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Transposed-letter effects as a function of the location of transpositions

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ABSTRACT

We examined how Transposed-Letter effects (TL effects: e.g., ASBENT, derived from ABSENT, compared to the substituted-letter [SL] control ALPENT) might vary as a function of the location of the TL effects relative to fixation. The positions of the TL and the initial fixation location (either at position 2 or 5 in 6-letter stimuli) were manipulated in a lexical decision task. Initial fixation remained centered on the screen while stimuli were shifted left or right. Six-letter stimuli were presented in lowercase (Experiment 1) or uppercase (Experiment 2), with critical stimuli being nonwords created by transposing consonants at positions 2–3 or 4–5 and compared with substituted-letter controls. Results showed stronger TL effects when the transpositions occurred farther from fixation. Implications of our findings for current models of letter-position coding are discussed, by emphasizing the important connection between letter visibility (vision) and orthographic processing (reading).

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Introduction

Since its popularization via the (in)famous "Cambrigde Univesrity" email, transposed-letter effects have attracted much attention from scientists aiming to understand how letter-order information is encoded during reading (see Bruner & O'Dowd, 1958, for an early study, and Grainger, 2018, 2024; Perea et al., 2025, for reviews), and continue to fascinate the general public. One key manipulation in scientific investigations of this phenomenon is the comparison between two types of nonwords created from the same base-word: (1) transposed-letter (TL) nonwords such as ASBENT created by transposing the B and the S in ABSENT; (2) matched substituted letter (SL) nonwords such as ALPENT, where the B and S in ABSENT are substituted by two different letters (e.g., L and P). These nonwords can either be presented as targets in a lexical decision task (speeded word/nonword classification) or presented as primes prior to the corresponding base-word target (e.g., asbent-ABSENT vs. alpent-ABSENT). The TL effect is defined as the difference in performance to TL targets compared with SL targets or the difference in performance to the same target words preceded by TL primes or SL primes. In simple lexical decision, TL nonwords are harder to reject as nonwords (longer response times [RTs] and more errors) compared with matched SL nonwords (e.g., Lupker et al., 2008; Perea et al., 2023; Perea & Lupker, 2004; see Martínez-Tomás et al., 2025, for a review). In masked priming studies, with brief prime exposures (typically 50–60 ms), TL primes facilitate subsequent target word identification compared with the matched SL primes (e.g., Perea et al., 2008; Perea & Lupker, 2003, 2004; Schoonbaert & Grainger, 2004).

Taken together, these findings have established TL effects as a benchmark phenomenon for models of orthographic processing and visual word recognition in languages that use an alphabetic script (Grainger, 2022).[1] In the present study we examined how a visual factor (the eccentricity of the transposed letters) might impact on TL effects obtained with stimuli presented in the fovea (see Veldre et al., 2024, for a study of how sensitivity to letter order depends on the location of the transposition within

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the letter string when stimuli are presented in the parafovea).

Although the present study has primarily an empirical focus, we nevertheless expect the results to be highly relevant for current explanations of TL effects. Crucially, our manipulation provides a link between work in vision science on factors affecting letter visibility, and work on orthographic processing and reading. Indeed, there is abundant evidence that positional uncertainty increases for letters located further from fixation (e.g., Chung & Legge, 2009; Estes et al., 1976). This arises because of the combined effects of decreased visual acuity and increased crowding with eccentricity (e.g., Coates et al., 2013; Pelli et al., 2007; Whitney & Levi, 2011). There is therefore a greater uncertainty that a given letter is left or right of another letter, hence leading to greater positional noise and a general disruption in letter-order encoding (see Grainger et al., 2016, for a review). This predicts that TL effects, as measured with a standard word recognition task, should be greater when the transposed letters are located farther from fixation. That is, greater positional uncertainty should primarily impact on the TL condition rather than the SL condition, hence leading to greater TL effects. The present study provides a test of this prediction.

To do so, we manipulated the location of transposed-letters relative to fixation in two experiments. Fixation was always at the center of the screen, and target stimuli were displaced either left or right of this central fixation (see Figure 1). In this way, we could manipulate the location of the critical transposed letters that could either be near fixation or further from fixation (see Grainger et al., 1992, for an identical manipulation examining the effects of orthographic neighbours on visual word recognition).

Prior research examining the impact of the location of the transposed-letters on the size of TL effects manipulated the position of the transposed letters in centrally fixated letter strings. Thus, the novelty of the present work lies in maintaining a central fixation location on the screen and shifting stimuli left or right of this fixation. It should also be noted that we only manipulated adjacent consonant letter transpositions such as the S and B in ASBENT (derived from the English word ABSENT). This was motivated by the fact that TL effects are typically stronger for consonant letter transpositions (Lupker et al., 2008, 2026; Perea & Lupker, 2004). We manipulated the location of the transposed letters (positions 2-3 vs. 4-5) in targets that were six letters in length. The position of initial fixation (2nd or 5th letter) was also manipulated across targets. As a result, the transposed letters could either be located close to fixation or far from fixation. The location of the two substituted letters in the control nonwords (e.g., ALPENT) was matched to that of the two transposed letters. We return to discuss the implications of our findings in the Discussion. Our initial aim was simply to empirically establish how the location of transposed letters relative to eye fixation might modify TL effects. Furthermore, in order to examine the generality and replicability of the role of eccentricity on TL effects, we conducted two experiments that differed in letter case (Experiment 1: lowercase; Experiment 2: uppercase).

Experiment 1 – Lowercase

Methods

Participants

A total of 84 participants (41 males) with a mean age of 36 years (*SD* = 11.95) were recruited via the Prolific platform (Palan & Schitter, 2018). With 84 participants and 80 items per condition the power of the experiment was largely superior to that recommended by Brysbaert and Stevens (2018). All participants were native speakers of French, with no history of neurological impairment, or developmental disorders. Prior to the beginning of the experiment, participants were informed that data would be collected anonymously, and they provided informed consent before the experiment was initiated.

