [0.51, 1.34]).

Word data Responses were slower and less accurate for two-line words than for one-line words (latency data: $b = 126.57$, SE = 9.04, 95% CI [108.84, 114.48]; accuracy data: $b = -1.25$, SE = 0.18, 95% CI [− 1.63, − 0.90]).

These results revealed that while there was some decrease in the magnitude of the transposed-letter effect for two-line stimuli, the effect was still highly robust. In addition, while there was some processing cost when reading two-line stimuli, the effect was not particularly disruptive (see Table 1).

To complement the inferential methods described above, we carried out exploratory data analysis methods (Tukey, 1977) in which we analyzed the temporal dynamics of the transposed-letter effects on latency and accuracy using delta plots and conditional accuracy functions.

Exploratory data analysis

Delta plots To characterize the time-course dynamics of the transposed-letter effect on the latency data in the two formats (i.e., one-line vs. two-line), we computed the delta plot of the transposed-letter effect (see Fig. 4). Delta plots (de Jong et al., 1994) display the RT difference between the two conditions at the 0.1, 0.3, 0.5, 0.7, and 0.9 quantiles. Thus, these plots show how the transposed-letter effect evolves as response times increase.

1. We obtain the RTs at the desired quantiles (here we use 0.1, 0.3, 0.5, 0.7, and 0.9 quantiles) for every participant for each of the conditions to be compared, only for correct responses.
2. We average the RTs obtained in Step 1 across participants (these averaged quantiles are also called vincentiles in the RT literature; see Ratcliff, 1979).
3. For each of the quantiles in the vincentiles, (a) we find the average between the two conditions, and (b) then compute the differences (i.e., the delta) preserving the sign.
4. The last step is to plot the points (as many points as there are quantiles), with the averages (Step 3a) on the x-axis and the delta (Step 3b) on the y-axis.

As is evident from Step 3b, delta plots are based on residual quantiles (i.e., RTs at quantiles for transposed-letter [TL] minus replacement-letter [RL] conditions), and hence can provide us with some indication of the temporal dynamics of an effect when interpreted within the lens of process models. For example, a flat line at around $y = 50$ ms would mean that there is a 50-ms shift in the RT distributions—this could be interpreted as faster encoding times in evidence accumulation models (see Gómez & Perea, 2013, for an example of such interpretation in the standard masked priming technique). Alternatively, an ascending function would indicate that the effect grows for slower responses, and it could be interpreted as a difference in the rate of evidence accumulation.

In delta plots, one needs to contrast two conditions; in our analysis, we focus on the transposition vs. replacement comparison. For the one-line format, the transposed-letter effect was sizeable even for the fast response times, and it grows with the slower responses (see left panel of Fig. 4). In contrast, in the two-line format, the difference in response times between the transposed-letter pseudowords vs. replaced-letter pseudowords is noticeably smaller along with the RT distribution relative to the one-line version, but still, sizably above zero (see right panel of Fig. 4).

Conditional accuracy functions Conditional accuracy functions (Bonnet & Dresp, 1993; Ollman, 1977) allow us to visualize how accuracy evolves as latencies increase. These plots were generated as follows:

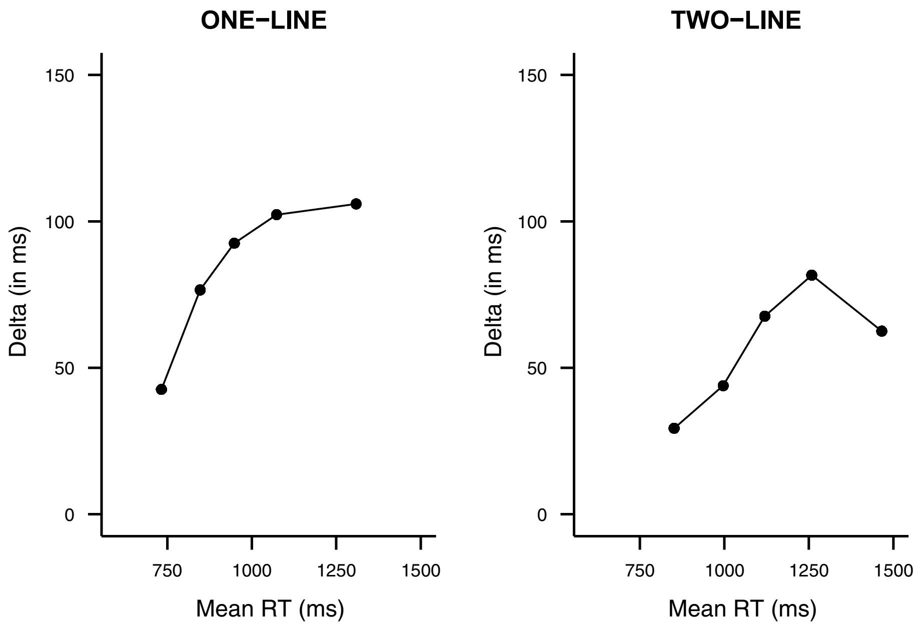


Fig. 4 The panels show the delta plots of the transposed-letter effect for one-line and the two-line pseudowords in Experiment 1

1. For each type of item and each participant, we found the RTs at quantiles 0.1, 0.3, 0.5, 0.7, and 0.9; to do so, we included both correct and error responses.
2. We assign each RT to equally sized bins based on the quantiles.
3. We averaged the RTs and accuracies for each bin across all participants, and then calculate (a) the average RT for each of the bins and (b) the average accuracy within each bin.
4. The last step is to plot the points (as many points as there are quantiles), with the average RTs (Step 3a) on the x-axis and the average accuracies (Step 3b) on the y-axis.

