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# Does Letter Rotation Decrease Transposed Letter Priming Effects?

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Perceptual learning accounts of orthographic coding predict that transposed-letter (TL) priming effects should be smaller when the prime and target stimuli are not presented in their canonical (left-to-right horizontal in English) orientation (Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger & Holcomb, 2009). In contrast, abstract letter unit accounts would propose that TL priming effects should be essentially unaffected by presenting stimuli in most unfamiliar text orientations (Witzel, Qiao, & Forster, 2011). In the present experiments, we examined masked TL priming effects with primes and targets presented in 3 different text orientations (e.g., 0°, as well as 90° and 180° rotations). Results revealed that the magnitude of the TL priming effect with native English readers was equivalent for stimuli presented in these three orientations, providing support for abstract letter unit accounts of orthographic coding.

*Keywords:* transposed-letter priming, text rotation, masked priming paradigm

In most languages, words are typically written left-to-right horizontally. However, words in Chinese, Japanese, and Korean are sometimes written vertically or, in Chinese, right-to-left horizontally. English readers, however, have limited experience in dealing with words written in different orientations, although some words can appear vertically, for example, the word "HOTEL" may appear vertically (in "marquee" format) in signs due to limited horizontal space. An important question for understanding the nature of orthographic coding is whether text orientation has an influence on the coding process. This question was addressed in the present research by examining the impact of text orientation on transposed letter (TL) priming effects (e.g., *jugde* priming *JUDGE*).

Most recent models of orthographic coding, such as the "noisy position" models (Adelman, 2011; Davis, 2010; Gómez, Ratcliff, & Perea, 2008; Norris & Kinoshita, 2012; Norris, Kinoshita, & van Casteren, 2010), and the "open-bigram" models (Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; Grainger & van Heuven, 2003; Schoonbaert & Grainger, 2004; Whitney & Marton, 2013; Whitney, 2001) can easily explain basic TL effects, however, none of these models concerns itself with the question of the influence of text orientation. Rather, in most of these models, the letter representations are simply assumed to be abstract.

One model that does explicitly deal with this issue was proposed by Dehaene et al. (2005). In their local combination detectors (LCDs) model, the assumption is that at least some proportion of TL effects (in general) is due to the activity of bigram neurons. That is, the LCDs are not only sensitive to letters but also to local combinations of letters. In addition, those bigram neurons can tolerate certain position imprecision of the component letters. Importantly, the LCDs are derived via the perceptual learning process, so that they only encode frequent, informative letters and letter combinations.

In a similar vein, Grainger and Holcomb (2009) have suggested that letter detectors are based on the visuospatial location with respect to the reader's eye fixation on the horizontal meridian. Letters in words that are presented in unfamiliar orientations require a transformation of the retinotopic coordinates into a special coordinate system in order to allow readers to successfully activate the open bigrams required for successful reading. The ability to do so develops through experience, which means that the usefulness of this special coordinate system would be affected by the characteristics of the input language. As a result of incorporating these types of spatially based assumptions, models of this sort predict that TL effects should decrease (but not necessarily vanish) when a TL stimulus is presented in what is an unfamiliar spatial orientation for readers. We refer these ideas as the "perceptual learning account".

The alternative assumption, and one which is adopted by most current models of orthographic coding, is typified by Witzel et al.'s (2011) abstract letter unit account. This account argues that "the mechanism responsible for TL priming operates at an entirely abstract level, in which the visuospatial relationships of the letters are irrelevant" (p. 915). According to this idea, the letter positions would be coded in an ordinal fashion (i.e., first-to-last, U is one or two letters before D in judge or jugde) instead of in terms of a visuospatial representations (e.g., horizontal vs. vertical, U is on the left side of D vs. above D), and this code allows the activation of lexical representations regardless of the presented word's orientation. Based on this account, TL priming effects should be independent of the presented word's orientation, that is, even those individuals who lack experience in reading text presented in non-

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canonical orientations should produce equivalent size TL priming effects regardless of the TL stimulus's orientation.

There is now a considerable amount of evidence supporting the abstract letter unit account of orthographic coding. One primary source comes from results in masked repetition priming experiments in which the nature of the letters in the prime and target are different. One consistent finding is that these priming effects are the same size for targets preceded by same case (e.g., TABLE-TABLE) versus different case (e.g., table-TABLE) primes (Grainger & Jacobs, 1993; Perea, Jiménez, & Gómez, 2014). Further, lowercase primes (e.g., table-TABLE) and mixed case primes (e.g., tAbLe-TABLE) were also equality effective in producing repetition priming effects (Perea, Vergara-Martínez, & Gomez, 2015). In contrast, the impact of text orientation on TL priming effects, and the question of whether perceptual learning processes may play a role in producing those priming effects, do not yet have an extensive literature.

In one of the initial attempts to test between perceptual learning and abstract letter unit accounts of masked TL priming effects when text orientation is varied, Witzel et al. (2011) examined TL priming effects for both Japanese-English bilinguals and monolingual English readers. Japanese-English bilinguals are used to reading both horizontally and vertically presented (in marquee format) Japanese words and horizontally presented English words, whereas they are unfamiliar with vertically presented English words. The expectation was that those readers would show equivalent size priming effects for horizontally and vertically presented Japanese words due to their familiarity with reading Japanese words in those two orientations. The more crucial empirical question was whether those readers would show similar size TL priming effects when reading familiar horizontally presented versus unfamiliar vertically presented English words, as their LCDs would not be well formed for the latter type of words due to those readers' lack of perceptual experience reading vertically presented English words.

In Experiment 1, Japanese-English bilinguals did show equivalent TL priming effects for horizontally and vertically (marquee) presented Japanese words (25 and 19 ms, respectively), and they also showed a TL priming effect for horizontally presented English words (35 ms). Marquee English words also produced a significant TL priming effect, however, it was noticeably smaller (15 ms) than the effect for horizontally presented English words. The contrast between vertically and horizontally presented English words was, however, compromised by a speed–accuracy trade-off. Therefore, the results of Experiment 1 did not appear to clearly favor either account.

In their Experiment 2, Witzel et al. (2011) found a vertical (marquee) TL priming effect (22 ms) for native English readers. However, in this experiment, Witzel et al. did not include a horizontal condition, meaning that they could not compare the size of this TL priming effect with the size of the TL priming effect when these words were presented horizontally, making it difficult to conclude which account was best supported by their findings. Therefore, the question remained as to what the impact of text orientation on masked TL priming is for English readers, that is, for readers who have little experience reading in any orientation other than left-to-right horizontal.