Design and stimuli

The set of critical stimuli was composed of 320 nonwords derived from 6-letter French words. Firstly, we selected monomorphemic nouns, adjectives and verbs (singular, masculine and infinitive forms) from the Lexique database (New et al., 2004). Then, a total of 160 stimuli were selected: 80 stimuli with two adjacent consonants either in positions 2 and 3 (e.g., ABSENT), and 80 stimuli with two adjacent consonants in positions 4 and 5 (e.g., CHANCE). The mean lexical frequency for the first set was 36 occurrences per million (*SD* = 146) and 30 occurrences per million (*SD* = 50) for the second set. Although the

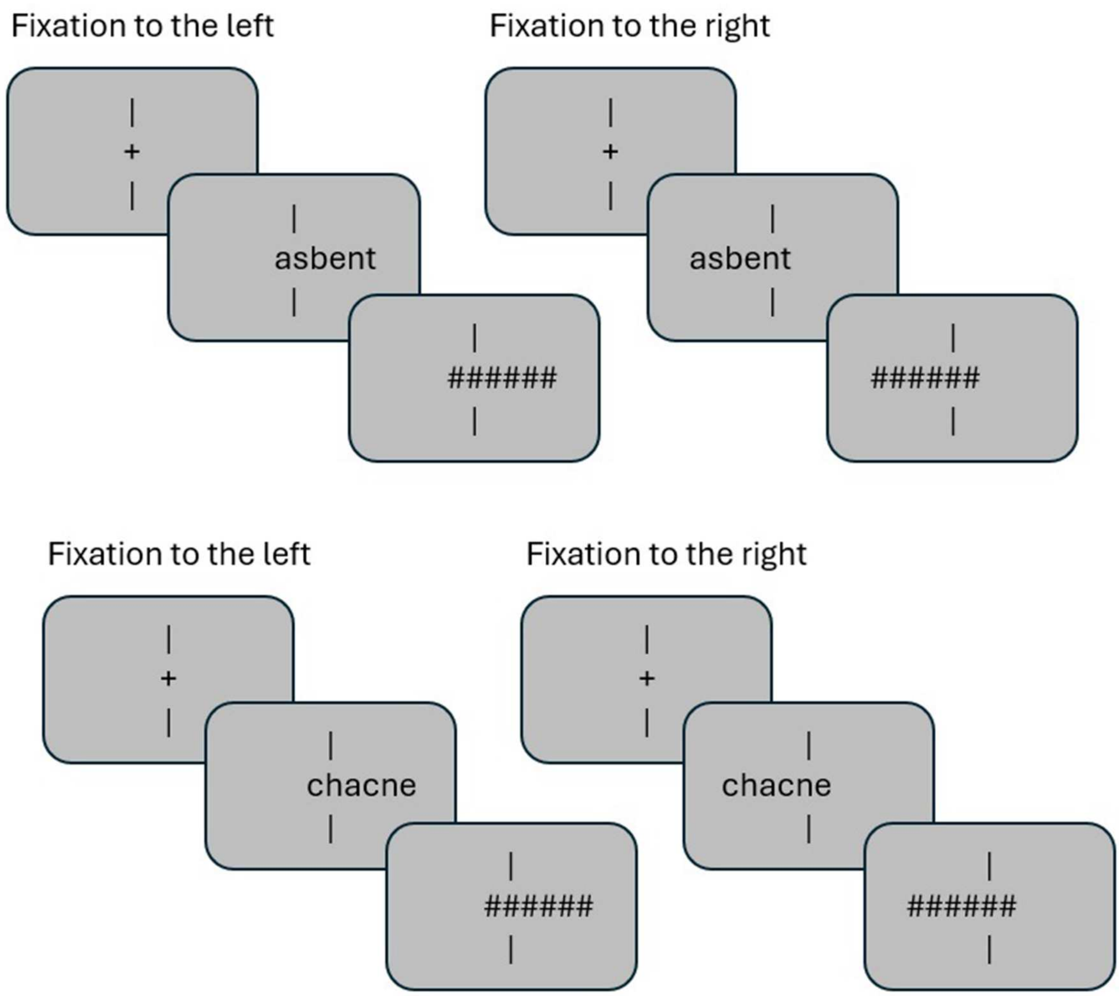

Figure 1. Illustration of the procedure and design used in the Experiments.

lexical frequencies of the two sets are numerically different, they were not significantly different ($p > .1$).

To create the critical nonwords, two nonwords were derived from each base word: (1) nonwords created by transposing two adjacent letters at either positions 2 and 3 or positions 4 and 5 (e.g., ABSENT → ASBENT; CHANCE → CHACNE) (80 stimuli per position), and (2) nonwords created by substituting these two adjacent consonants with different consonants (e.g., ABSENT → ALPENT; CHANCE → CHAPLE) (80 stimuli per position). Furthermore, relative to the central fixation stimuli could be either shifted to the right with the initial fixation being located at position 2 or shifted to the left with the initial fixation being located at position 5.

An additional set of 320 French words was selected for the purposes of the lexical decision task. The mean lexical frequency of these words was matched with the base words used to create the critical nonword stimuli (31 occurrences per million, $SD = 73$, $p > .1$).

A 2 × 2 within-participants factorial design was used, with Type-of-Change (transposition vs. substitution), and Fixation location (close vs. far) as main factors. The stimulus set was divided into two experimental lists presented to two groups of participants. In each of these lists, a total of 320 nonwords were presented. All participants saw the TL nonwords and the SL nonwords, presented either shifted to the right (i.e., fixation located at position 2) or shifted to the left (i.e., fixation located at position 5). For instance, if ASBENT was presented shifted to the right to one participant, the participant saw also the control condition, that is ALPENT shifted to the right. The choice to present both the TL and SL versions of the same base-word to the same participant was made in order to obtain 80 trials per condition per participant and therefore to increase statistical power. See Figure 1 for a summary of the design and the procedure.

Procedure

Participants performed this task on-line. The experiment was created using LabVanced (Finger et al., 2017) and displayed on the personal computer screen of participants. Before the experiment, we informed participants that the data would be collected anonymously, and we asked participants to select their gender and their age. Then the experimental instructions were presented on the screen. All stimuli were presented in lowercase in black Courier New font (size 20 pt.) on a light grey background. Each trial began with a fixation cross at the center of the screen accompanied by two vertical bars positioned at the center of the screen that remained on the screen during the whole trial duration in order to help participants to maintain their gaze on the central fixation. About 300 ms later, the stimulus was presented for 150 ms. This was immediately followed by a backward mask composed of hash marks at all positions that were occupied by a letter in the previous stimulus in order to avoid refixations (see Figure 1). Participants were instructed to fixate (focus their gaze) on the fixation cross between the two vertical bars, to maintain their gaze on this central fixation location, and to decide as rapidly and as accurately as possible whether or not the target was a word in French (lexical decision task). They responded "yes" by pressing the "right arrow" button on the keyboard and "no" by pressing the "left arrow" button. The trial ended with a blank screen displayed for 200 ms. Response times (RTs), measured from target onset until participants' response, were accurate to the nearest millisecond. A short practice session (12 trials) was administered before the main experiment to familiarize participants with the procedure of the lexical decision task.