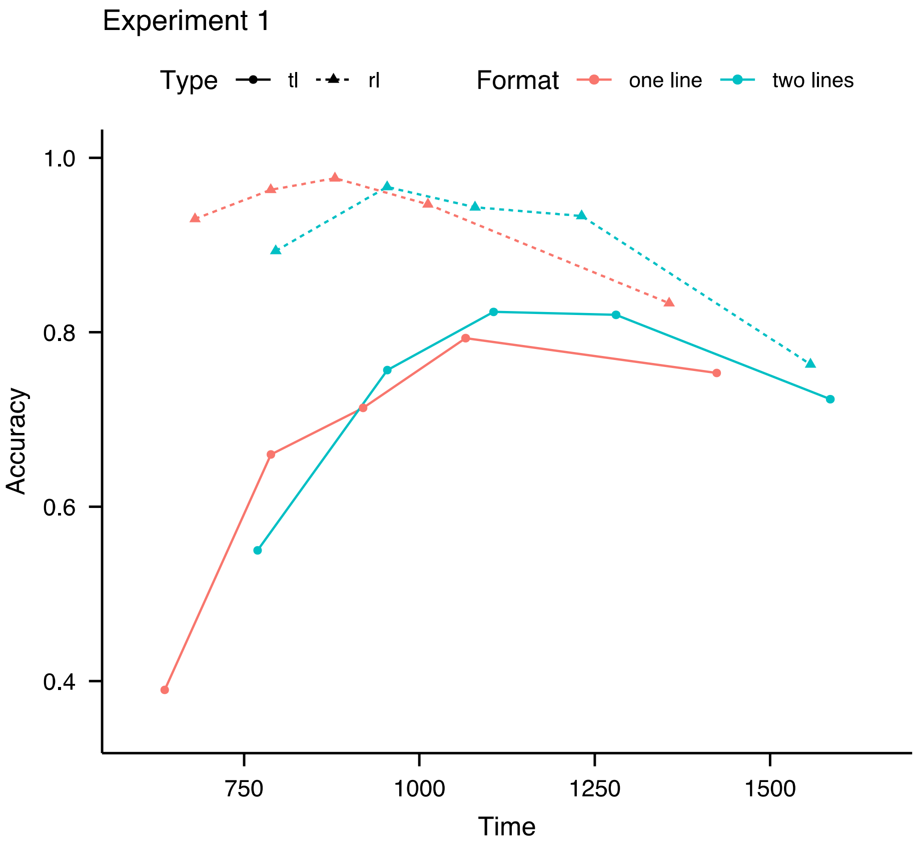
As is evident from Step 3b, conditional accuracy functions can indicate if the accuracy in the responses for a given condition varies across the latency of the responses to such condition. For example, a flat line at around $y=0.90$ would mean that the accuracy for that condition (90%) is equal for fast and for slow responses. In contrast, an ascending function would indicate that the fast responses tend to be less accurate, and a descending function would indicate that slow responses tend to be less accurate.

The panels in Fig. 5 show the conditional accuracy for all the conditions in Experiment 1. The critical comparison is between the two presentation formats in the two response modalities. The replacement-letter condition yields high accuracy across all RTs; however, the transposed-letter condition shows large dips in accuracy in the fast responses particularly. This pattern indicates that fast responses are the main driver of the transposed-letter effect in both the one-line and the two-line conditions. That is, transposed-letter effects on accuracy are not a product of the long RTs in the two-line condition, and the conditional accuracy functions graphs are qualitatively similar for one-line and two-line presentations.

Experiment 2

Experiment 1 showed a decrease in the size of the transposed-letter effect for two-line nonwords when compared to one-line nonwords; however, the magnitude of the effect for two-line nonwords was still sizeable in both latency and error data (69 ms and 15.9%, respectively). One might argue that one reason for the robustness of this effect is that participants read the two-line items in the canonical top-to-down direction. That is, readers typically scan words from left to right and then from top to bottom. Thus, readers in Experiment 1 could have used well-learned strategies (i.e., first line, then the second line) to encode the stimuli. Indeed, transposed-letter effects are quite strong when the letters are

Fig. 5 Conditional accuracy function for Experiment 1



in marquee format (i.e., each letter below each other; see Perea et al., 2018; Witzel et al., 2011). To minimize this interpretive issue, Experiment 2 was parallel to Experiment 1 except for a twist. The two-line stimuli had to be read from bottom to top, as in:

LUTION
REVO-

As a result, when encountering two-line items, readers had to rely on an unfamiliar reading direction and, hence, Experiment 2 would constitute a stronger test of the tolerance of letter position coding to visual disruptions.

Methods

Participants

We recruited 40 university students, native speakers of Spanish, with no reading problems and with normal (corrected) vision (19 females; 17 males; 4 chose not to indicate gender) from Prolific Academic (http://prolific.ac). While all the key effects in Experiment 1 were quite large, we slightly increased sample size as we were concerned by the extra variability of an online setting due to the covid pandemic. They signed an informed consent form before the experiment and received monetary compensation according to Prolific's participant policy.

Materials

The words and pseudowords were the same as in Experiment 1. The only difference was that, in the two-line format, the reading direction was from the second line to the first line (see Table 1).

Procedure

The setup was parallel to Experiment 1 except that it was programmed in PsychoPy 3 (Peirce & MacAskill, 2018) and conducted online via Pavlovia (www.pavlovia.org). Participants were instructed to do the experiment in a quiet room without any distractions and were told that the letter strings could appear in one line or in two lines—and that in this latter scenario the reading direction was from the second line to the first line.

Results and discussion

All the analyses were parallel to Experiment 1. Table 4 displays the mean RTs and error rates for each condition in the experiment.

Pseudoword data Response times were slower for transposed-letter pseudowords than for replacement-letter pseudowords ($b = 75.99$, SE = 8.00, 95% CrI [60.59, 92.13]) and for two-line pseudowords than for one-line pseudowords ($b = 294.37$, SE = 13.29, 95% CrI [268.10, 320.62]). As deduced from the interaction between the two factors ($b = -58.92$, SE = 12.08, 95% CrI [− 82.75, − 35.09]), the transposed-letter effect was substantially greater for one-line pseudowords than for two-line pseudowords—indeed, for two-line pseudowords, its corresponding estimate 95% CrI crossed zero (95% CrI [− 36.7, 3.26]).

The analyses of the accuracy data showed that participants were more accurate for replacement-letter than for transposed-letter pseudowords ($b = -2.42$, SE = 0.28, 95% CrI [− 2.98, − 1.89]) they were also more accurate for one-line than for two-line pseudowords ($b = -0.94$, SE = 0.28, 95% CrI [− 1.50, − 0.41]). The transposed-letter effect did not differ for one-line and two-line pseudowords (interaction: $b = 0.55$, SE = 0.30, 95% CrI [− 0.05, 1.14]).