An attempt to follow up on Witzel et al.'s (2011) results was reported by Perea, Marcet, and Fernández-Lopez (2018) using Spanish readers (who also have generally read words that are written horizontally left-to-right). In this experiment, the authors compared TL priming effects for marquee presented words and 90° rotated words, working under the assumption that the marquee words represented a somewhat familiar format of presentation because "Letters in marquee format have the same upright orientation as in canonical horizontal text" (p. 2). Their results showed similar TL priming effects for marquee and rotated words, allowing Perea et al. to argue for the abstract letter unit position.

Unfortunately, the contrast created by Perea et al. (2018) is problematic. Specifically, their participants appear to have had considerable difficulty with the marquee words as, overall, those words were actually responded to slightly more slowly (15 ms) than the rotated words were. Therefore, it would seem that in order to create a truly appropriate comparison, the familiar condition would need to involve horizontally presented words, because, for both English and Spanish readers, that is the orientation that is most familiar to those readers.

Additionally, in order to examine the question of orientation in a theoretical meaningful way, one needs to know how unfamiliar the orientation should be in order to be able to legitimately assume that normal processing operations should be disrupted for letters in that orientation. As Whitney (2002) has argued, "the act of mental rotation decreases the amount of input reaching the letter nodes, and that this degradation increases with the amount of rotation" (p. 117) and, according to Dehaene et al. (2005), the LCD model suggests that "letter detectors should be disrupted by rotation ($>$40°)" (p. 340). Indeed, previous research has repeatedly shown that RTs are shorter for horizontal words/letters than for rotated words/letters that are rotated more than 40° (Chang et al., 2015; Koriat & Norman, 1985; Risko, Medimorec, Chisholm, & Kingstone, 2014). Hence, it does seem likely that Dehaene et al.'s estimate of $>$40% is legitimate.

In the present experiments, therefore, the question was what is the impact of text rotation of both primes and targets to different degrees (e.g., 0° vs. 90° and 180°) on TL priming effects? In Experiment 1, we used a masked priming paradigm examining TL priming effects with horizontally presented text and 90° rotated text. Based on Perea et al.'s (2018) results with 90° rotations, we expected those stimuli to produce a TL priming effect. If the effect is the same size as that in the horizontal condition, that result would provide evidence for an abstract letter unit account. Alternatively, if the letter input from rotated words really creates a processing cost (in the sense suggested by perceptual learning accounts), one would expect to find a smaller TL priming effect for 90° rotated words than for horizontally presented words.

To foreshadow, similar size effects were found for the two orientations, supporting the abstract letter unit account. Experiment 2, then, was designed to determine whether a similar result/conclusion would apply to an even more extreme orientation. Experiment 2 involved the same paradigm with the same stimuli as used in Experiment 1 with the text being rotated 180° (upside down presentations). According to perceptual learning accounts, the TL priming effects should greatly decrease or even vanish with 180° rotated words. In contrast, abstract letter/character unit accounts would not make such a prediction. Although there is likely a limit in terms of the degree of transformation the system would be able to successfully deal with (i.e., Davis, Kim, & Forster, 2008 failed to obtain any priming effects when the [English] primes and targets were both presented backward), there is no a priori reason to assume that a 180° rotation would be outside that limit.

## Experiment 1

### Method

**Participants.** Thirty-eight undergraduate students from Western University participated in this experiment. All were native speakers of English and had normal or corrected-to-normal vision with no reading disorder.

**Materials.** Ninety-six single-syllable 5 letter word targets were selected from the English lexicon project (Balota et al., 2007). Their average SUBTLWF frequency is 42.05 (range: 2.08–453.98) and their mean orthographic neighborhood size (Coltheart, Davelaar, Jonasson, & Besner, 1977) is 4.07 (range: 0–13) (values obtained from the English Lexicon Project Database [Balota et al., 2007]). In addition, 96 single-syllable 5 letters nonwords were also selected. Each word target was preceded by two different types of primes, (1) a TL prime involving two middle adjacent transposed letters (e.g., *porve-PROVE*, the TL condition); (2) a substitution letter (SL) prime in which the two adjacent letters used in the TL condition were substituted with different letters (e.g., *pamve-PROVE*, the SL condition). The average position of first letter transposition/substitution was position 2.5. The same stimuli were used in the horizontal and rotated blocks, which means that each prime and target was presented twice.

The word and nonword targets were divided into two sets of size 48. Based on this division, two lists of stimuli were created. In one list, one set of targets was preceded by a TL prime with the other set of targets being preceded by an SL prime. In the other list, the prime-target conditions were reversed for all the targets. Each participant received the same list in the two (orientation) blocks. Given the nature of the difference between the orientation blocks, it was expected that the repetition manipulation would not weaken the TL priming effects substantially in the second block (see Witzel et al., 2011). The manipulation of prime type for the nonword targets was done in the same fashion as for word targets, however, there was only one list of primes (48 TL primes and 48 SL primes) and targets. One half of the participants was assigned to each of these two lists. All primes were presented in 35-pt Courier New typeface, whereas the targets were presented in 40-pt Courier New typeface. The stimuli used in this experiment are reported in the Appendix.

**Procedure.** The data were collected using Eprime 2.0 software (Psychology Software Tools, Pittsburgh, PA; see Schneider, Eschman, & Zuccolotto, 2002). The background color was white whereas the stimulus color was black. All the stimuli were presented centrally. The sequence of stimuli on each trial was seven hash marks (#######) presented for 500 ms, a lowercase prime for 50 ms and then an uppercase target presented for 3000 ms or until the participant's response. Participants were asked to decide whether each presented string of uppercase letters was a real English word or not, pressing the "J" button if it is a real English word and the "F" button if not. They were asked to respond as quickly and as accurately as possible. Text orientation (horizontal vs. 90° rotation) was maintained within a block and the order of blocks was counterbalanced over participants. (Examples of text presented in different orientations are shown in Figure 1.) Trial order was also randomized for each participant. Each experimental block had 192 trials. Sixteen practice trials preceded each experiment block. This research was approved by the Western University REB (Protocol # 104255).

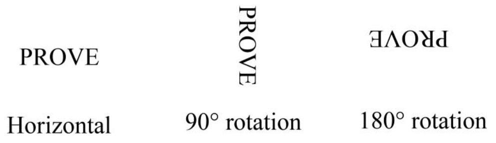

*Figure 1.* Examples of text presented in different rotation degree.