Results

Nonword trials

Statistical analyses were performed on the critical nonword trials as well as for the word targets. To ensure that participants were correctly performing the task, we excluded participants that were performing close to chance level (i.e., more than 45% errors). The dataset from one participant was excluded based on this criterion (51.64% errors). We used linear mixed-effects (LME) models to analyze response times (RTs) and generalized linear mixed-effects models (GLME) to analyze accuracy. Both models included items and participants as crossed random effects (including by-item and by-participant random intercepts; Baayen et al., 2008) along with random slopes (Barr et al., 2013). We started with (G)LME models with minimal random structure (random intercepts and slopes) and incrementally increased model complexity until reaching the most complex structure that still converged. For each of the analyses, the model included Type-of-Change (transposition vs. substitution) and Fixation Location (close vs. far) as fixed-factors. The analyses were conducted taking the substitution condition as reference for the Type-of-Change factor, and the close condition as reference for the Fixation Location factor. The models were fitted with the *lmer* (for LMEs) and the *glmer* (for GLMEs) functions from the *lme4* package (Bates et al., 2015) in the R statistical computing environment (version 4.5.1; R Core Team, 2025). RTs were inverse transformed (−1000/RT) prior to analysis to reduce the positive skew of the RT data. In the analyses of the error rate data, we employed a parallel strategy with generalized linear models (i.e., GLMEs). The accuracy data were coded as 1 = correct and 0 = incorrect. We tested overall effects using Type II sum of squares and χ^2 Wald tests. Post-hoc contrasts were tested using the *phia* package (de Rosario-Martinez, 2025). Note that we also conducted analyses including participants' age. The results of these analyses are reported in a supplementary analysis file available at: https://osf.io/nk68y/. Taking into account the age of our participants (range 21–75 yrs, $M = 36.42$ yrs, $SD = 11.91$) did not affect the main findings concerning the critical nonword trials.

Response times (RTs). RTs were recorded from target onset up to participant's response. After excluding trials associated with an incorrect response (21.13%), RT values below 300 ms or above 1,500 ms were also excluded (2.34%). The final dataset was composed of 20,329 observations. The condition means are presented in Figure 2 and in Table 1. The maximal random-effects structure that converged was −1,000/RT = Type-of-Change X Fixation Location + (Type-of-Change + 1| subject) + (Type-of-Change + 1| item).

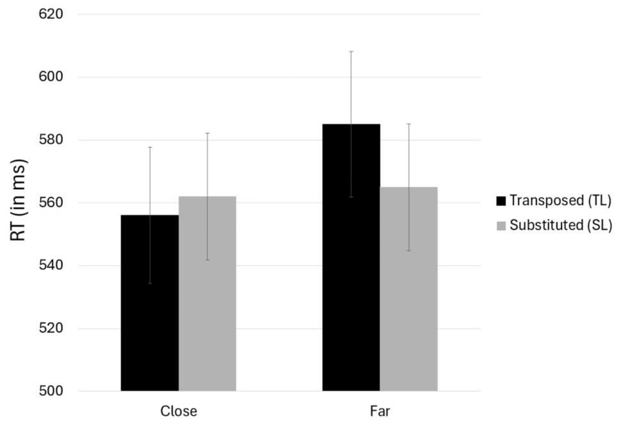

Figure 2. Mean RTs for the critical nonword targets per experimental condition in Experiment 1. Note. Error bars are standard errors.

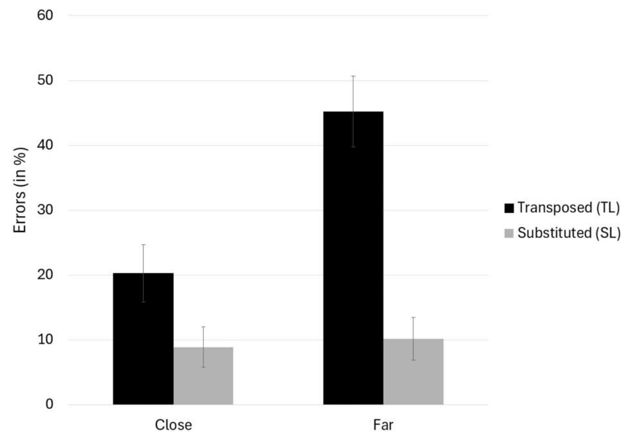

Figure 3. Mean error rates for the critical nonword stimuli as a function of experimental condition in Experiment 1. Note. Error bars are standard errors.

The main effect of Type-of-Change was not significant ($\chi^2(1) = 2.80$, $p = .094$). The effect of Fixation Location was significant ($\chi^2(1) = 84.19$, $p < .001$), with shorter RTs in the condition in which the Type-of-Change manipulation occurred close to the Fixation Location as compared to the condition in which it occurred far from the Fixation Location (559 ms vs. 575 ms respectively). Crucially, the Type-of-Change X Fixation Location interaction was significant ($\chi^2(1) = 79.53$, $p < .001$). This interaction reflects the fact that the transposed-letter effect was only significant in the condition in which the Type-of-Change manipulation occurred far from fixation (close: $\chi^2(1) = 0.41$, $p > .1$; far: $\chi^2(1) = 20.04$, $p < .001$).

Error rates. Mean error rates per experimental condition are shown in Figure 3 and in Table 1. The maximal random-effects structure that converged was: accuracy ~ Type-of-Change X Fixation Location + (Type-of-Change X Fixation Location + 1| subject) + (1| item).