Word data Participants responded more slowly and less accurately to two-line words than one-line words (latency data: $b = 185.23$, SE = 7.86, 95% CrI [169.83, 200.70]; accuracy data: $b = -0.69$, SE = 0.18, 95% CrI [− 1.05, − 0.33]).

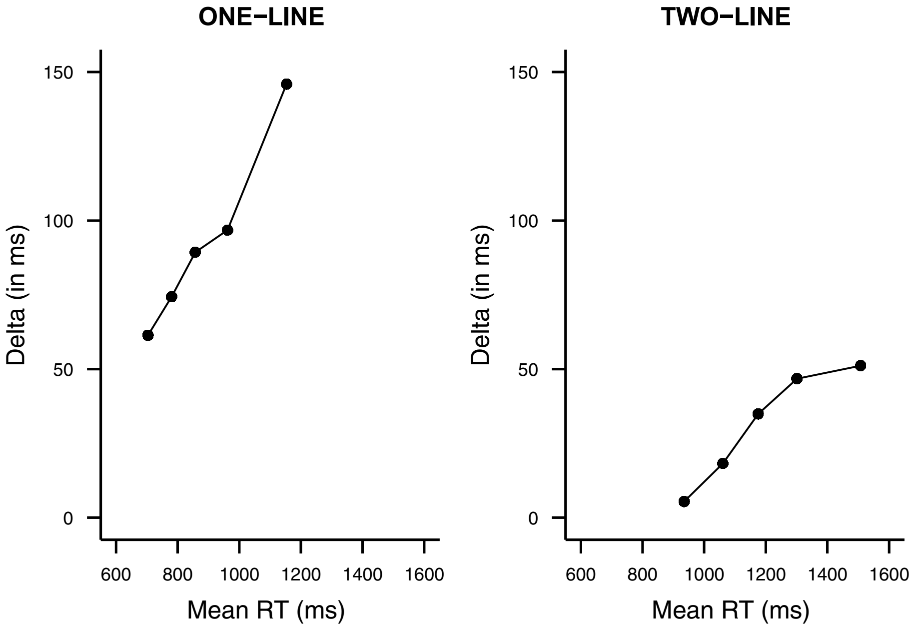
Delta plots As in Experiment 1, we created delta plots where the y-axis reflected the size of the transposed-letter effect across quantiles. Unsurprisingly, we found a robust transposed-letter effect for the standard, one-line pseudowords in the leading edge of the RT distribution that grew progressively larger in the upper quantiles (see left panel of Fig. 6). Critically, the pattern of transposed-letter effects was quite different for two-line pseudowords: (1) the transposed-letter effect was negligible (less than 10 ms) in the leading edge of the distribution (0.1 quantile); (2) the increase in size of the transposed-letter effect across quantiles with two-line pseudowords had a lesser slope than with one-line pseudowords (see right panel of Fig. 6).

Conditional accuracy function We generated a CAF graph in the same manner as in Experiment 1. Notably, the accuracy for the replacement-letter condition is quite

Table 4 Mean correct lexical times (in ms) and error rates (in percentage) for one-line and two-line stimuli in Experiment 2 (reading from bottom to the top)

	Word	Transposed-letter pseudoword	Replacement-letter pseudoword	Transposed-letter effect
Format				
One-line	800 (2.2)	943 (15.3)	854 (1.8)	89 (13.5)
Two-line	1016 (5.2)	1209 (17.7)	1183 (4.1)	26 (13.6)

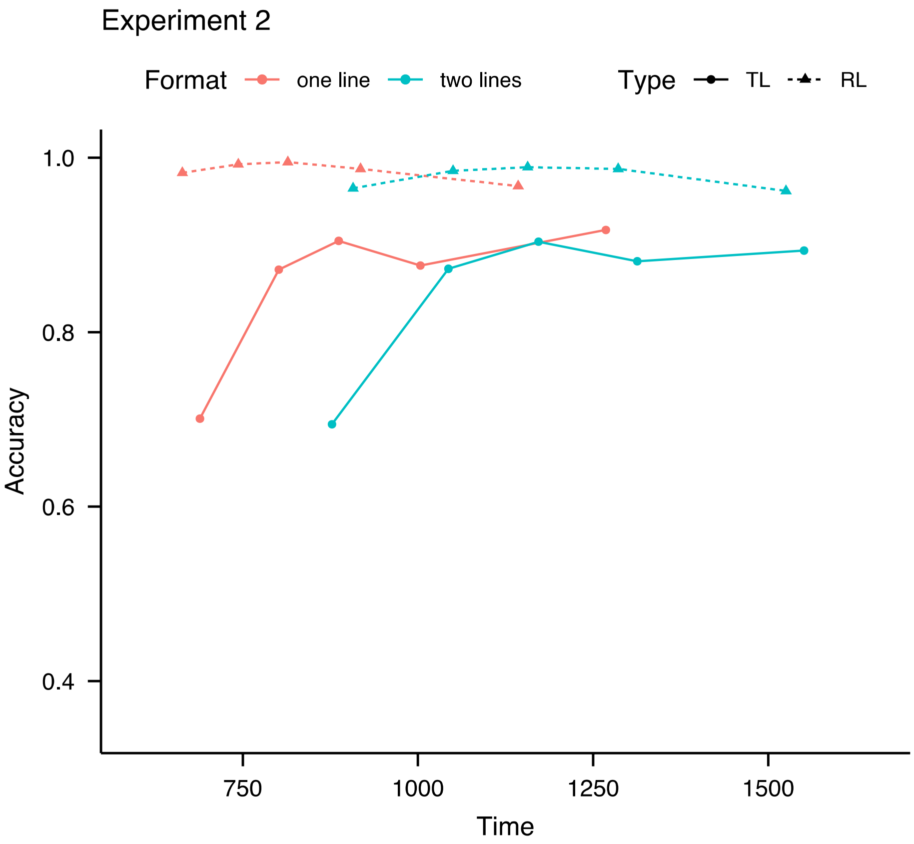
Fig. 6 The panels show the delta plots of the transposed-letter effect for one-line and two-line pseudowords in Experiment 2



high at all RT levels, and just like in Experiment 1, there is a transposed-letter effect across all bins of RT for both the one-line and two-line conditions; however, the transposition effect is particularly pronounced in the fastest responses (see Fig. 7).