### Results

For word targets, response latencies less than 300 ms, more than 3 standard deviations from the participant's mean latency and from incorrect trials (7.6% of the data) were excluded from the latency analyses. The data from nonword targets were not analyzed due to the fact that the nonword targets were not counterbalanced across prime type. Before running the model, R-default treatment contrasts were altered to sum-to-zero contrasts (Levy, 2014; Singmann & Kellen, 2017).

Generalized Linear mixed-effects (GLMM) models from the lme4 packages were used to analyze the latency and error rate data (Bates, Mächler, Bolker, & Walker, 2015; Lo & Andrews, 2015; R Core Team, 2015). We performed a generalized linear mixed-effects model analysis, instead of a linear mixed-effects model analysis, because the linear mixed-effects model analysis requires a normal distribution of RTs whereas raw RTs usually have a positively skewed distribution. Although this problem can be solved by analyzing inverted RTs (e.g., invRT = −1000/reaction time (RT)), doing so can change the size and pattern of interaction effects (Balota, Aschenbrenner, & Yap, 2013; Lo & Andrews, 2015). That is, the RT transformation can make the interaction smaller, vanish, or even reverse (Balota et al., 2013). Because interactions between factors were the focus of our experiments, we chose to use the GLMM analysis instead, as it allowed us to specify the RT distribution. We initially tried to use more complex models which included all relevant random structures in our analyses but we ultimately had to use a random intercepts only model due to convergence failures with the more complex models (Barr, 2013).

For the latency analysis, the GLMM structure was: RT = glmer (RT ~ Prime Type* Orientation + (1|subject) + (1|item), family = Gamma(link = "identity")). For the error rate analysis the GLMM structure was: Accuracy = glmer (accuracy ~ Prime Type* Orientation + (1|subject) + (1|item), family = "binomial"). The mean RTs and percentage error rates from a subject-based analysis for the word targets are shown in Table 1.[1]

We also analyzed the nature of our priming effects across the latency distributions by examining quantile plots for each condition. The graphs of the latencies as a function of quantile can be

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[1] The priming effects in terms of mean latencies from an item-based analysis for the horizontal, vertical 90° rotation and 180° rotation conditions were 34 ms, 31 ms and 31 ms, respectively. The priming effects in terms of percentage error rates from an item-based analysis were the same size as those reported for the subject-based analysis in Table 1.

Table 1
*Mean Lexical Decision Latencies (RTs, in Milliseconds) and Percentage Error Rates Based on the Subject Analysis*

| Condition | RT | %E |
|---|---|---|
| Horizontal | | |
| Transposed prime | 635 | 5.0 |
| Substitution prime | 668 | 7.0 |
| Priming | 33 | 2.0 |
| Vertical 90° rotation | | |
| Transposed prime | 759 | 4.6 |
| Substitution prime | 788 | 7.0 |
| Priming | 29 | 2.4 |
| 180° rotation | | |
| Transposed prime | 986 | 10.7 |
| Substitution prime | 1021 | 13.5 |
| Priming | 35 | 2.8 |

*Note*. RT = reaction time; %E = percentage error rate. The overall mean RT and error rate of the nonword targets in horizontal orientation were 751 ms and 8.3% respectively; The overall mean RT and error rate of the nonword targets in 90° rotation orientation were 940 ms and 10.5% respectively. The overall mean RT and error rate of the nonword targets in 180° rotation orientation were 1275 ms and 12% respectively.

seen in Figure 2. In order examine the quantile data statistically, we added Quantile Group as a fixed factor in a second analysis. For the latency analysis, the Quantile Group model was: RT = glmer (RT ~ Prime Type* Orientation* Quantile Group + (1|subject) + (1|item), family = Gamma(link = "identity")). The Quantile Group factor had four levels, with 10 trials in each of these levels. It should be noted that not all participants provided 10 trials in some conditions in the fourth quantile level and, in fact, we removed 1 participant's data from the Quantile Group analysis because that person had less than 6 trials in the fourth quantile in one of the experimental conditions. Missing data was, of course, also a problem (to an even greater extent) for a fifth quantile level which could be created based on any remaining latencies. Therefore, we did not include the data from this fifth level in our analysis, however, the means for that level are shown in Figure 2. The function Anova in the Car package (Fox & Weisberg, 2016) was used to test for significance and to provide the $p$ values for this analysis.

In the basic analysis of the latency data, the main effect of Prime Type was significant, ß = 16.529, $SE = 1.698$, $z = 9.74$, $p < .001$, as targets following SL primes (728 ms) were processed more slowly than targets following TL primes (697 ms). There was also a main effect of Orientation, ß = −55.674, $SE = 1.729$, $z = -32.21$, $p < .001$. Targets presented in the horizontal orientation (651 ms) were processed faster than targets presented in the vertical orientation (773 ms). More importantly, the interaction between those two factors did not approach significance, ß = 0.680, $SE = 1.656$, $z = 0.41$, $p = .681$, indicating that the priming effect was the same for the horizontal and vertical stimuli.

In the basic analysis of the error rate, the main effect of Prime Type was significant, ß = −0.211, $SE = 0.05$, $z = -4.19$, $p < .001$, indicating a tendency for targets in the SL conditions to elicit more errors (7.0%) than targets in the TL conditions (4.8%). The main effect of Orientation and the interaction between these two factors were not significant (both $p$s > .10).

In the Quantile Group analysis the default model failed to converge even when fitting was restarted from the apparent optimum. We then proceeded to rerun the model using all available optimizers. The results reported are the results from the BOBYQA optimizer. The three main effects of Prime Type, Orientation, and Quantile Group were significant (all $p$s < .001), as was the interaction between Orientation and Quantile Group, $\chi^2 = 438.48$, $p < .001$, which suggests that the latency difference between the horizontal and 90° rotation conditions increased from Quantile Group 1 to Quantile Group 4. The two-way interaction, Prime Type by Quantile Group, failed to approach significance $\chi^2 = 1.86$, $p = .602$. Most importantly, neither the interaction between Prime Type and Orientation $\chi^2 = 0.07$, $p = .796$, nor the three-way interaction between Prime Type, Orientation and Quantile Group approached significance, $\chi^2 = 0.22$, $p = .974$. These results indicate that the overall priming effect was constant across quantiles and that such was the case in both Orientation conditions.

# Experiment 2

## Method

**Participants.** Forty Western University undergraduate students participated in Experiment 2. All were native speakers of English and had normal or corrected-to-normal vision with no reading disorder.