There was a significant effect of Type-of-Change ($\chi^2(1) = 376.30$, $p < .001$), with more errors in the transposed condition than in the substituted-letter condition (32.73% vs. 9.53% respectively). The effect of Fixation Location was also significant ($\chi^2(1) = 214.36$, $p < .001$), with more errors in the condition in which the Type-of-Change manipulation occurred far from fixation compared with the condition in which it occurred close to fixation (27.68% vs. 14.59% respectively). Crucially, the Type-of-Change X Fixation Location interaction was significant ($\chi^2(1) = 173.34$, $p < .001$). This interaction reflects the fact that the size of the transposition effect was greater in the condition in which the Type-of-Change manipulation occurred far from fixation ($\chi^2(1) = 543.11$, $p < .001$) compared with the condition where it occurred close to fixation ($\chi^2(1) = 88.22$, $p < .001$).

The results of the critical nonword trials therefore confirm our predictions: TL effects were significantly greater when the transposed letters were located further from initial fixation location relative to the condition where the transposed letters were located close to fixation.

Word trials

For completeness, we also performed parallel statistical analyses on the non-critical word trials. In these

Table 1. Mean reaction times (ms) and error rates (%) in Experiment 1 (lowercase) and Experiment 2 (uppercase). Standard errors are presented in parentheses.

		Reaction times		Error rates	
		Transposed	Substituted	Transposed	Substituted
Experiment 1					
	Close	556 (22)	562 (20)	20.27 (5.46)	8.9 (4.41)
	Far	585 (23)	565 (20)	45.2 (3.32)	10.17 (3.13)
Experiment 2					
	Close	584 (21)	546 (18)	23.13 (4.33)	6.75 (2.57)
	Far	625 (23)	583 (19)	53.79 (5.12)	12.46 (3.39)

Note. “Close” and “Far” refer to the distance of the transposed and substituted letters from initial fixation location (see Figure 1).

analyses, the model included only Fixation Location (fixation being located at position 2 vs. position 5) as fixed factor – position 2 was the reference.

Response times (RTs). After excluding trials associated with an incorrect response (13.28%), RT values below 300 ms and above 1,500 ms were also excluded (6.01%). The final dataset was composed of 21,370 observations. The maximal random-effects structure that converged was −1,000/RT = Fixation Location + (Fixation Location + 1| subject) + (1| item). Analyses revealed a significant effect of Fixation Location ($\chi^2(1) = 30.94$, $p < .001$), with shorter RTs in the condition when the initial fixation was located at position 2 as compared to when it was located at position 5 (510 ms vs. 543 ms respectively) (see left panel of Figure 4).

Error rates. The maximal random-effects structure that converged was accuracy ~ Fixation Location + (Fixation Location + 1 | subject) + (1| item). Analysis showed that there was a significant effect of Fixation Location ($\chi^2(1) = 14.44$, $p < .001$), with more errors in the condition in which the Fixation Location was located at position 5 as compared to the condition in which it was located at position 2 (15.11% vs. 11.44% respectively) (see right panel of Figure 4).

Discussion

The results of the analysis of the word targets therefore confirm the classic "optimal viewing position" effect (O'Regan et al., 1984). Written word identification is better (faster and more accurate) when initial fixations are left of the word's center (for languages written from left-to-right) compared with rightward fixations (e.g., Brysbaert & Nazir, 2005; O'Regan & Jacobs, 1992; Stevens & Grainger, 2003). This provides empirical support that our initial fixation manipulation was effective.

In sum, Experiment 1 showed that TL effects are significantly greater when the transposed-letters are located farther from fixation. To examine whether the same pattern holds when letter shapes are more uniform (i.e., thereby minimizing potential confounds arising from the ascending/descending lowercase letters), we conducted Experiment 2, which used the same design as Experiment 1 but with uppercase stimuli.

Experiment 2 – Uppercase

Methods

Participants

A new sample of 99 participants (52 males) with a mean age of 33 years ($SD = 9.76$) from the same population as Experiment 1 were recruited via the Prolific platform (Palan & Schitter, 2018). With 99 participants and 80 items per condition the power of the experiment was largely superior to that recommended by Brysbaert and Stevens (2018). All participants were native speakers of French, with no history of neurological impairment, or developmental disorders. Prior to the beginning of the experiment, participants were informed that data would be collected anonymously, and they provided informed consent before the experiment was initiated.

Design & stimuli

The same sets of critical TL nonwords and non-critical stimuli tested in Experiment 1 were used in

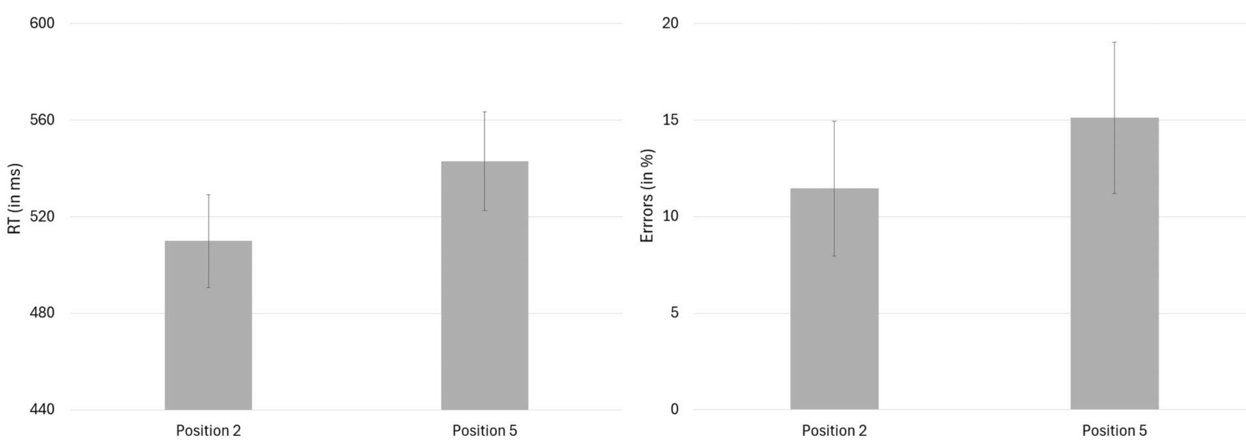

Figure 4. Mean RTs (left panel) and mean error rates (right panel) for the word stimuli as a function of Fixation Location in Experiment 1. Note. Error bars are standard errors.

Experiment 2. Regarding the SL nonwords, they were also created by substituting two adjacent consonants with different consonants (SL nonwords: e.g., ABSENT → ALPENT; CHANCE → CHAPLE). As a further control, in Experiment 2 the two sets of stimuli (i.e., TL nonwords and SL nonwords) were matched in terms of bigram frequency ($p > .1$), hence the SL nonwords were not identical to those used in Experiment 1.