The present experiment examined the limits of the transposed-letter effect by presenting two-line stimuli that were read from the bottom to the top. This manipulation did have a substantial impact on the magnitude of the transposed-letter effect. Indeed, to our knowledge, this is the second

Fig. 7 Conditional accuracy function for Experiment 2



instance where the transposed-letter effect in a Latin-based orthography has been dramatically reduced in the latency data (see Fig. 6)—note that Lee and Taft (2009) found a vanishing transposed-letter effect with "Hangulized" presentations. However, this finding must be interpreted with caution because the transposed-letter effect was still sizeable in the error rate data (a 13.6% transposed-letter effect). Unsurprisingly, latencies for two-line presentations were slower than for one-line presentations. Note that the RTs for the two-line presentation tended to be quite large, even compared to the two-line presentation in Experiment 1, perhaps because there are different patterns of fixation that add processing time.

Experiment 3

Experiment 2 showed that the transposed-letter effect can be dramatically reduced; however, this reduction affected the latency data, but not the accuracy data. To further study the limits of the transposed-letter effect, in Experiment 3, we employed a visual-spatial manipulation intended to make the syllables more salient—note that all letter transpositions/replacements occur in different syllables. The manipulation was similar to Experiment 1 except that each syllable was presented in one line as in:

RE
VO
LU
TION

This format can be found relatively often in billboards and advertisements; in fact, the examples in Fig. 1 are syllabically parsed. As in Experiments 1–2, we employed the standard one-line format as a control.

Methods

Participants

We recruited an additional sample of 40 university students (17 male, 23 female) from the same population as in Experiments 1 and 2.

Materials

They were the same as in Experiments 1 and 2. The only difference was that the two-line format was replaced by a "syllable-per-line" format where each syllable corresponded to one line.

Procedure

It was parallel to that in Experiment 2; participants were told that items could be presented in one line or syllabified in various lines.

Results and discussion

All the analyses were parallel to Experiments 1 and 2. Table 5 shows the average lexical decision times and error rates for each condition.

Pseudoword data Lexical decision times were slower for transposed-letter than for replacement-letter pseudowords ($b = 80.32$, SE = 7.26, 95% CrI [66.21, 94.67]) and for syllabic pseudowords than for one-line pseudowords ($b = 375.98$, SE = 16.11, 95% CrI [344.58, 408.20]). The interaction between the two factors ($b = -72.60$, SE = 11.77, 95% CrI [− 95.78, − 49.26]) revealed that the transposed-letter effect was substantially greater for one-line pseudowords than for syllabic pseudowords—as occurred in Experiment 2, the estimate 95% CrI of the transposed-letter effect for syllabic pseudowords crossed zero (95% CrI [− 30.6, 14.5]).

The analyses of the accuracy data showed that participants were more accurate for replacement-letter than for transposed-letter pseudowords ($b = -2.97$, SE = 0.28, 95% CrI [− 3.53, − 2.44]) they were also more accurate for one-line than for syllabic pseudowords ($b = -1.54$, SE = 0.25, 95% CrI [− 2.06, − 1.09]). The transposed-letter effect was greater for one-line than for syllabic pseudowords ($b = 1.53$, SE = 0.27, 95% CrI [1.02, 2.09])—note that the transposed-letter effect was still robust for syllabic pseudowords (95% CrI [1.07, 1.80]).

Word data Participants responded more slowly and less accurately to syllabic words than one-line words (latency data: $b = 237.41$, SE = 11.46, 95% CrI [215.11, 260.16]; accuracy data: $b = -1.29$, SE = 0.18, 95% CrI [− 1.64, − 0.94]).

Table 5 Mean correct lexical times (in ms) and error rates (in percentage) for one-line and syllabic stimuli in Experiment 3

	Word	Transposed-letter pseudoword	Replacement-letter pseudoword	Transposed-letter effect
Format				
One-line	802 (2.4)	946 (24.3)	866 (2.0)	80 (22.2)
Syllabic	1078 (8.8)	1279 (22.6)	1266 (7.3)	13 (15.3)

Exploratory data analysis

As in Experiments 1 and 2, we created delta plots to examine the variations of the magnitude of the transposed-letter effect across quantiles. For one-line pseudowords, we found a substantial transposed-letter effect that grew across quantiles (see left panel of Fig. 8). In contrast, for syllabic pseudowords, the transposed-letter effect was much weaker—it was not greater than 25 ms in any quantile (see right panel of Fig. 8).

Thus, when considering the response times, the present experiment showed a dramatic decrease in the transposed-letter effect in the syllabic format (13 ms) when compared to the standard format (80 ms). However, the transposed-letter effect in the syllabic format was still robust in the error rates (the effect was 15.3%). In fact, this pattern can be seen in Fig. 9, which shows the conditional accuracy function; like in the previous experiments, the transposed-letter effect on accuracy spans all the levels of latency, with the most pronounced effects in the fastest responses. In addition, the difference in accuracy is larger for the single-line presentation than for the multiple-line presentation (in this case, syllabic).

General discussion

We conducted three lexical decision experiments to test the limits of the transposed-letter during visual word recognition with a visuo-spatial manipulation. Transposed-letter pseudowords and their replacement-letter controls were presented in the standard one-line format, or in different lines—one of them was always the initial letter of the other line (see Table 1): two-line items read in the canonical direction, (i.e., top to bottom; Experiment 1), two-line items read from bottom to the top (Experiment 2), and syllable-per-line items (Experiment 3). The critical transposed (replacement) letters always corresponded to separate lines. Unsurprisingly, the stimuli (both words and pseudowords) presented in one line took shorter to recognize than the stimuli presented in several lines. Still, the two-line or syllabic formats were not dramatically disruptive.