**Materials.** The materials were the same as in Experiment 1.

**Procedure.** The procedure was the same as in Experiment 1, except that the primes and targets were presented only in an (upside-down) 180° rotation orientation.

## Results

For word targets, response latencies less than 300 ms, more than 3 standard deviations from the participant's mean latency and from incorrect trials (13.4% of the data) were excluded from the latency analyses. The mean RTs and percentage error rates from a subject-based analysis for the word targets are shown in Table 1. The mean RTs from the subject-based analysis for the different Quantile Groups in Experiment 2 are shown in Figure 3.

For the basic latency analysis, the model was: RT = glmer (RT ~ Prime Type + (1|subject) + (1|item), family = Gamma(link = "identity")). For the basic error rate analysis, the model was: Accuracy = glmer(accuracy ~ Prime Type + (1|subject) + (1|item), family = "binomial"). The other details were same as in Experiment 1.

In the latency data, the difference between TL (986 ms) and SL (1021 ms) conditions was significant, ß = 20.421, $SE = 3.655$, $z = 5.59$, $p < .001$. Targets following TL primes also produced significantly less errors (10.7%) than targets following SL primes (13.5%), ß = −0.148, $SE = 0.052$, $t = -2.86$, $p = .004$.

We further contrasted the priming effect in this experiment with those in the horizontal and vertical conditions in Experiment 1. The basic GLMM analysis paralleled that in Experiment 1 except that the Orientation factor now had three levels. We also carried out analyses that involved both having three levels of the Orientation factor and adding Quantile Group as a factor. As in the previous quantile analysis, we removed participants from this analysis if they had fewer than 6 trials in either Prime Type condition in quantile 4 (the 1 participant in Experiment 1 and 4 of the participants in Experiment 2).

In the basic analyses of both the latency data and error rate data, the two main effects of Prime Type and Orientation were significant (both $ps < .001$). Crucially, the interaction between those two factors did not approach significance in either the latency data, $\chi^2 = 0.85$, $p = .654$; or the error rate data, $\chi^2 = 1.02$, $p = .599$.[2]

In the Quantile Group analysis, the default model again failed to converge even when fitting was restarted from the apparent optimum. We then proceeded to rerun the model using all available optimizers. The results reported are the results from the BOBYQA optimizer. The three main effects of Prime Type, Orientation, and Quantile Group were significant (all $ps < .001$), and the interaction between Orientation and Quantile Group was also significant, $\chi^2 = 2288.28$, $p < .001$, which suggests that the latency difference between different orientations are increasing from Quantile Group 1 to Quantile Group 4. There was no significant interaction between Prime Type and Orientation, $\chi^2 = 1.64$, $p = .440$, however, there were marginal trends for the two-way interaction between Prime Type and Quantile Group, $\chi^2 = 7.02$, $p = .071$, and the three-way interaction between Prime Type, Orientation and Quantile Group, $\chi^2 = 11.97$, $p = .063$. These marginal interactions appear to be due to the growth in the priming effect in the fourth quantile in the 180° rotation orientation condition.

## Discussion

Two experiments were conducted in order to examine the impact of rotated letters/words on TL priming effects and, in doing so, contrast a perceptual learning account (e.g., Dehaene et al., 2005) with an abstract letter unit account such as that presented by Witzel et al. (2011). To do so, we included three orientation formats in Experiments 1 and 2. In Experiment 1, we obtained similar size TL priming effects in the horizontal and 90° rotation orientations (33 ms and 29 ms, respectively). In Experiment 2 we found a significant TL priming effect with a 180° rotation orientation (35 ms). Importantly, the magnitude of TL priming effect in Experiment 2 was essentially the same as those in Experiment 1, supporting the conclusion that the TL priming effects do not vary as a function of the text orientations used here.

We further examined the nature of the priming effects as a function of quantile in the three orientation conditions. In the two conditions in Experiment 1, those effects were virtually identical across quantiles. In the 180° rotation condition in Experiment 2 there was some suggestion that the effect size did increase in the fourth quantile, however, the relevant interaction was not significant and there is also no evidence that the effect increased in size in the, admittedly fragile, fifth quantile. Identical size priming effects across quantiles are typically taken to imply that the prime provides a "headstart" to target processing (Balota, Yap, Cortese, & Watson, 2008) as a result of activating the target's processing structures. Hence, the implication would be that the primes used in these experiments not only provided equivalent priming effects but they did so in essentially the same way (i.e., by boosting the activation of the target) regardless of their orientation (and that of the target). Such a conclusion would, of course, be consistent with the proposal that, in all instances, that activation is coming from the prior activation of a shared set of abstract letter units. That is, the facts that: 1) the rotated stimuli did not disrupt the size of the TL priming effect and 2) the quantile analyses showed that that effect is likely a headstart effect support the claim that a similar priming operation is at work in all three situations, an operation based on an abstract ordinal code, regardless of text orientation (e.g., Witzel et al., 2011).

In contrast, as Perea et al. (2018) have argued, a perceptual learning account would appear to have some difficulty explaining the equivalent overall effect sizes in the three presentation conditions. For example, in Dehaene et al.'s (2005) model, English readers would not have developed the local combination detectors that would allow them to process rotated words in the same way that they process canonical words. Therefore, the expectation is that the primes would be less effective when they are rotated, a result that did not obtain.

Do note, however, that our argument is not that the initial processing stages underlying the formation and use of the abstract orthographic code for familiar orientations versus unfamiliar orientations are identical.[3] As many behavioral studies have shown, unfamiliar formats (e.g., low text contrast words, MiXeD case words and vertically presented words) induce a strong length effect (Bub & Lewine, 1988; Lavidor, 2002; Legge, Ahn, Klitz, & Luebker, 1997), and functional MRI (fMRI) studies have shown that unfamiliar formats tend to produce a larger activation in the posterior visual word form area (Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008). Such results caused Cohen et al. to propose their perceptual expertise hypothesis which suggests a parallel word recognition process for letters in words presented in a familiar format and a (qualitatively different) serial reading strategy for words presented in an unfamiliar format (i.e., a format which is outside the readers' field of expertise). As a result, position encoding for words in unfamiliar orientations requires attention shifts across the letters, leading to longer latencies.