Procedure

Participants performed the lexical decision task online. The experiment was created using LabVanced (Finger et al., 2017) and displayed on the personal computer screen of participants. The procedure was the same as in Experiment 1, except that the stimuli were presented in uppercase.

Results

Nonword trials

Data analysis was the same as for Experiment 1. The datasets from 4 participants were excluded, based on an overall error rate above 45%. Note that we also conducted analyses including participants' age. The results of these analyses are reported in a supplementary analysis file available at: https://osf.io/nk68y/. Taking into account the age of our participants (range 18–57 yrs. $M = 33.60$, $SD = 9.83$) did not affect the main findings concerning the critical nonword trials.

Response times (RTs). RTs were recorded from target onset up to participant's response. After excluding trials associated with an incorrect response (24.04%), RT values below 300 ms and above 1,500 ms were also excluded (2.79%). The final dataset was composed of 22,245 observations. The condition means are presented in Figure 5 and in Table 1. The maximal random-effects structure that converged was −1,000/RT ~ Type-of-Change X Fixation Location + (Type-of-Change X Fixation Location + 1| subject) + (Type-of-Change X Fixation Location + 1| item). The main effect of Type-of-Change was significant ($\chi^2(1) = 65.40$, $p < .001$), with longer RTs for TL nonwords than for SL nonwords (604 ms vs. 565 ms respectively). The effect of Fixation Location was significant ($\chi^2(1) = 157.01$, $p < .001$), with shorter RTs in the condition in which the Type-of-Change manipulation occurred close to fixation as compared to the condition where it occurred far from the fixation

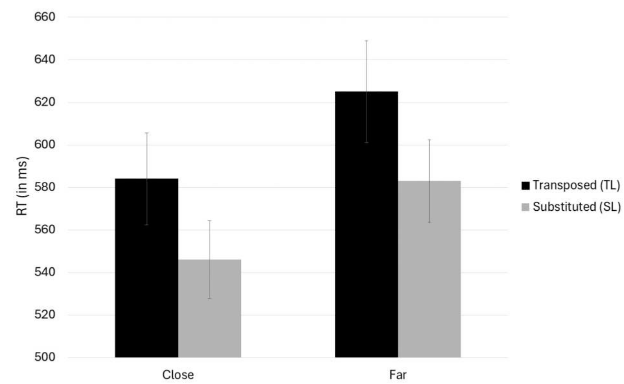

Figure 5. Mean RTs for the critical nonword targets per experimental condition in Experiment 2. Note. Error bars are standard errors.

(565 ms vs. 604 ms respectively). However, the Type-of-Change X Fixation Location interaction was not significant ($\chi^2(1) = 0.66$, $p = .413$).

Error rates. Mean error rates per experimental condition are shown in Figure 6 and in Table 1. The maximal random-effects structure that converged was: accuracy ~ Type-of-Change X Fixation Location + (Type-of-Change X Fixation Location + 1| subject) + (Type-of-Change + 1| item). There was a significant effect of Type-of-Change ($\chi^2(1) = 352.10$, $p < .001$), with more errors in the TL condition than in the SL condition (38.46% vs. 9.61% respectively). The effect of Fixation Location was also significant ($\chi^2(1) = 629.67$, $p < .001$), with more errors in the condition in which the Type-of-Change manipulation occurred far from fixation compared with the condition where it occurred close to fixation (33.13% vs. 14.94% respectively). Crucially, the Type-of-Change X Fixation Location interaction was significant ($\chi^2(1)$

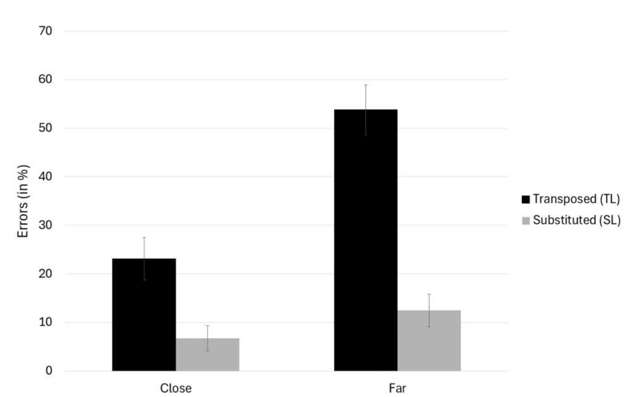

Figure 6. Mean error rates for the critical nonword stimuli as a function of experimental condition in Experiment 2. Note. Error bars are standard errors.

= 82.55, $p < .001$). This interaction reflects the fact that the size of the transposition effect was greater in the condition in which the Type-of-Change manipulation occurred far from fixation ($\chi^2(1) = 425.26$, $p < .001$) compared with the condition where it occurred close to fixation ($\chi^2(1) = 169.55$, $p < .001$).

Word trials

Like Experiment 1, we performed statistical analyses on the non-critical word trials.

Response times (RTs). After excluding trials associated with an incorrect response (16.52%), RT values below 300 ms and above 1,500 ms were also excluded (3.92%). The final dataset was composed of 24,186 observations. The maximal random-effects structure that converged was −1,000/RT ∼ Fixation Location + (Fixation Location + 1| subject) + (1| item). Analyses revealed a significant effect of Fixation Location ($\chi^2(1) = 42.13$, $p < .001$), with shorter RTs when fixation was located at position 2 compared to when it was located at position 5 (515 ms vs. 557 ms respectively) (see left panel of Figure 7).

Error rates. The maximal random-effects structure that converged was accuracy ∼ Fixation Location + (Fixation Location + 1 | subject) + (Fixation Location + 1| item). Analysis showed that there was a significant effect of Fixation Location ($\chi^2(1) = 23.31$, $p < .001$), with more errors in the condition where fixation was located at position 5 as compared to where it was located at position 2 (19.55% vs. 13.50% respectively) (see right panel of Figure 7). These results therefore replicate the results of Experiment 1 and further highlight the fact that our initial fixation manipulation was effective.

Discussion

Overall, Experiment 2 provided a replication of the results obtained in Experiment 1, with greater TL effects when the Type-of-Change manipulation (TL vs. SL nonwords) occurred far from fixation compared with the close to fixation condition. The results of the critical nonword trials therefore confirm our predictions and replicate the results of Experiment 1 in the accuracy data. Thus, the effects of eccentricity on the TL manipulation in unprimed lexical decision hold both for lowercase and uppercase stimuli.

