

Reading with letter transpositions in central and peripheral vision

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We used a letter transposition (LT) technique to investigate letter position coding during reading in central and peripheral vision. Eighteen subjects read aloud sentences in a rapid serial visual presentation task. The tests contained a baseline and three LT conditions with initial, internal, and final transpositions (e.g., “reading” to “erading”, “raeding”, and “readign”). The four reading conditions were tested in separate blocks. We found that LT had a smaller cost on peripheral (10° lower field) than on central reading speed, possibly due to the higher intrinsic position uncertainty of letters in the periphery. The pattern of cost (initial > final > internal) was the same for central and peripheral vision, indicating a similar lexical route for both. In the periphery, LT only affected transposed words, while in central vision it also affected untransposed words. This spread of the LT effect in central vision could not be accounted for by increased attention or memory load, or by decreased sentence context.

reading speed), followed by transpositions of final letters (26% decrease), and lastly by transpositions of internal letters (12% decrease), providing insight into the process for lexical access.

These empirical findings focused on reading with central vision. The impact of LTs on peripheral reading is not yet known. Reading with peripheral vision is important for understanding the pattern-recognition capabilities across the visual field. It is also important for understanding the problems faced by low-vision patients with central vision loss who must read with their peripheral vision (Legge, Ross, Isenberg, & LaMay, 1992; Fletcher, Schuchard, & Watson, 1999). It is well-known that peripheral reading is slower and much more effortful than central reading, but the reasons are not fully understood (Rayner & Bertera, 1979; Legge, Mansfield, & Chung, 2001). For example, when the reduced visual acuity in peripheral vision is compensated with enlarged print, or when difficulty with reading eye movements is minimized with rapid serial visual presentation (RSVP), slower reading in peripheral vision persists (Rubin & Turano, 1994; Chung, Mansfield, & Legge, 1998). Therefore, understanding the limiting factors for peripheral reading is of both practical and theoretical significance.

We used the LT technique as a probe to compare letter position coding during reading in central and peripheral vision. We focused on three issues: (a) Whether the cost of LT on reading speed is quantitatively similar in peripheral and central vision. We hypothesized that LT would have smaller impact on peripheral reading due to the higher intrinsic position uncertainty in peripheral vision (Pelli, 1985; Chung & Legge, 2009). (b) Whether the pattern of LT (initial > final > internal) cost on reading speed is the same in peripheral and central vision. This would be expected if the

Introduction

In 2004, an internet hoax claimed that reading with transposed letters within words is easy, and therefore letter position coding was not important for reading. However, a subsequent study showed that letter transpositions (LTs) always reduce reading speed (Rayner, White, Johnson, & Liversedge, 2006; White, Johnson, Liversedge, & Rayner, 2008). Specifically, when subjects silently read through continuous text, reading speed significantly slowed down when the positions of adjacent letters in words were switched, indicating that letter position is actually important for efficient reading. They found that transpositions of initial letters had the greatest cost (a 36% decrease of

Citation: Xiong, Y.-Z., Qiao, C., & Legge, G. E. (2019). Reading with letter transpositions in central and peripheral vision. *Journal of Vision*, 19(3):17, 1–8, <https://doi.org/10.1167/19.3.17>.

<https://doi.org/10.1167/19.3.17>

Received December 12, 2018; published March 29, 2019

ISSN 1534-7362 Copyright 2019 The Authors



process of lexical access is similar, as indicated in previous behavioral and fMRI studies (Lee, Legge, & Ortiz, 2003; Yu, Jiang, Legge, & He, 2015). (c) As an exploratory question, we asked whether the impact of LT is specific to the transposed words or also spreads to untransposed words. Previous studies focused on the reduction of reading speed in the LT conditions. However, it is not yet known whether the reduction of reading speed is due entirely to slower processing of the transposed words, or if the detrimental effects also spread to processing of untransposed words. In short, we have used LT as a probe for comparing three aspects of reading in central and peripheral vision: spatial encoding of single letters, lexical access of words, and between-word interactions.