More importantly, we found a substantially decrease of the transposed-letter effect in the two-line and syllabic formats when compared to the standard one-line format in the latency data (69 vs. 92 ms in Experiment 1; 26 vs. 89 ms in Experiment 2; 13 vs. 80 ms in Experiment 3). Clearly, in Experiment 2–3, the visuo-spatial manipulations dramatically reduced the magnitude of the transposed-letter effect. However, we did find a sizeable transposed-letter effect for the non-canonical two-line and syllabic formats in the error data [15.9%, 13.6%, and 15.3% in Experiments 1, 2, and 3, respectively (the corresponding transposed-letter effects in the horizontal format were 26.3%, 13.5%, and 22.2% in the horizontal format, respectively)]. Thus, even in a non-canonical format, transposed-letter pseudowords are confusable with their base words. One might wonder why is it that the transposed-letter effect is robust to the presentation format manipulation in the accuracy measurement but not so much in the response times. We believe that this is related to the rather long RTs in the non-canonical presentation formats, which might induce different fixation and response patterns that add noise to the latency measurements. Notably, the accuracy effects were so large and so ubiquitous (see the conditional accuracy functions in Figs. 5, 7, 9) that we can confidently assume that the transposed-letter is better captured by the accuracy measurement (see Baciero et al., 2022;

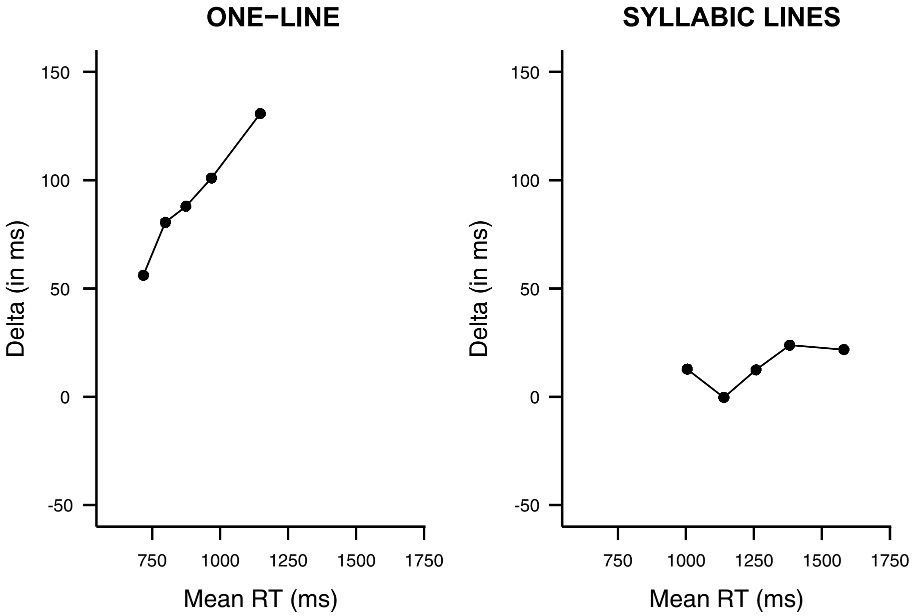
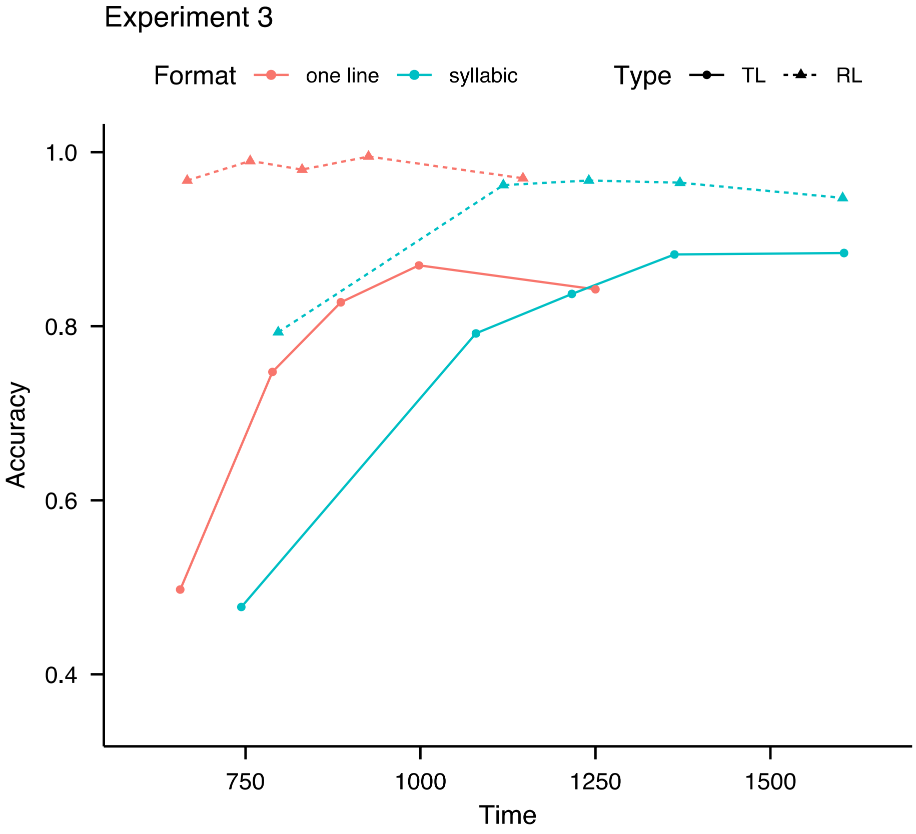


Fig. 8 The panels show the delta plots of the transposed-letter effect for one-line and syllabic pseudowords in Experiment 3

Fig. 9 Conditional accuracy function for Experiment 3



Gómez et al., 2021; Lee & Taft, 2005, for similar observations). Of note, the fact that, under non-canonical format presentations, the transposed-letter effect emerges mainly in accuracy rather than in response times aligns very well with recent research showing the same pattern for transposed-word effects (e.g., "you that read wrong") under "serial" reading conditions (e.g., when reading from right to left; Mirault et al., 2022).

What are the implications of these findings for the models of letter position coding? We tested a visuo-spatial account of the transposed-letter effect. To do so, we implemented a 2-D version of the overlap model (Gómez et al., 2008), shown in Fig. 3 and Table 2 (see Appendix 1 for details). The model predicted a null (or negligible) transposed-letter effect in the two-line and syllabic formats because the amount of overlap between the two-line transposed-letter pseudoword RELO-VUCIÓN and its base word REVO-LUCIÓN is very similar as that obtained with the replacement-letter pseudoword RESO-TUCIÓN. The substantial transposed-letter effect found with the multiple-line pseudowords poses problems for the overlap model and likely other perceptual uncertainty models that assume that the thee uncertainty at locating letters in words is purely visuo-spatial in nature.