These findings are in line with the literature concerning TL effects obtained in unprimed lexical decision: TL effects are generally more sensitive to accuracy than to RTs (e.g., see Baciero et al., 2022; Perea et al., 2023). This could be partly due to the high error rates in the TL conditions as compared to the control conditions, hence excluding a large number of datapoints in the RT analyses. Indeed, in Experiment 2 of the present study error rates were above 50% for TL nonwords when the transposition occurred far from fixation.

General discussion

In the present experiments, we examined how transposed-letter (TL) effects might be affected by the distance of the transposed-letters relative to fixation location. The phenomenon in question (TL effects) involves the comparison of nonwords derived from real words by transposing two letters (e.g., ASBENT derived from the English word ABSENT [TL nonwords]) compared with nonwords derived from the same base-words by substituting two letters (e.g.,

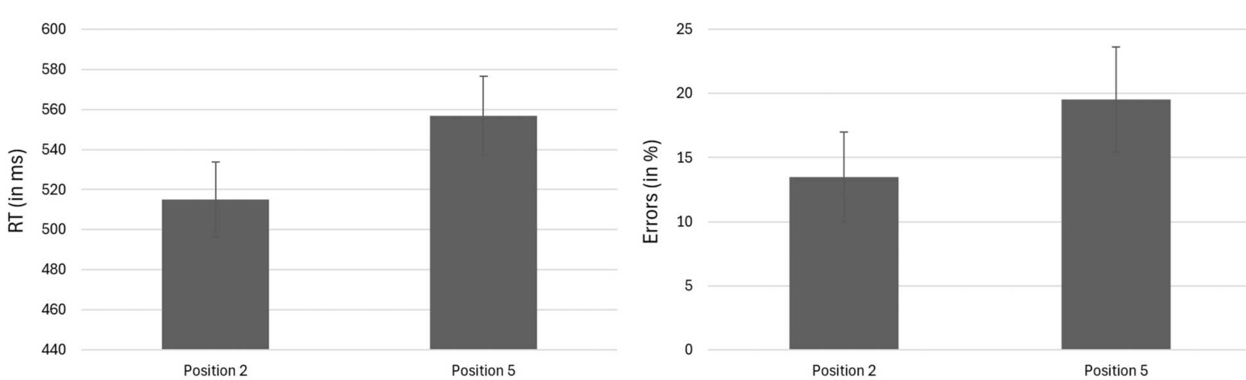

Figure 7. Mean RTs (left panel) and mean error rates (right panel) for the word stimuli as a function of fixation location. Note. Error bars are standard errors.

ALPENT [(SL) nonwords]). Prior research has reported that, in a lexical decision task, TL nonwords are harder to classify as nonwords compared with their SL controls (e.g., Lupker et al., 2008; Perea et al., 2023; Perea & Lupker, 2004). Manipulating the position of the transposed-letters relative to fixation provided a link between prior research in the field of vision science (e.g., Coates et al., 2013; Pelli et al., 2007; Whitney & Levi, 2011) showing that positional uncertainty increases with eccentricity, and different accounts of TL effects in the field of experimental psychology and reading research.

Applying a paradigm adapted from prior work on the effects of orthographic neighbours on visual word recognition (Grainger et al., 1992), we maintained a central fixation location on all trials and shifted the target stimuli left or right of this central fixation (see Figure 1). The transposed letters were either located at positions 2&3 or positions 4&5 of the 6-letter target stimuli. In this way, the transposed letters were either close to initial fixation location or far from that location. In the two experiments (Experiment 1 with lowercase stimuli, and Experiment 2 with uppercase stimuli), we found that TL effects increased when the transposed letters were located farther from fixation compared with the condition where they were close to fixation. Furthermore, we replicated the "optimal viewing position" effect obtained with the non-critical word targets (e.g., O'Regan & Jacobs, 1992; Stevens & Grainger, 2003). Word identification was faster and more accurate when initial fixations were left of the word's center compared with rightward initial fixations.

These results have important implications concerning models of orthographic processing during reading. Firstly, these models need to integrate letter eccentricity as a key factor. Although at first sight this might not appear surprising, what is important is how letter eccentricity impacts on orthographic processing, as demonstrated in the present findings (see also Stevens & Grainger, 2003). So, how might current models of visual word recognition accommodate the present results, and what mechanisms naturally predict a modulation of TL effects as a function of eccentricity? Although the effects of eccentricity on letter identification are well established (e.g., Chung & Legge, 2009), what the present study brings to the picture is how such effects of eccentricity impact on TL effects in a standard word recognition task.

The present findings are most easily integrated with one predominant explanation of TL effects – that they reflect the operation of positional noise on the encoding of location-specific gaze-centered letter identities (e.g., Gomez et al., 2008). This account builds on broad principles from models of visual attention, where spatial uncertainty arises naturally from variability in attentional resolution across the visual field (e.g., Ashby et al., 1996; Logan, 1996). The positional noise hypothesis accounts for the effect of the location of the transposed letters by the well-established principle that visual acuity diminishes and crowding increases as a function of eccentricity (e.g., Coates et al., 2013; Grainger et al., 2016; Pelli et al., 2007; Whitney & Levi, 2011), and because of this, positional noise also increases as a function of eccentricity (Chung & Legge, 2009). Notably, this account would also predict a similar pattern in masked priming. Specifically, the priming advantage for transposed-letter primes over substituted-letter primes (i.e., transposed-letter priming) should be greater when the transposed letters are farther from fixation.

Another model that explicitly acknowledges a role for positional noise that varies as a function of eccentricity is Davis (2010) spatial coding model. Indeed, Davis added positional noise to the spatial code for letter order to account for TL effects. Critically, the parameter responsible for positional noise (σ) "is assumed to increase linearly as a function of distance from fixation" (Davis, 2010, p. 717), based on the findings of Estes et al. (1976) and Chung and Legge (2009). Therefore, in the spatial coding model, letters farther from fixation are encoded with less precise positional information than letters that are close to fixation. As a consequence, TL nonwords in which the transposed letters are farther from fixation (e.g., ASBENT when fixating the 5th position) are more confusable with their base word (ABSENT), and therefore more difficult to reject than their SL controls, compared with TL nonwords in which the transposed letters are close to fixation (e.g., ASBENT when fixating the 2nd position). It is important to note that positional noise should not affect the processing of substituted letter (SL) nonwords, or at least significantly less so than TL nonwords, since they are on average likely to be equally different from their basewords independently of their positions.