To answer these questions, we made two important methodological changes from previous LT studies. First, we presented sentences word-by-word via the RSVP method to minimize eye movements during reading. This was important for tests of reading in peripheral vision because subjects are not familiar with targeting reading saccades to nonfoveal retinal locations. Second, subjects were asked to read the sentences aloud, which permitted analysis of accuracy for both transposed and untransposed words.

Method

Subjects

Native English speakers ($N = 18$; mean age 21.4 years, range from 18 to 34 years) were recruited from the University of Minnesota. To achieve 80% power at $p = 0.05$, for a large LT effect size (Cohen's d) of 0.8 when comparing reading speed in baseline and LT conditions, a sample size of 15 would be required. We used a sample size of 18. All subjects had normal or corrected-to-normal vision and had no known reading disorders. This study was approved by the University of Minnesota Institutional Review Board and followed the Declaration of Helsinki. Consent forms were acquired from all subjects prior to their participation in this study.

Apparatus and stimuli

Stimulus sentences for all tasks were black letters (luminance 1.9 cd/m^2) on a white background (luminance 298.5 cd/m^2). Letters were rendered in Times New Roman font. Sentences were generated by Psychtoolbox 3.0 with MATLAB (R2010a; MathWorks, Natick, MA) on a NEC MultiSync CRT monitor (refresh rate = 100 Hz, resolution = $1680 \times$

Condition	Sample sentence
Baseline	She was ready for a piece of his famous chocolate cream pie.
Initial	She was erady for a ipece of his afmous hcocolate rcream pie.
Internal	She was raedy for a picee of his famuos chocloate craem pie.
Final	She was reayd for a pieec of his famosu chocolaet crema pie.

Table 1. Sample sentences in the RSVP task.

1050 pixels). In the RSVP task, a chinrest was used to stabilize the subject's head, and a webcam was used to monitor the subject's eye movements. A similar method was shown to reliably detect saccades that exceed 2° (Cheong, Legge, Lawrence, Cheung, & Ruff, 2007). The RSVP test was conducted binocularly at a 40-cm viewing distance.

The sentences used in the RSVP task were selected from the sentence database used in a previous RSVP study (Chung et al., 1998). The RSVP database was generated using high-frequency vocabulary, with sentence length ranging from nine to 13 words. Each sentence was randomly assigned to one of the following four conditions: (a) initial transposition, in which the first two letters of the word exchanged their position (e.g., "reading" vs. "erading"); (b) internal transposition, in which two randomly selected neighboring letters in the middle of the word exchanged their position (e.g., "reading" vs. "reaidng"); (c) final transposition, in which the last two letters of the word exchanged their position (e.g., "reading" vs. "readign"); and (d) baseline condition with no transpositions (Table 1). LT manipulations were only applied to words consisting of at least five letters. A sentence was selected only if four to five words met this criterion for LT manipulation. In LT conditions, sentences were rejected if transposed words formed new words (e.g., "dairy" \rightarrow "diary"). As a result, the base words were always transposed into nonwords. For all three LT conditions, an average 41% of the words were transposed.

Procedure

Before the reading test, subjects were told that "Some of the words are strangely spelled. Please try to guess what the original words are and read it accordingly." Subjects were then shown examples of RSVP trials in both central and peripheral conditions. Subjects were required to read the sentences aloud throughout the test; they didn't have to track the high-speed presentation by speech and could complete reading the sentence after the RSVP sequence was