In contrast, Whitney (2018) has presented experimental evidence for serial letter processing in both types of situations. The difference is that the rate of letter activation is faster for canonical presentations (~15 ms/letter) than for noncanonical presentations (~40 ms/letter or more) because the former allow the use of a more practiced mechanism (i.e., the distinction Whitney proposed is a quantitative rather than a qualitative one). Consistent with both proposals, of course, our 180° rotated words were identified as words more slowly (1003 ms) than 90° rotated words (773 ms), and they were both identified as words more slowly than horizon-

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[2] Note that, due to the fact that we had a number of long latencies, particularly in Experiment 2, we also explored (in both experiments) the impact of using a stricter outlier removing procedure, the recursive moving criterion procedure suggested by Van Selst and Jolicoeur (1994). In this procedure, a 3 standard deviation cutoff for removing RTs is used for the correct trials within each experimental condition for each participant and this procedure is conducted repeatedly (with a new mean and standard deviation calculated after each iteration) until there are no latencies outside 3 standard deviations in any experimental condition. This trimming process removed 9.4% of the experiment trials in Experiment 1 and 11% of the experimental trials in total for the comparison of the three orientations. After using this trimming procedure, we again compared the priming effects using the same GLMM analyses. The data pattern did not change. Crucially, when comparing the horizontal and 90° rotation orientations in Experiment 1, the interaction between Prime Type and Orientation was not significant, $\chi^2 = 1.75$, $p = .19$. When comparing the three orientations following Experiment 2, the interaction between Prime Type and Orientation was also not significant, $\chi^2 = 2.03$, $p = .36$.

[3] We thank Carol Whitney for bringing these issues to our attention.

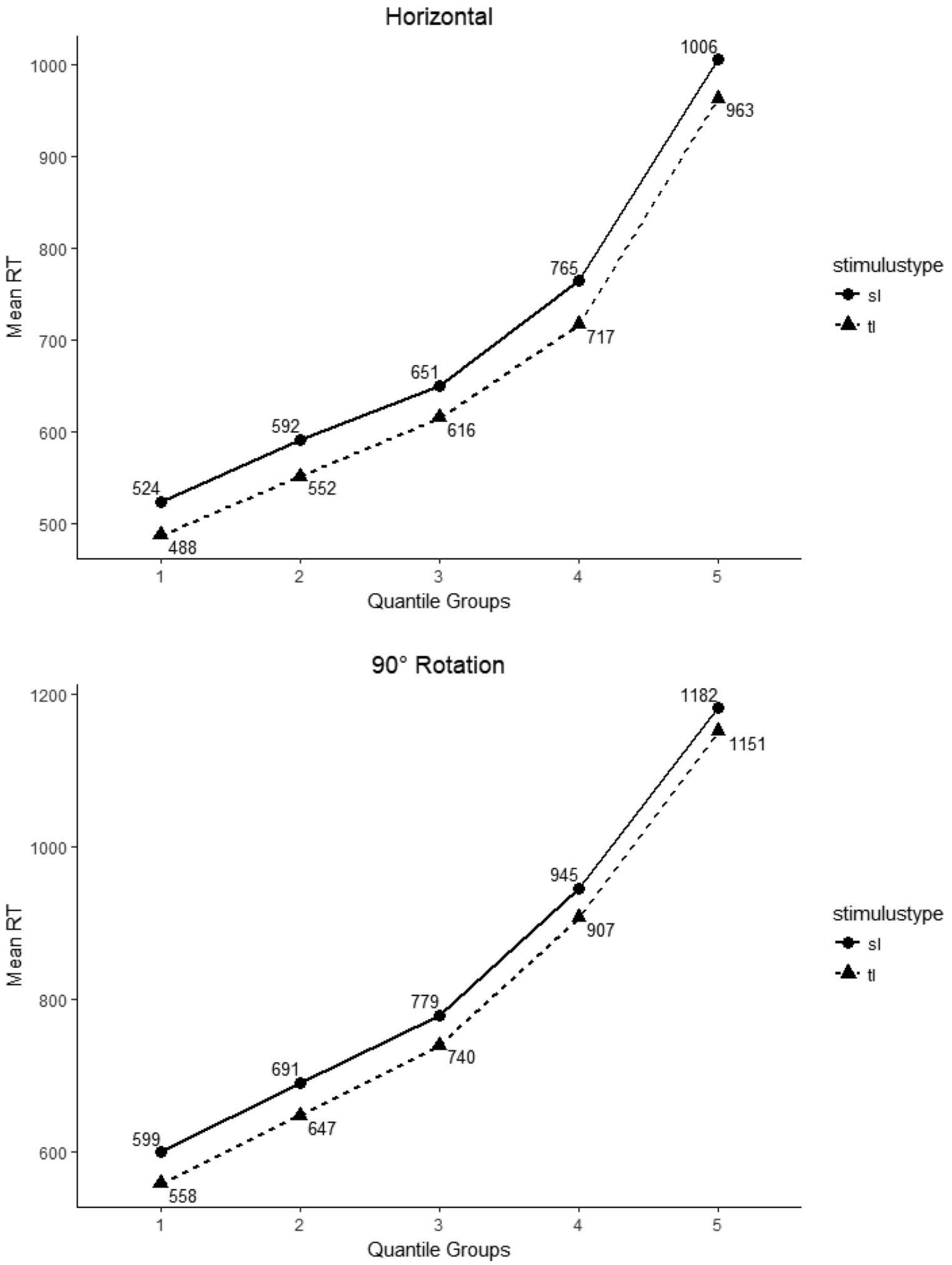

*Figure 2.* Quantile plot for Experiment 1. The priming effects for Quantile Groups 1 to 5 were 36 ms, 40 ms, 35 ms, 48 ms and 43 ms respectively for the horizontally presented words. The priming effects for Quantile Groups 1 to 5 was 41 ms, 44 ms, 39 ms, 38 ms and 31 ms respectively for the 90° rotated words.

tal words (651 ms). More importantly, the fact that the present data provide good support for the role of abstract letter units in all situations investigated here would appear to be more consistent with a quantitatively based account such as Whitney's rather than a qualitatively based account such as that proposed by Cohen et al. (2008).