We acknowledge that order uncertainty can occur at other levels that are not just visuo-spatial. Indeed, as stated in "Introduction", congenitally blind individuals show robust adjacent transposed-letter effects in a non-visual modality, braille (Baciero et al., 2022). Importantly, uncertainty principles have been proposed for order information in memory (and specifically in working/short-term memory). In the case of our paradigm, letters in the visual input are mapped onto a memory store, and their order could be subject to positional noise. This memory-based assumption can be easily implemented in the overlap model: the overlap among letters would also occur in the memory trace. The idea of uncertainty for the order or items in memory is in line with classical memory models of item and order information (e.g., Lee & Estes, 1977; Ratcliff, 1981; Shiffrin & Cook, 1978). Indeed, the Lee and Estes (1977; see also Estes, 1975) model was developed in the context of a short-term recall paradigm using lists of items presented sequentially where memory for order information was only approximate. Ratcliff's overlap memory model (1981), which was inspired by Estes' (1975) model, assumed that "the representation of letters in memory is distributed" (p. 55), linked the noisy positional information to the representation in memory, but not to a visuo-spatial representation of letter objects. Shiffrin and Cook's (1978) model of letter order information made a similar point for memory experiments in which participants had to recall the order of five consonants presented sequentially. Thus, this assumptions about the locus of the uncertainty in letter position encoding could explain the interaction found in this paper by positing that positional information is less accurately encoded for those stimuli presented in the same line, perhaps because of memory chunking based on the line, or perhaps because of the visuo-spatial contribution to the order uncertainty.

The problems faced by the original version of Gomez et al.'s (2008) overlap model also generalize to models in which letter position is coded based on a visuo-spatial representation of the letter string. The Start End Position Code model (Houghton, 2018) uses a coding scheme in which the visuo-spatial representation of a word allows for identifying the start and end letters (e.g., R and N in REVOLUTION). These letters act as markers to encode the order position of the letter identities in a word. The Start End Position Code model successfully captures many benchmark effects in the literature of letter position coding. However, it is unlikely to capture the sizeable transposed-letter effects reported here with multiple-line stimuli: for the word REVO-LUTION, the Start End Position Code model would yield two start/end markers for each line (R–O for REVO; L–N for LUTION). Therefore, the resulting letter start/end markers for the two-line transposed-letter pseudoword RELO-VUTION (i.e., R–O for RELO; V–N for VUTION) would be comparable from those in the two-line replacement-letter pseudoword RENO-CUTION (i.e., R–O for RENO; C–N for CUTION), thus predicting a dramatic decrease in the letter transposition effect for two-line stimuli. As occurs with the overlap model, the Start End Position Code model would need to assume that order information is obtained not directly from an array of letter objects "held in a visuo-spatial store" (Houghton, 2018, p. 94), but rather at a more abstract level of processing.

We acknowledge that a more straightforward explanation of the present findings might be offered by word recognition models that assume that letter position coding arises at an orthographic level in the form of open bigrams (e.g., JU, JD, JG, JE, UD, UG, UE, DG, DR, and GE for the word JUDGE; see Grainger & van Heuven, 2003). Although to our knowledge there are no implemented models of this family that can deal with multi-line reading, one could assume that the abstract open bigrams might be similar in the two-line presentation and in the one-line presentation. These accounts can also explain some findings that are specific to letter processing that are beyond the scope of position uncertainty models, such as the greater transposition effects for letter strings than for other types of visual objects (e.g., strings of digits; strings of symbols; see Massol et al., 2013; Massol & Grainger, 2022). However, a strong version of orthographic-based models cannot capture the transposition effects observed for other types of visual objects (e.g., geometrical shapes, visual objects, notes in a staff). All in all, as anticipated by Estes (1975), letter position coding may reflect both generic processes common to other visual objects and orthographic-related processes specific to letter strings. Indeed, as indicated in "Introduction", several models of visual word recognition have already incorporated these two mechanisms (e.g., Adelman, 2011; Grainger & Ziegler, 2011).

Conclusions

The study of how the word recognition system encodes letter position has attracted considerable attention in the past decades and this work continues that tradition. On the one hand, we have ruled out a common explanation of these effects as being only due to a visuo-spatial effect based on position uncertainty of letter objects in space. On the other hand, there is a substantial literature that uses the principles of perceptual uncertainty to explain why transposition effects occur not only for letter strings but also for other objects, as well as the reduced transposition effects for letters from unknown alphabets for which there are no orthographic internal representations. Reconciling these two sets of facts is challenging, but we can propose a tentative explanation. It is possible that the position uncertainty might occur when this information is encoded in short-term memory rather than purely based on visuo-spatial codes. One such option is in the form of a compositional neural code acting between the object-selective lateral occipital and the left temporal gyrus [visual word form area] regions (see Agrawal et al., 2020, for a recent proposal). The idea is that the orthographic representation (once it is achieved) might allow the word recognition system to resolve any perceptual uncertainty using the abstract letter representations. A compatible proposal was espoused by Logan (2021), who suggests that there is a unitary serial process across different domains such as memory, perception, and production. This process, which might be better described as general domain as opposed to either perceptual or abstract, naturally accounts for the relative lack of sensitivity of the transposed-letter effect to the multi-line manipulation in the present experiments.

To sum up, we examined how serial order, as measured by a proxy like the transposed-letter effect, is resilient to a visuo-spatial manipulation (two-line or syllable-per-line formats). While smaller in size, the transposed-letter effect under these manipulations—especially in accuracy—poses limits of perceptual, visuo-spatial accounts of letter position coding, such as Gómez et al.'s (2008) overlap model see also (Gómez & Silins, 2012; Kinoshita & Norris, 2013; and Norris and Kinoshita, 2012). These findings favor the idea that a fundamental locus of the encoding of serial order during visual word recognition is related to memory processes common to perception and action (Logan, 2021). The work presented here unveils paths for future work: on the empirical end, we have shown that reading across multiple lines might be a productive methodology for exploring different processes (see Slattery & Parker, 2019, for evidence during sentence reading); on the modeling end, delimiting the boundaries and interactions among the visuo-spatial, memory, and orthographic aspects of word recognition should be an important goal in the near future.