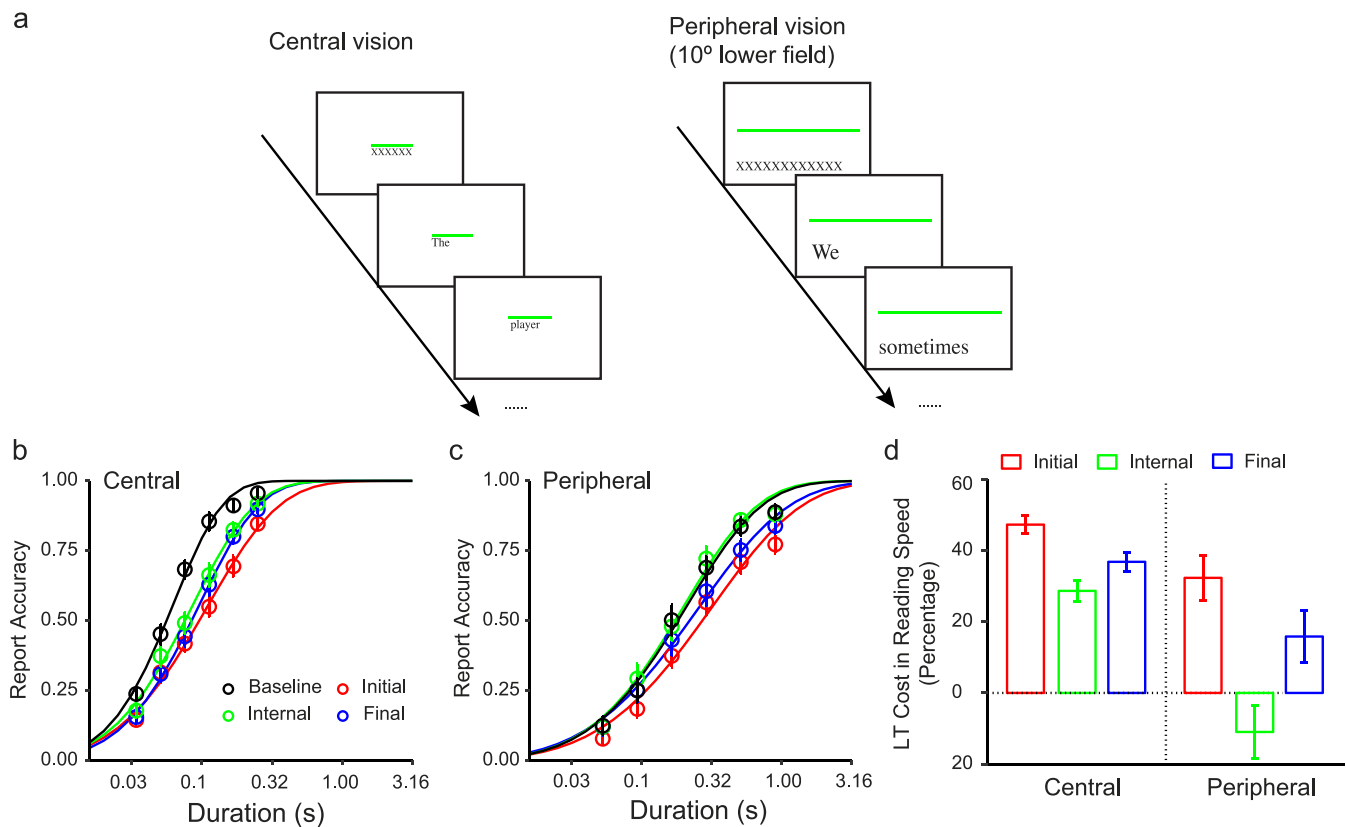


Figure 1. The procedure of an RSVP trial (a) and the LT cost on RSVP reading speed (b–d). An RSVP sentence was displayed in a word by word manner, the words were left-justified with a row of “x” preceding and following the sentence. The sentences were presented at the center of the screen in central reading and at 10° eccentricity in the lower visual field in peripheral reading. Panel (b) and panel (c) show the group average RSVP reading curves in central and peripheral vision, respectively. Panel (d) shows the average LT cost in LT conditions, which was calculated as the percentage decrease of reading speed compared to baseline. Error bars represent ± 1 SE.

finished. The experimenter marked the incorrect and missed words on a recording sheet. LT transposed words were considered correct if they were reported as the base words.

In a RSVP trial, subjects pressed the spacebar to initiate a sentence. A RSVP sentence was displayed in a word by word manner, the words were left-justified with a row of “x” as the premask and postmask (Figure 1a). In each block six word-exposure times (central reading: 34, 51, 76, 113, 168, and 250 ms; peripheral reading: 53, 93, 165, 290, 511, and 900 ms) were measured in a random order, each tested eight times. In central reading, the sentences were presented at the center of the screen, and the letter size was fixed at 0.5°. In peripheral reading, the sentences were presented at 10° eccentricity in the lower visual field, and the letter size was fixed at 3.5°. Note that letter sizes were determined as approximately 2.5 times the critical print size in central and peripheral reading respectively (Chung et al., 1998). In peripheral reading, subjects were allowed to move their eyes along a fixation line in the middle of the screen; however, a trial was discarded if a vertical eye movement was observed. A total of

1.5% of the trials were discarded. Eight blocks were tested, with each reading conditions tested once in both central and peripheral vision in a random order. Subjects were not told the reading condition before each block started.