The notion of positional noise or uncertainty is also a key aspect of the model proposed by Grainger and Van Heuven (2004) according to which orthographic processing begins with the processing of letter identities and their positions relative to fixation location. That is, this first stage of orthographic processing is akin to the model proposed by Gomez et al. (2008), but the Grainger and van Heuven model adds a further stage of orthographic processing (prior to word identification) whereby location-specific information about letter identities is transformed into a location-independent letter-order code (see Agrawal & Dehaene, 2025, for neurobiological evidence for this distinction). This additional stage of letter-specific order encoding has proved useful in explaining differences in transposed-character effects found with letter stimuli compared with non-letter stimuli (e.g., Massol et al., 2013; Massol & Grainger, 2022; 2024). The findings of Massol and Grainger (2022) are particularly relevant with respect to the present study. Using the same-different matching task Massol and Grainger examined the impact of the location of transposed-characters (letters, digits, or symbols). Compared with the present experiments, the Massol and Grainger study differed not only in the task that was used, but also in terms of how the location of the transposed letters was manipulated (by shifting the target stimulus relative to fixation location). Moreover, the transposed characters in the Massol and Grainger study were non-adjacent (separated by one intervening character). Target displacement was found to increase transposed-character effects for all three types of character, thus pointing to a relatively low-level perceptual locus of the effects (such as positional noise). On the other hand, in a second experiment it was found that increasing inter-character spacing only impacted on transposed-character effects for letter stimuli, pointing to the role of a second letter-specific mechanism in accounting for the complete scenario of TL effects.

However, other models of letter position coding during visual word recognition might find the present results challenging. The SERIOL model (Whitney, 2001) uses a fast beginning-to-end temporal (rather than spatial) encoding of letter positions and transforms that serial code into a word-centered letter-order code as in the Grainger and Van Heuven (2004) model (which was largely inspired by Whitney's work). Thus, the key mechanism for explaining TL effects in the SERIOL model is flexible letter-order encoding and not positional noise. However, the findings of the present study and the Massol and Grainger (2022) study point to positional noise as one key factor.

Contiguous n-gram encoding models, based on the principles of "statistical learning" (e.g., the wickelgraph coding used in the Seidenberg & McClelland, 1989, model), cannot account for TL effects in the first place, so there is little value in examining how they could accommodate the present findings (see Perea & Lupker, 2004; and Grainger, 2008). However, more recent developments of such models (e.g., Snell, 2025) might do better. Snell (2025) proposed a model of orthographic processing and word recognition (PONG [Positional Ordering of N-Grams]) that applies the notion of a split-fovea to assign letters (unigrams) and contiguous letter combinations (n-grams) to the left or right of fixation (i.e., two bags of contiguous n-grams and unigrams). However, we suspect that the inclusion of contiguous n-grams in the model should greatly dilute any TL effects that might arise via positional uncertainty in unigrams. Crucially, we have recently performed simulations with the PONG model to examine its ability to account for TL effects (Özkan et al., 2026). Our simulation results led us to conclude that PONG was not able to provide a complete account of TL effects.

Finally, we note that the present results converge with those of Grainger et al. (1992), where the location of a critical letter in a 5-letter word that distinguished that word from a higher-frequency orthographic neighbour could either be the 2nd letter or the 4th letter. As in the present study, the critical letter could either be on fixation or off fixation (i.e., initial fixation was either on the 2nd or the 4th letter). Neighbourhood frequency effects were found to be greater when the critical letter was further from initial fixation (see also Stevens & Grainger, 2003). The current findings fit well with this prior research and confirm the importance of how changes in letter visibility across the visual field modulate basic orthographic processing (i.e., the processing of letter identities and letter order).

Conclusions

In the present study we provided a novel investigation of Transposed-Letter (TL) effects where we manipulated the distance of the transposed letters from fixation. Given prior evidence for an increase in noisy letter position coding with an increase in eccentricity (see e.g., Chung & Legge, 2009), we hypothesized that TL effects should increase as the distance from fixation increases. In two lexical decision experiments, where the critical stimuli were nonwords (either TL nonwords or their SL controls), this is precisely what we observed, and we therefore conclude that TL effects are at least partly driven by positional noise.

Note

1. Note that transposed-character effects have been observed in Chinese (e.g., Gu et al., 2023). However, Chinese characters are morphemic units rather than letters, so these effects may reflect position flexibility at a different representational level.

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Data availability statement

The authors confirm the availability of shared data. The datasets are accessible on the OSF website (https://osf.io/nk68y/).

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Appendix: Cross-experiment analyses

Here we combine the results of Experiment 1 with those of Experiment 2 in order to formally assess whether the effects of transposition and fixation location differ between lowercase and uppercase stimuli. To do so, Case (lowercase vs. uppercase) was added to the analyses in the Nonword data. The analyses were conducted taking the substitution condition as reference for the Type-of-Change factor, the close condition as reference for the Fixation Location factor, and the lowercase condition as reference for the Case factor.

Response times (RTs). The condition means are presented in Figure A1. The maximal random-effects structure that converged was −1,000/RT ∼ Type-of-Change X Fixation Location X Case + (Type-of-Change X Fixation Location + 1| subject) + (1| item).

Similar to the results reported in the main analysis, the effect of Type-of-Change was significant ($\chi^2(1) = 126.05$, $p < .001$), with longer RTs for TL nonwords than for SL nonwords (587 ms vs. 564 ms respectively). The effect of Fixation Location was significant ($\chi^2(1) = 303.95$, $p < .001$), with shorter RTs in the condition in which the Type-of-Change manipulation occurred close to fixation as compared to the condition where it occurred far from the fixation (562 ms vs. 589 ms respectively). The Type-of-Change X Fixation Location interaction was also significant ($\chi^2(1) = 22.89$, $p < .001$). Furthermore, the effect of Case was not significant ($\chi^2(1) = 0.54$, $p > .1$) but did interact with the Type-of-Change factor ($\chi^2(1) = 76.04$, $p < .001$), revealing that the effect of Type-of-Change was larger when stimuli were presented in uppercase ($\chi^2(1) = 180.14$, $p < .001$) than in lowercase ($\chi^2(1) = 10.27$, $p = .001$). The interaction between Fixation Location and Case was also significant ($\chi^2(1) = 81.88$, $p < .001$), reflecting that the effect of Fixation Location was stronger when the stimuli were in uppercase ($\chi^2(1) = 295.38$, $p < .001$) than in lowercase ($\chi^2(1) = 59.70$, $p < .001$). The three-way interaction was significant ($\chi^2(1) = 32.37$, $p < .001$).