Appendix 1: 2-D overlap account

As stated in "Introduction", the overlap model's assumptions of location uncertainty can be easily extended to the 2-dimensional stimuli presentation used in the present experiments—for simplicity, we focused on the two-line manipulation of Experiments 1–2. Specifically, we assumed that the position uncertainty could be explained as a bivariate Gaussian function as depicted by the blobs/ellipses in Fig. 3. This two-dimensional position uncertainty is centered in the middle of the letter. Because the horizontal and vertical dimensions are independent, they have zero covariance and independent sigmas (i.e., for all letters, the position uncertainty in the vertical dimension is independent of the position uncertainty in the horizontal dimension).

We made basic assumptions in line with the Gómez et al.'s (2008) paper, namely that the first location in each line would benefit from the empty space and would have a smaller position uncertainty along the horizontal dimension ($s_1 = 0.5$), and the position uncertainty would be higher for subsequent letters ($s_{>1} = 1.2$). Similarly, we assumed that along the vertical dimension the position uncertainty would be equal for both lines ($s_1 = s_2 = 0.5$). The panels in Fig. 3 were drawn under those assumptions. Using this 2-D model for the two-line presentation, along with the standard overlap model, we calculated the overlap between pseudowords and the base word for all letter lengths (the columns labeled "Overlap" in Table 2; for comparison, we also present transposed-letter effects for all word lengths in this experiment).

Fits of the data

While the empirical transposed-letter effect in the two-line nonwords (Experiments 1–2) was more than half of that in the one-line nonwords, the 2-D overlap model predicts a rather miniscule transposed-letter effect for the two-line presentation which is orders of magnitude smaller than the overlap for one-line presentation.

It is important to note that the overlap model is not a model of the lexical decision task. Hence, the overlap measurement must be scaled somehow to make predictions about RT and accuracy. Nonetheless, the difference in overlap between one- and two-line presentations is so large for all letter lengths that there is no realistic scaling factor that could account for the sizable empirical transposed-letter effects in the two-line condition.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The procedures involving human participants in this study were approved by the Experimental Research Ethics Committee of the Universitat de València and they were in accordance with the Declaration of Helsinki. All the participants provided written informed consent before starting the experimental session.

References

Adelman, J. S. (2011). Letters in time and retinotopic space. *Psychological Review, 118*, 570–582. https://doi.org/10.1037/a0024811

Agrawal, A., Hari, K. V. S., & Arun, S. P. (2020). A compositional neural code in high-level visual cortex can explain jumbled word reading. *eLife, 9*, e54846. https://doi.org/10.7554/elife.54846

Baciero, A., Gómez, P., Duñabeitia, J. A., & Perea, M. (2022). Raeding with the fingres. Towards a universal model of letter position coding. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/s13423-022-02078-0

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68*, 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Bonnet, C., & Dresp, B. (1993). A fast procedure for studying conditional accuracy functions. *Behavior Research Methods, Instruments & Computers, 25*, 2–8. https://doi.org/10.3758/BF03204443

Bruner, J. S., & O'Dowd, D. (1958). A note on the informativeness of parts of words. *Language and Speech, 1*, 98–101. https://doi.org/10.1177/002383095800100203

Brysbaert, M., & Stevens, M. (2018). Power analysis and effect size in mixed effects models: A tutorial. *Journal of Cognition*. https://doi.org/10.5334/joc.10

Bürkner, P.-C. (2016). brms: An R package for Bayesian multilevel models using Stan. *Journal of Statistical Software, 80*(1), 1–28. https://doi.org/10.18637/jss.v080.i01

De Jong, R., Liang, C. C., & Lauber, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance, 20*(4), 731–750. https://doi.org/10.1037/0096-1523.20.4.731

Duchon, A., Perea, M., Sebastián-Gallés, N., Martí, A., & Carreiras, M. (2013). EsPal: One-stop shopping for Spanish word properties. *Behavior Research Methods, 45*, 1246–1258. https://doi.org/10.3758/s13428-013-0326-1

Estes, W. K. (1975). The locus of inferential and perceptual processes in letter identification. *Journal of Experimental Psychology:*

General, 104, 122–145. https://doi.org/10.1037/0096-3445.104.2.122

Fernández-López, M., Marcet, A., & Perea, M. (2021). Does orthographic processing emerge rapidly after learning a new script? *British Journal of Psychology, 112*, 52–91. https://doi.org/10.1111/BJOP.12469

Forster, K. I., & Forster, J. C. (2003). DMDX: A Windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers, 35*, 116–124. https://doi.org/10.3758/bf03195503

García-Orza, J., Perea, M., & Estudillo, A. (2011). Masked transposition effects for simple vs. complex non-alphanumeric objects. *Attention, Perception & Psychophysics, 73*, 2573–2582. https://doi.org/10.3758/s13414-011-0206-7

García-Orza, J., Perea, M., & Muñoz, S. (2010). Are transposition effects specific to letters? *Quarterly Journal of Experimental Psychology, 63*, 1603–1618. https://doi.org/10.1037/e520562012-240

Gómez, P., & Perea, M. (2013). From models to special populations. The case of the overlap model. *Paper presented at the 11th International Symposium of Psycholinguistics*, Tenerife, Spain.

Gómez, P., Marcet, A., & Perea, M. (2021). Are better young readers more likely to confuse their mother with their mohter? *Quarterly Journal of Experimental Psychology, 74*, 1542–1552. https://doi.org/10.1177/17470218211012960

Gómez, P., Ratcliff, R., & Perea, M. (2008). The overlap model: A model of letter position coding. *Psychological Review, 115*, 577–601. https://doi.org/10.1037/e512682013-035

Gómez, P., & Silins, S. (2012). Visual word recognition models should also be constrained by knowledge about the visual system. *Behavioral and Brain Sciences, 35*(5), 287. https://doi.org/10.1017/s0140525x12000179

Grainger, J. (2018). Orthographic processing: A "mid-level" vision of reading. *Quarterly Journal of Experimental Psychology, 71*, 335–359. https://doi.org/10.1080/17470218.2017.1314515

Grainger, J., & van Heuven, W. J. B. (2003). Modeling letter position coding in printed word perception. In P. Bonin (Ed.), *Mental lexicon: Some words to talk about words* (pp. 1–23). Nova Science Publishers.