Data analyses

The RSVP reading speed was calculated based on the percentage of words read correctly in each sentence (Chung et al., 1998). Specifically, the word report accuracy was obtained at each exposure duration. Individual psychometric functions (accuracy vs. duration) were fitted by a Weibull function (Zhang, Zhang, Liu, & Yu, 2012). Duration thresholds (second per word) were calculated as the duration yielding 80% accuracy. RSVP reading speed (word per minute [wpm]) was then calculated from the duration threshold (60/threshold). (See Supplementary Figure S1 for individual psychometric functions.)

Because subjects were required to read aloud, the report accuracies could be tracked for both transposed and untransposed words. The accuracies of transposed and untransposed words were obtained at each exposure duration in the LT conditions. Although no transposition was applied to the baseline condition, two baseline accuracies were obtained from words that had the same lengths as the transposed words (≥ 5 letters) and untransposed words (< 5 letters), respectively.

The main statistical analysis (unless otherwise specified) was a repeated measures analysis of variance (ANOVA). Significant main effects were followed by a post hoc analysis with Bonferroni adjustment.

Results

LT effects on RSVP reading speed

In central vision, the reading speed in the baseline condition was 577 wpm, it decreased by 277 wpm (equivalent to a 48.0% decrement) in the initial condition, $t(17) = 14.85$, $p < 0.001$, Cohen's $d = 3.50$, 95% confidence interval (CI) = [0.02, 0.24], two-tailed t test on reading speed (log wpm), by 170 wpm (29.5%) in the internal condition, $t(17) = 8.41$, $p < 0.001$, Cohen's $d = 1.98$, 95% CI = [0.02, 0.11], and by 216 wpm (37.5%) in the final condition, $t(17) = 11.99$, $p < 0.001$, Cohen's $d = 2.83$, 95% CI = [0.02, 0.17] (Figure 1b).

In peripheral vision, the reading speed in the baseline condition was 147 wpm; it decreased by 55 wpm (37.6%) in the initial condition, $t(17) = 4.89$, $p < 0.001$, Cohen's $d = 1.15$, 95% CI = [0.12, 0.29], slightly increased by 9 wpm (–6.1%) in the internal condition, $t(17) = -0.77$, $p = 0.45$, Cohen's $d = 0.18$, 95% CI = [–0.09, 0.04], and decreased by 31 wpm (21.3%) in the final condition, $t(17) = 2.75$, $p = 0.014$, Cohen's $d = 0.65$, 95% CI = [0.02, 0.18] (Figure 1c).

We conducted a 2 (Eccentricity) \times 3 (LT Condition) ANOVA to compare the LT cost on reading speed (Figure 1d). The result showed a significant main effect of eccentricity, $F(1, 17) = 17.16$, $p = 0.001$, $\eta_p^2 = 0.50$, a significant main effect of the LT condition, $F(2, 34) = 22.57$, $p < 0.001$, $\eta_p^2 = 0.57$, and an interaction between the two, $F(2, 34) = 4.96$, $p = 0.013$, $\eta_p^2 = 0.23$. LT costs were larger in the center than the periphery in all three LT conditions (initial: $p = 0.042$, 95% CI = [0.01, 0.29]; internal: $p < 0.001$, 95% CI = [0.22, 0.57]; final: $p = 0.016$, 95% CI = [0.05, 0.38]). In central vision, the magnitude of LT costs followed the pattern: initial $>$ final $>$ internal (initial vs. final: $p < 0.001$, 95% CI = [0.05, 0.16]; initial vs. internal: $p < 0.001$, 95% CI = [0.10, 0.27]; final vs. internal: $p = 0.012$, 95% CI = [0.02, 0.15]). In peripheral vision, the magnitude of LT costs

also followed the same pattern, although not all pairwise comparisons were statistically significant (initial vs. final: $p = 0.17$, 95% CI = [–0.05, 0.38]; initial vs. internal: $p < 0.001$, 95% CI = [0.21, 0.66]; final vs. internal: $p = 0.017$, 95% CI = [0.04, 0.49]).