Note also that the argument is not that perceptual learning processes would never play a role in orthographic coding but rather that the basis of orthographic coding in skilled readers is abstract letter units. As Grainger (2018) has described, orthographic processing is the interface between lower level visual processing and high level language processing. Visual processing mainly involves obtaining information about the featural components of a word's letters, and orthographic processing is mainly focused on deriving information about letter identities and letter positions. One can, therefore, make a strong ecological argument that it is computationally more effective to solve any visual shape invariance issues at the letter level ($N = 26$ for alphabetical

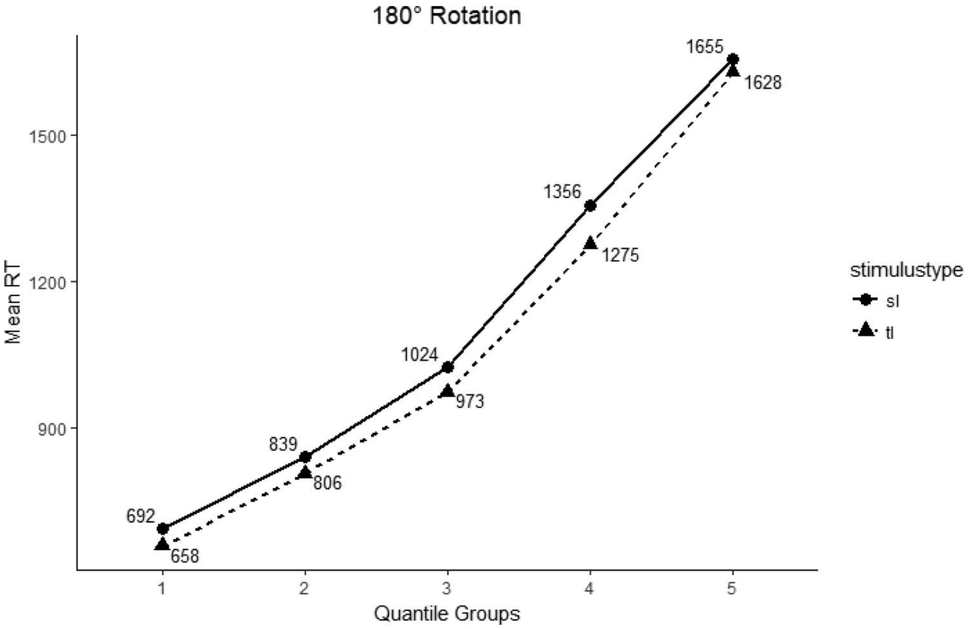

*Figure 3.* Quantile plot for Experiment 2. The priming effects for Quantile Groups 1 to 5 were 34 ms, 33 ms, 51 ms, 81 ms and 27 ms respectively for the 180° rotated words.

language like English) instead of at some other level (e.g., for the word level, $N = 30{,}000+$). As such, it would make sense that our orthographic coding system would be tuned to recognize letters (and, therefore, words) independently of the precise form that the visual input takes (e.g., MiXeD case vs. pure case, lowercase vs. UPPERCASE, as well as printed words vs. handwritten words - Gil-López, Perea, Moret-Tatay, & Carreiras, 2011). That is, it would make sense that people would recognize letters and words via the use of abstract representations with the difficulties created by changes in orientation dealt with at the visual processing level instead of at the orthographic coding level.

A potential question this analysis raises, however, is to what extent these ideas apply to people trying to learn to read in an L2, particularly an L2 having a different script than that of their L1? As noted, Witzel et al. (2011) compared the TL priming effects in an unfamiliar vertical orientation to those in a standard horizontal orientation in English with Japanese-English bilinguals. Those individuals produced a smaller TL priming effect with marquee English words than with horizontal English words, in contrast to our results with English L1 readers, although, as noted, this contrast was compromised by a speed–accuracy trade-off. If this difference is real, it may reflect a distinct difference between first language (L1) and second language (L2) readers. That is, the possibility exists that perceptual learning processes may play a role in the orthographic coding process when readers are learning to read in their L2 whereas the orthographic coding process in a reader's L1 is, instead, based on abstract representations (i.e., representations that are independent of, among other things, the presented text's orientation) and, importantly, those abstract representations are ones that may emerge only as a result of prolonged exposure to the script of that language.

## Conclusion

Our results suggest that native English readers rapidly convert the unfamiliar visuospatial code of rotated words into an abstract letter-based code, the code that would then be used to drive subsequent (e.g., lexical, semantic) processing.

## References

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

Balota, D. A., Aschenbrenner, A. J., & Yap, M. J. (2013). Additive effects of word frequency and stimulus quality: The influence of trial history and data transformations. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39,* 1563–1571. http://dx.doi.org/10.1037/a0032186

Balota, D. A., Yap, M. J., Hutchison, K. A., Cortese, M. J., Kessler, B., Loftis, B., . . . Treiman, R. (2007). The English lexicon project. *Behavior Research Methods, 39,* 445–459. http://dx.doi.org/10.3758/BF03193014

Balota, D. A., Yap, M. J., Cortese, M. J., & Watson, J. M. (2008). Beyond mean response latency: Response time distributional analyses of semantic priming. *Journal of Memory and Language, 59,* 495–523. http://dx.doi.org/10.1016/j.jml.2007.10.004

Barr, D. J. (2013). Random effects structure for testing interactions in linear mixed-effects models. *Frontiers in Psychology, 4,* 328. http://dx.doi.org/10.3389/fpsyg.2013.00328

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67,* 1–48. http://dx.doi.org/10.18637/jss.v067.i01

Bub, D. N., & Lewine, J. (1988). Different modes of word recognition in the left and right visual fields. *Brain and Language, 33,* 161–188. http://dx.doi.org/10.1016/0093-934X(88)90060-0

Chang, C. H. C., Pallier, C., Wu, D. H., Nakamura, K., Jobert, A., Kuo, W. J., & Dehaene, S. (2015). Adaptation of the human visual system to the statistics of letters and line configurations. *NeuroImage, 120,* 428–440. http://dx.doi.org/10.1016/j.neuroimage.2015.07.028

Cohen, L., Dehaene, S., Vinckier, F., Jobert, A., & Montavont, A. (2008). Reading normal and degraded words: Contribution of the dorsal and ventral visual pathways. *NeuroImage, 40,* 353–366. http://dx.doi.org/10.1016/j.neuroimage.2007.11.036

Coltheart, M., Davelaar, E., Jonasson, T., & Besner, D. (1977). Access to the internal lexicon. In S. Domic (Ed.), *Attention and Performance VI* (pp. 535–555). New York, NY: Academic Press.