Grainger, J., & Ziegler, J. C. (2011). A dual-route approach to orthographic processing. *Frontiers in Psychology, 2*, 54. https://doi.org/10.3389/fpsyg.2011.00054

Houghton, G. (2018). Action and perception in literacy: A common-code for spelling and reading. *Psychological Review, 125*, 83–116. https://doi.org/10.1037/rev0000084

Kinoshita, S., & Norris, D. (2013). Letter order is not coded by open bigrams. *Journal of Memory and Language, 69*, 135–150. https://doi.org/10.1016/j.jml.2013.03.003

Lee, C. L., & Estes, W. K. (1977). Order and position in primary memory for letter strings. *Journal of Verbal Learning and Verbal Behavior, 16*(4), 395–418. https://doi.org/10.1016/s0022-5371(77)80036-4

Lee, C. H., & Taft, M. (2009). Are onsets and codas important in processing letter position? A comparison of TL effects in English and Korean. *Journal of Memory and Language, 60*(4), 530–542. https://doi.org/10.1016/j.jml.2009.01.002

Logan, G. D. (1996). The CODE theory of visual attention: An integration of space-based and object-based attention. *Psychological Review, 103*, 603–649. https://doi.org/10.1037/0033-295x.103.4.603

Logan, G. D. (2021). Serial order in perception, memory, and action. *Psychological Review, 128*, 1–44. https://doi.org/10.1037/rev0000253

Marcet, A., Perea, M., Baciero, A., & Gómez, P. (2019). Can letter position encoding be modified by visual perceptual elements*?*. *Quarterly Journal of Experimental Psychology, 72*, 1344–1353. https://doi.org/10.1177/1747021818789876

Massol, S., Duñabeitia, J. A., Carreiras, M., & Grainger, J. (2013). Evidence for letter-specific position coding mechanisms. *PLoS One, 8*, e68460. https://doi.org/10.1371/journal.pone.0068

Massol, S., & Grainger, J. (2022). Effects of horizontal displacement and inter-character spacing on transposed-character effects in same-different matching. *PLoS One, 17*(3), e0265442. https://doi.org/10.1371/journal.pone.0265442

Mirault, J., Vandendaele, A., Pegado, F., & Grainger, J. (2022). Transposed-word effects when reading serially. Manuscript submitted for publication.

Norris, D., & Kinoshita, S. (2012). Reading through a noisy channel: Why there's nothing special about the perception of orthography. *Psychological Review, 119*, 517–545. https://doi.org/10.1037/a0028450

Ollman, R. T. (1977). Choice reaction time and the problem of distinguishing task effects and strategic effects. In S. Dornic (Ed.), *Attention and Performance 6* (pp. 99–113). Erlbaum.

Peirce, J. W., & MacAskill, M. R. (2018). *Building experiments in PsychoPy*. Sage.

Perea, M., Baciero, A., Marcet, A., Fernández-López, M., & Gómez, P. (2021). Do grading gray stimuli help to encode letter position? *Vision, 5*(1), 12. https://doi.org/10.3390/vision5010012

Perea, M., García-Chamorro, C., Centelles, A., & Jiménez, M. (2013). Position coding effects in a 2D scenario: The case of musical notation. *Acta Psychologica, 143*, 292–297. https://doi.org/10.1016/j.actpsy.2013.04.014

Perea, M., Jiménez, M., & Gómez, P. (2016). Does location uncertainty in letter position coding emerge because of literacy training? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42*, 996–1001. https://doi.org/10.1037/xlm0000208

Perea, M., Marcet, A., & Fernández-López, M. (2018). Does letter rotation slow down orthographic processing in word recognition? *Psychonomic Bulletin & Review, 25*, 2295–2300. https://doi.org/10.3758/s13423-017-1428-z

Perea, M., Winskel, H., Abu Mallouh, R., Barnes, L., & Gómez, P. (2015). In defense of position uncertainty: A reply to Duñabeitia, Orihuela, and Carreiras. *Psychological Science, 26*, 545–547. https://doi.org/10.1177/0956797614566468

Pollatsek, A., Raney, G. E., Lagasse, L., & Rayner, K. (1993). The use of information below fixation in reading and in visual search. *Canadian Journal of Experimental Psychology, 47*(2), 179–200. https://doi.org/10.1037/h0078824

Ratcliff, R. (1979). Group reaction time distributions and an analysis of distribution statistics. *Psychological Bulletin, 86*(3), 446–461. https://doi.org/10.1037/0033-2909.86.3.446

Ratcliff, R. (1981). A theory of order relations in perceptual matching. *Psychological Review, 88*, 552–572. https://doi.org/10.1037/0033-295x.88.6.552

Scarf, D., Boy, K., Reinert, A. U., Devine, J., Güntürkün, O., & Colombo, M. (2016). Orthographic processing in pigeons (Columba livia). *Proceedings of the National Academy of Sciences, 113*, 11272–11276. https://doi.org/10.1073/pnas.1607870113

Shiffrin, R. M., & Cook, J. R. (1978). Short-term forgetting of item and order information. *Journal of Verbal Learning and Verbal Behavior, 17*, 189–218. https://doi.org/10.1016/s0022-5371(78)90146-9

Slattery, T. J., & Parker, A. J. (2019). Return sweeps in reading: Processing implications of undersweep-fixations. *Psychonomic Bulletin & Review, 26*, 1948–1957. https://doi.org/10.3758/s13423-019-01636-3

Tukey, J. W. (1977). *Exploratory data analysis*. Addison-Wesley Pub.

Witzel, N., Qiao, X., & Forster, K. (2011). Transposed letter priming with horizontal and vertical text in Japanese and English readers. *Journal of Experimental Psychology: Human Perception and Performance, 37*, 914–920. https://doi.org/10.1037/a002219

Ziegler, J. C., Hannagan, T., Dufau, S., Montant, M., Fagot, J., & Grainger, J. (2013). Transposed-letter effects reveal orthographic processing in baboons. *Psychological Science, 24*, 1609–1611. https://doi.org/10.1177/0956797612474322