LT effects on transposed and untransposed words

Central vision

Figure 2a and c illustrate the report accuracies of transposed and untransposed words at the six durations. Overall accuracies were then obtained by pooling data at all durations. Figure 2b and d illustrate the overall accuracy reductions of transposed and untransposed words in LT conditions compared to the baseline condition.

For transposed words, the overall accuracies in all three LT conditions were significantly lower than the baseline condition (initial: $t[17] = 16.88$, $p < 0.001$, Cohen's $d = 3.98$, 95% CI = [0.21, 0.27]; internal: $t[17] = 12.29$, $p < 0.001$, Cohen's $d = 2.90$, 95% CI = [0.11, 0.16]; and final: $t[17] = 13.73$, $p < 0.001$, Cohen's $d = 3.24$, 95% CI = [0.14, 0.20]). A one-way ANOVA showed a significant main effect of LT conditions on the accuracy reductions, $F(2, 34) = 23.48$, $p < 0.001$, $\eta_p^2 = 0.58$ (Figure 2b). Pairwise comparisons on the accuracy reductions showed the pattern: initial $>$ final $>$ internal (initial vs. final: $p = 0.001$, 95% CI = [0.03, 0.11]; initial vs. internal: $p < 0.001$, 95% CI = [0.06, 0.15]; final vs. internal: $p = 0.025$, 95% CI = [0.004, 0.07]).

For untransposed words, the overall accuracies in all three LT conditions were also significantly lower than the baseline condition (initial: $t[17] = 10.36$, $p < 0.001$, Cohen's $d = 2.44$, 95% CI = [0.12, 0.18]; internal: $t[17] = 5.44$, $p < 0.001$, Cohen's $d = 1.28$, 95% CI = [0.05, 0.12]; and final: $t(17) = 10.12$, $p < 0.001$, Cohen's $d = 2.39$, 95% CI = [0.10, 0.15]). Again, a one-way ANOVA showed a significant main effect of LT conditions on the accuracy reductions, $F(2, 34) = 10.57$, $p < 0.001$, $\eta_p^2 = 0.38$. The accuracy reduction followed a similar pattern to transposed words: initial $>$ final $>$ internal (initial vs. final: $p = 0.10$, 95% CI = [–0.004, 0.05]; initial vs. internal: $p = 0.022$, 95% CI = [0.02, 0.10]; final vs. internal: $p = 0.06$, 95% CI = [–0.002, 0.07]).

Peripheral vision

Figure 2e and g illustrate the report accuracies of transposed and untransposed words at the six durations. Figure 2f and h illustrate the overall accuracy reductions of transposed and untransposed words in LT conditions.