Davis, C. J. (2010). The spatial coding model of visual word identification. *Psychological Review, 117,* 713–758. http://dx.doi.org/10.1037/a0019738

Davis, C., Kim, J., & Forster, K. I. (2008). Being forward not backward: Lexical limits to masked priming. *Cognition, 107,* 673–684. http://dx.doi.org/10.1016/j.cognition.2007.07.016

Dehaene, S., Cohen, L., Sigman, M., & Vinckier, F. (2005). The neural code for written words: A proposal. *Trends in Cognitive Sciences, 9,* 335–341. http://dx.doi.org/10.1016/j.tics.2005.05.004

Fox, J., & Weisberg, S. (2016). car: Companion to applied regression. *R Package Version 2.1–2*. Retrieved from http://socserv.socsci.mcmaster.ca/jfox/Books/Companion

Gil-López, C., Perea, M., Moret-Tatay, C., & Carreiras, M. (2011). Can masked priming effects be obtained with handwritten words? *Attention, Perception, & Psychophysics, 73,* 1643–1649. http://dx.doi.org/10.3758/s13414-011-0174-y

Gómez, P., Ratcliff, R., & Perea, M. (2008). The overlap model: A model of letter position coding. *Psychological Review, 115,* 577–600. http://dx.doi.org/10.1037/a0012667

Grainger, J. (2018). Orthographic processing: A 'mid-level' vision of reading: The 44th Sir Frederic Bartlett Lecture. *The Quarterly Journal of Experimental Psychology, 71,* 335–359. http://dx.doi.org/10.1080/17470218.2017.1314515

Grainger, J., Granier, J. P., Farioli, F., Van Assche, E., & van Heuven, W. J. B. (2006). Letter position information and printed word perception: The relative-position priming constraint. *Journal of Experimental Psychology: Human Perception and Performance, 32,* 865–884. http://dx.doi.org/10.1037/0096-1523.32.4.865

Grainger, J., & Holcomb, P. J. (2009). Watching the word go by: On the time-course of component processes in visual word recognition. *Language and Linguistics Compass, 3,* 128–156. http://dx.doi.org/10.1111/j.1749-818X.2008.00121.x

Grainger, J., & Jacobs, A. M. (1993). Masked partial-word priming in visual word recognition: Effects of positional letter frequency. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 951–964. http://dx.doi.org/10.1037/0096-1523.19.5.951

Grainger, J., & Van Heuven, W. J. B. (2003). Modeling letter position coding in printed word perception. In P. Bonin (Ed.), *The mental lexicon*. New York, NY: Nova Science.

Koriat, A., & Norman, J. (1985). Reading rotated words. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 490–508. http://dx.doi.org/10.1037/0096-1523.11.4.490

Lavidor, M. (2002). An examination of the lateralized abstractive/form specific model using MiXeD-CaSe primes. *Brain and Cognition, 48*(2–3), 413–417.

Legge, G. E., Ahn, S. J., Klitz, T. S., & Luebker, A. (1997). Psychophysics of reading—XVI. The visual span in normal and low vision. *Vision Research, 37,* 1999–2010. http://dx.doi.org/10.1016/S0042-6989(97)00017-5

Levy, R. (2014). Using R formulae to test for main effects in the presence of higher-order interactions. arXiv:1405.2094v2 [stat.ME]. Retrieved from https://arxiv.org/pdf/1405.2094.pdf

Lo, S., & Andrews, S. (2015). To transform or not to transform: Using generalized linear mixed models to analyse reaction time data. *Frontiers in Psychology, 6,* 1171. http://dx.doi.org/10.3389/fpsyg.2015.01171

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. http://dx.doi.org/10.1037/a0028450

Norris, D., Kinoshita, S., & van Casteren, M. (2010). A stimulus sampling theory of letter identity and order. *Journal of Memory and Language, 62,* 254–271. http://dx.doi.org/10.1016/j.jml.2009.11.002

Perea, M., Jiménez, M., & Gómez, P. (2014). A challenging dissociation in masked identity priming with the lexical decision task. *Acta Psychologica, 148,* 130–135. http://dx.doi.org/10.1016/j.actpsy.2014.01.014

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

Perea, M., Vergara-Martínez, M., & Gomez, P. (2015). Resolving the locus of cAsE aLtErNaTiOn effects in visual word recognition: Evidence from masked priming. *Cognition, 142,* 39–43. http://dx.doi.org/10.1016/j.cognition.2015.05.007

R Core Team. (2015). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://cran.r-project.org/doc/manuals/r-release/R-ints.html

Risko, E. F., Medimorec, S., Chisholm, J., & Kingstone, A. (2014). Rotating with rotated text: A natural behavior approach to investigating cognitive offloading. *Cognitive Science, 38,* 537–564. http://dx.doi.org/10.1111/cogs.12087

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime: User's guide*. Pittsburgh, PA: Psychology Software Tools.

Schoonbaert, S., & Grainger, J. (2004). Letter position coding in printed word perception: Effects of repeated and transposed letters. *Language and Cognitive Processes, 19,* 333–367. http://dx.doi.org/10.1080/01690960344000198

Singmann, H., & Kellen, D. (2017). An Introduction to Mixed Models for Experimental Psychology. In D. Spieler & E. Schumacher (Eds.), *New methods in neuroscience and cognitive psychology* (pp. 1–39). Hove, England: Psychology Press. Retrieved from https://cran.r-project.org/web/packages/afex/vignettes/introduction-mixed-models.pdf

Van Selst, M., & Jolicoeur, P. (1994). A Solution to the Effect of Sample Size on Outlier Elimination. *The Quarterly Journal of Experimental Psychology, 47,* 631–650. http://dx.doi.org/10.1080/14640749408401131

Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin & Review, 8,* 221–243. http://dx.doi.org/10.3758/BF03196158

Whitney, C. (2002). An explanation of the length effect for rotated words. *Cognitive Systems Research, 3,* 113–119. http://dx.doi.org/10.1016/S1389-0417(01)00050-X

Whitney, C. (2018). When serial letter processing implies a facilitative length effect. *Language, Cognition and Neuroscience, 33,* 659–664. http://dx.doi.org/10.1080/23273798.2017.1404115

Whitney, C., & Marton, Y. (2013). *The SERIOL2 model of orthographic processing*. Advance online publication. Retrieved from http://eric.ed.gov/?id=ED543279

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. http://dx.doi.org/10.1037/a0022194