Error rates. Mean error rates per experimental condition are shown in Figure A2. The maximal random-effects structure that converged was: accuracy ∼ Type-of-Change X Fixation Location X Case + (Type-of-Change X Fixation Location + 1| subject) + (Type-of-Change X Fixation Location + 1| item). As previously, there was a significant effect of Type-of-Change ($\chi^2(1) = 504.61$, $p < .001$), with more errors in the transposed-letter condition than in the substituted-letter condition (35.59% vs. 9.57% respectively). The effect of Fixation Location was also significant ($\chi^2(1) = 489.56$, $p < .001$), with more errors in the condition in which the Type-of-Change manipulation occurred far from fixation compared with the condition in which it occurred close to fixation (30.40% vs. 14.77% respectively). The Type-of-Change X Fixation Location interaction was significant ($\chi^2(1) = 141.27$, $p < .001$). Moreover, while the effect of Case did not reach significance ($\chi^2(1) = 1.67$, $p > .1$), the two-way interactions as well as the three-way interaction ($\chi^2(1) = 7.16$, $p = .007$) were significant. The interaction between Type-of-Change and Case ($\chi^2(1) = 4.88$, $p = .027$) reflected the fact that the Type-of-Change factor was greater when the stimuli were presented in uppercase ($\chi^2(1) = 280.13$, $p < .001$) as compared with the lowercase version ($\chi^2(1) = 167.20$, $p < .001$). The Fixation Location X Case interaction ($\chi^2(1) = 19.82$, $p < .001$) revealed that the Fixation Location effect was larger when stimuli were presented in uppercase ($\chi^2(1) = 354.72$, $p < .001$) than in lowercase ($\chi^2(1) = 168.84$, $p < .001$). Discussion overall, this analysis revealed that the main effects as well as the critical interactions are stronger in Experiment 2, when stimuli were presented in uppercase, than in Experiment 1 in which stimuli were presented in lowercase. However, the Type-of-Change × Fixation Location interaction differed by Case: it was larger for lowercase stimuli in RTs but larger for uppercase stimuli in error rates.

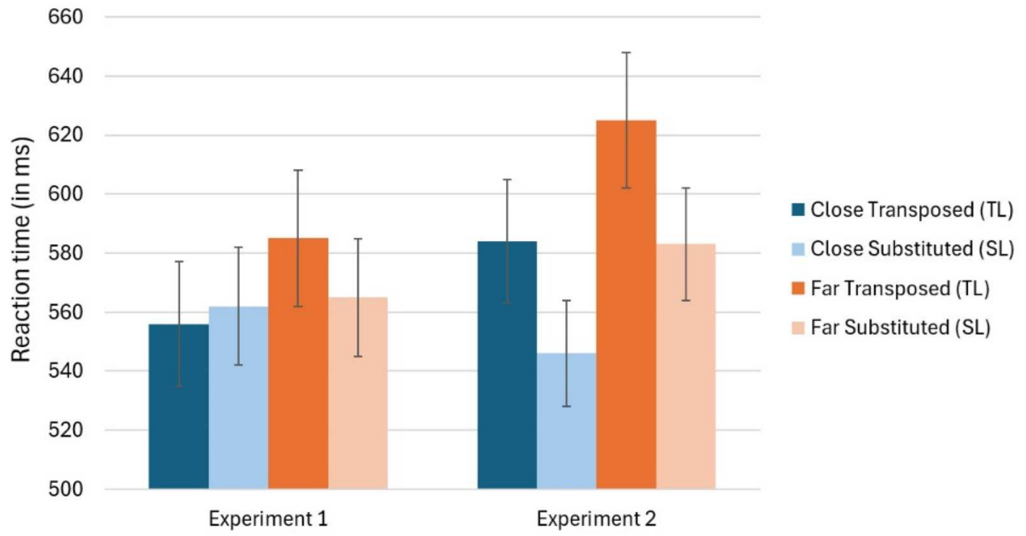

Figure A1. Mean RTs for the critical nonword stimuli as a function of experimental condition in Experiments 1 and 2. Note. Error bars are standard errors.

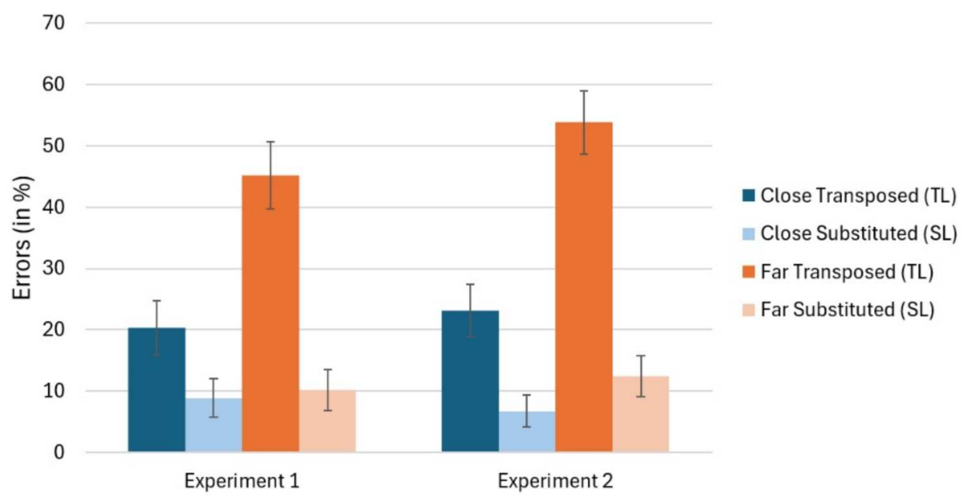

Figure A2. Mean error rates for the critical nonword stimuli as a function of experimental condition in Experiments 1 and 2. Note. Error bars are standard errors.