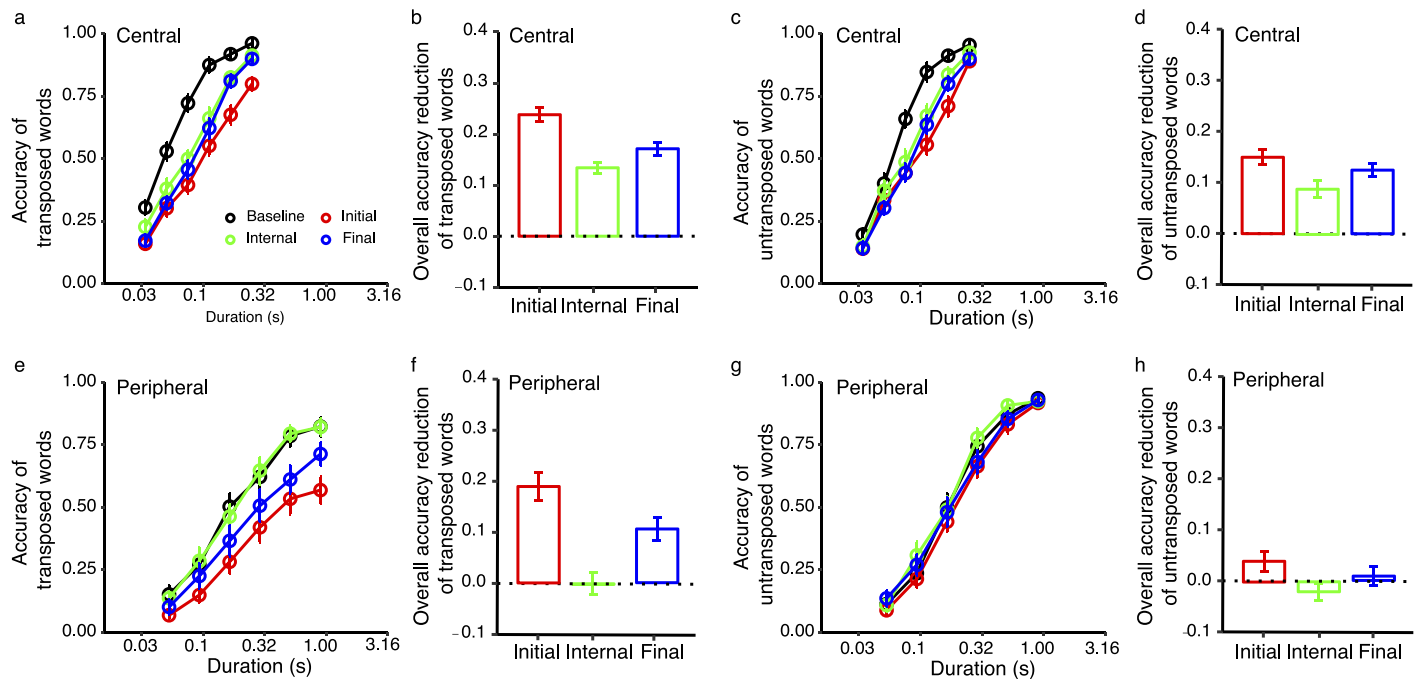


Figure 2. LT effect on report accuracies of transposed and untransposed words. The report accuracies of transposed words and untransposed words were obtained in central (a and c) and peripheral (e and g) vision. The overall accuracy reduction of transposed and untransposed words as compared to baseline condition, were then obtained for both central (b and d) and peripheral (f and h) vision. Error bars represent ± 1 SE.

For transposed words, the overall accuracies in initial condition and final condition, but not internal condition were significantly lower than the baseline condition (initial: $t[17] = 6.82$, $p < 0.001$, Cohen's $d = 1.61$, 95% CI = [0.13, 0.25]; internal: $t[17] = 0.04$, $p = 0.97$, 95% CI = [-0.04, 0.05]; and final: $t[17] = 4.73$, $p < 0.001$, Cohen's $d = 1.11$, 95% CI = [0.06, 0.15]). ANOVA showed a significant main effect of LT conditions on the accuracy reductions, $F(2, 34) = 23.15$, $p < 0.001$, $\eta_p^2 = 0.58$. The accuracy reduction showed the pattern: initial > final > internal (initial vs. final: $p = 0.063$, 95% CI = [-0.004, 0.17]; initial vs. internal: $p < 0.001$, 95% CI = [0.12, 0.26]; final vs. internal: $p < 0.001$, 95% CI = [0.05, 0.16]).

For untransposed words, there were no significant reductions in the overall accuracies in any of the LT conditions (initial: $t[17] = 2.06$, $p = 0.06$, 95% CI = [-0.001, 0.08]; internal: $t(17) = -1.15$, $p = 0.27$, 95% CI = [-0.05, 0.02]; final: $t[17] = 0.45$, $p = 0.66$, 95% CI = [-0.03, 0.05]).

Discussion

This study used a LT technique to explore the impact of letter positions on reading speed in central and peripheral vision. To briefly summarize our major findings, the results showed that the LT cost on reading

speed was smaller in peripheral vision than in central vision, but the pattern of LT cost was similar: initial > final > internal. In central vision LT affected the recognition accuracy of both transposed and untransposed words, while in peripheral vision LT only affected transposed words.