# Appendix

## Word and Nonword Stimuli Used in Experiments 1 and 2

| Word target | TL Prime | SL prime | Nonword target | TL Prime | SL prime |
|---|---|---|---|---|---|
| PROVE | porve | pamve | POUGH | poguh | posih |
| DREAM | deram | dulam | GOUTH | gotuh | gosih |
| FRUIT | furit | fohit | JEIST | jesit | jecut |
| SMOKE | somke | sarke | DOISE | dosie | dozae |
| PLAIN | palin | pehin | LOUCH | locuh | loreh |
| SHOCK | sohck | salck | HEIZE | hezie | hesae |
| PROUD | porud | penud | BLORE | blroe | blgue |
| CHEAP | cehap | corap | LOAST | losat | locit |
| PLATE | palte | puhte | VOUGH | voguh | vojah |
| TREAT | terat | tolat | PLICE | plcie | plbee |
| CREAM | ceram | cowam | TOGUE | touge | toake |
| CHAIN | cahin | curin | BRILE | brlie | brfoe |
| JOINT | jonit | jolut | SPAIL | sapil | sotil |
| FAULT | falut | fagot | THEAD | tehad | tutad |
| GUILT | gulit | gudet | STOAL | sotal | siral |
| TOUGH | toguh | tonih | STEAN | setan | siran |
| GUIDE | gudie | gucae | PRAIL | paril | pehil |
| FAINT | fanit | famut | GRITE | girte | galte |
| COACH | cocah | cosuh | SHERE | sehre | sorre |
| MOUNT | monut | morit | SLAIR | salir | sorir |
| PAUSE | pasue | pacoe | BRONE | borne | bulne |
| WOUND | wonud | worad | CROVE | corve | cunve |
| GUEST | guset | gulat | DRUDE | durde | dinde |
| BEARD | berad | becud | GRUTE | gurte | gilte |
| SHORE | sohre | sacre | GUTCH | gucth | gurnh |
| SHADE | sahde | sirde | CHIRM | chrim | chlum |
| SHAME | sahme | sonme | SNART | snrat | snmit |
| SCORE | socre | sarre | CHULK | chluk | chtok |
| PRIZE | pirze | palze | GLIMB | glmib | glcub |
| BENCH | bnech | blach | PLOTH | pltoh | plnuh |
| BRAVE | barve | butve | GLUCK | glcuk | glmik |
| TRACE | tarce | tolce | GLUNK | glnuk | glgak |
| SNAKE | sanke | solke | CRIMB | crmib | crceb |
| STAKE | satke | sidke | RODGE | rogde | rorle |
| SCOPE | socpe | suspe | HETCH | hecth | hesdh |
| SLAVE | salve | sihve | FLIRK | flrik | flwok |
| TASTE | tatse | tadce | SLUNT | sulnt | sornt |
| FLESH | flseh | flrah | GLASH | galsh | gutsh |
| TRUCK | trcuk | trtok | FLUMP | fulmp | fermp |
| CLERK | clrek | clcuk | GLURP | gulrp | gabrp |
| DEPTH | detph | denlh | TRUSH | tursh | tilsh |
| FENCE | fecne | fesle | SPACK | sapck | sibck |
| TREND | trned | trvid | DRIRK | dirrk | dulrk |
| GROSS | grsos | grcas | SCIFF | sicff | sohff |
| SOLVE | sovle | sosre | PLUFF | pulff | porff |
| SMART | smrat | smlit | THILL | tihll | terll |
| FLASH | flsah | flrih | CHORT | cohrt | ciprt |
| STRIP | stirp | stacp | BLICK | bilck | borck |
| SKILL | sikll | sojll | GRAWN | grwan | grgen |
| SPLIT | slpit | srbit | PROCK | prcok | prmak |
| BLIND | bilnd | behnd | TURGE | tugre | tunle |
| CLOCK | colck | circk | SLAMP | slmap | slrep |
| SHIFT | sihft | sarft | TRANT | trnat | trsot |
| HENCE | hnece | hmoce | SHARF | shraf | shlef |
| SWING | siwng | sotng | BISER | biesr | biacr |
| GRANT | garnt | gilnt | LOVEN | loevn | loawn |
| SHELL | sehll | sibll | CRECK | crcek | crlak |
| STORM | sotrm | sulrm | TRONG | trnog | trmig |

(*Appendix continues*)

Appendix (*continued*)

| Word target | TL Prime | SL prime | Nonword target | TL Prime | SL prime |
|---|---|---|---|---|---|
| STIFF | sitff | serff | SNART | snrat | sngot |
| FIFTH | ffith | ftoth | BLILD | bllid | bltud |
| QUICK | qucik | qusek | DRAID | darid | delid |
| BEACH | becah | benuh | PRAIN | parin | polin |
| NOISE | nosie | nogue | TREAK | terak | tulak |
| BOUND | bonud | bosad | BLIEF | bilef | bahef |
| LAUGH | laguh | lasih | BRUNE | burne | bolne |
| COAST | cosat | cocet | CHAVE | cahve | curve |
| RAISE | rasie | rague | SLUTE | sulte | sarte |
| TEACH | tecah | tenuh | BRUEL | burel | balel |
| ROUGH | roguh | rotah | DRAIL | daril | dolil |
| POUND | ponud | pomid | FLEAK | felak | forak |
| ROUTE | rotue | ronie | GLAIN | galin | gepin |
| PAINT | panit | palut | FLEAD | felad | fuhad |
| CLOUD | colud | carud | PROKE | prkoe | prjue |
| SWEAT | sewat | sipat | PLORE | plroe | plsae |
| GRAIN | garin | gehin | KNOUT | knuot | knaet |
| TRAIL | taril | tupil | GLAST | glsat | glnit |
| SPITE | sipte | salte | PLEND | plned | plmud |
| CRIME | cirme | cohme | GLIND | glnid | glcud |
| SPARE | sapre | sirre | PLUNT | plnut | plcit |
| BLAME | balme | bihme | GOTCH | gocth | gonlh |
| CHOSE | cohse | carse | FRICK | frcik | frtek |
| GRAVE | garve | gohve | TRINK | trnik | trwok |
| THEME | tehme | tanme | BRITH | brtih | brceh |
| GRACE | garce | gohce | PROWN | prwon | prlin |
| YIELD | yiled | yigud | GRIVE | girve | gonve |
| SAUCE | sacue | sasoe | DRINE | dirne | dacne |
| VAGUE | vauge | vaije | SORGE | sroge | slage |
| TRUST | trsut | trcot | SCADE | sacde | sunde |
| THICK | thcik | thzek | DRAZE | darze | dolze |
| CROSS | crsos | crles | SNAZE | sanze | sutze |
| WASTE | watse | wafce | TRAKE | tarke | totke |
| SMELL | smlel | smtil | STELL | setll | sarll |
| STUFF | stfuf | stsef | STORT | sotrt | surrt |
| BIRTH | bitrh | bicdh | DIGHT | dgiht | druht |
| GUESS | guses | gutas | TRULL | turll | tahll |
| MATCH | macth | masdh | CRUNK | curnk | calnk |

*Note*. Due to a programming error, the nonword target SNART was presented twice.

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