The smaller LT effect in peripheral vision is consistent with our hypothesis that position uncertainty for letters in peripheral vision is intrinsically high and is therefore less sensitive to LT (Pelli, 1985; Chung & Legge, 2009). An alternative possibility is that the slower reading speed in peripheral vision allows longer time for lexical processing. This possibility would be predicted by a simple model in which word-reading times (and hence reading speed) is determined only by lexical access time. If this is true, slower readers should also show smaller LT cost than faster readers. Although our subjects showed a wide range of baseline reading speed, we did not find a significant correlation between LT costs and baseline reading speed, in either central or peripheral vision (central vision: initial ($r = -0.05$, $p = 0.86$), internal ($r = 0.15$, $p = 0.55$), final ($r = 0.18$, $p = 0.47$); peripheral vision: initial ($r = 0.36$, $p = 0.14$), internal ($r = 0.32$, $p = 0.20$), final ($r = -0.03$, $p = 0.91$)).

The effect of internal transpositions was almost absent in peripheral reading. It is plausible to associate this result with the crowding effect in letter recognition in peripheral vision. Crowded letters lose considerable

position and identity information (Levi, 2008; Zhang et al., 2012; Strasburger & Malania, 2013; Xiong, Yu, & Zhang, 2016). In peripheral vision internal letters of words have extra position uncertainty from crowding and are thus less sensitive to LT manipulation; it is also likely that reduced access to identity information renders internal letters less reliable for word recognition. If the latter case is true, a future study eliminating the identity of internal letters, e.g., by substituting the internal letters (letter substitution), should have similar impact on reading as exchanging the positions of internal letters (LT). This approach has been used to study letter coding in central vision (Chambers, 1979; O'Connor & Forster, 1981; Perea & Lupker, 2003a, 2003b; Christianson, Johnson, & Rayner, 2005).

In both central and peripheral vision, the LT cost on reading speed followed the same rank order: initial > final > internal. This result is consistent with previous findings that exterior, especially initial letters, are more crucial than interior letters in word recognition and reading (Estes, Allmeyer, & Reder, 1976; Chambers, 1979; Rayner et al., 2006; White et al., 2008). In central vision, we found a larger LT cost on reading speed than Rayner et al. (2006; initial: 48% vs. 36%; internal: 30% vs. 12%; final: 38% vs. 26%); the discrepancy is likely due to differences between the two studies in the testing protocol (static sentence vs. RSVP), reading manner (silent vs. oral), and reading speed calculation method (based on eye movement vs. word report accuracy).

The qualitatively similar pattern of LT cost in central and peripheral vision supports our hypothesis that peripheral reading follows the same route of lexical access in the two cases. It's known that the visual word form area, which plays a fundamental role in word recognition, has a response bias for text presented in central vision (Cohen & Dehaene, 2004; Rauschecker, Bowen, Parvizi, & Wandell, 2012). Therefore, it's possible that the lexical access for words presented in peripheral vision would show a different pattern from central vision. However, in a previous study comparing lexical decisions in central and peripheral vision (Lee et al., 2003), the authors found that lexical decisions are slower in peripheral vision but show a similar word frequency effect (i.e., faster reaction times for high-frequency words than for low-frequency words), indicating that lexical processing in peripheral vision is qualitatively similar to central vision. Our current finding now provides new behavioral evidence for similar lexical processing in central and peripheral reading.

Surprisingly, LT also imposed a cost on untransposed word recognition in central reading. This was a serendipitous finding which emerged during data analysis. We recognize that in our study, the transposed and untransposed words did not have equal proportions (transposed words: 41%, untransposed words:

59%) and lengths (transposed words: >5 letters, untransposed words: <5). Given this limitation, we can't be sure that the LT effect would apply to longer untransposed words. The LT cost in untransposed words was qualitatively similar to transposed words in that its magnitude followed the same pattern: initial > final > internal (Figure 2c). It appears that the LT effect spreads from the transposed words to intact words in sentence reading.

Why does the LT effect spread to untransposed words in central vision? One possibility is that LT interferes with the sentence context, thereby accounting for reduced accuracy for both transposed and untransposed words. However, this possibility would predict LT effects on untransposed words in both central and peripheral vision, since there is evidence showing that both central and peripheral reading benefit from sentence context (Fine & Peli, 1996; Latham & Whitaker, 1996; Fine, Hazel, Petre, & Rubin, 1999). Our results show clear evidence that there was no significant LT effect on untransposed words in peripheral vision, which casts doubt on this possibility. Further, the absence of the spread of the LT effect in peripheral reading was unlikely due to the smaller LT effect on transposed words, because in the initial condition the LT effect on transposed words should have been large enough to spread to untransposed words (Figure 2f and h).

Another possibility is that lexical processing of the transposed words requires more cognitive resources (e.g., attention or working memory), which hinders the processing of subsequent untransposed words. If this is true, the LT effect should be most prominent on those untransposed words that immediately follow transposed words. To test this possibility, we separated untransposed words into two groups based on whether they immediately followed a transposed word. For both groups of untransposed words, accuracy reductions in LT conditions were calculated and compared to the baseline condition (Figure 3). There were no significant differences between the accuracy reduction in the two groups of untransposed words in both central and peripheral reading (central: $F[1, 17] = 2.90, p = 0.11, \eta_p^2 = 0.15$; peripheral: $F[1, 17] = 1.50, p = 0.24, \eta_p^2 = 0.08$). The presence of the "spread" of LT effect in central reading, and the absence of it in peripheral reading, need to be investigated in future studies.

Conclusions

We used LTs as a probe to investigate spatial encoding of single letters, lexical access of words, and between-word interactions in central and peripheral reading. We found that peripheral reading has less

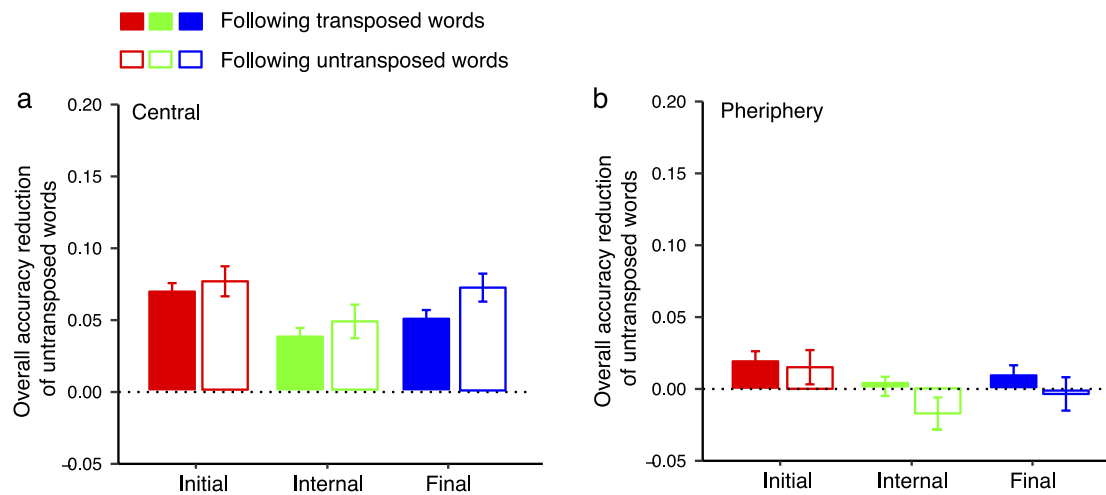


Figure 3. Decomposition of LT effect on untransposed words in central (a) and peripheral reading (b). Overall accuracy reduction across all exposure durations was obtained in initial, internal, and final conditions. The solid bars represent untransposed words immediately following a transposed word, and the hollow bars represent untransposed words immediately following an untransposed word. Error bars represent ± 1 SE.

precise letter encoding, similar lexical access and less between-word interactions than central reading. Our findings extend our understanding of the differences between pattern recognition in central and peripheral reading.

Keywords: reading, letter transposition, central vision, peripheral vision

Acknowledgments

This research was supported by NIH grant EY002934.

Commercial relationships: none.

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