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Not all visual features are created equal: Early processing in letter and word recognition

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In four experiments, we investigated the effect of deleting specific features of letters on letter and word recognition in the context of reading aloud. Experiments 1 and 2 assessed the relative importance of vertices versus midsegments in letter recognition. Experiments 3 and 4 tested the relative importance of vertices versus midsegments in word recognition. The results demonstrate that deleting vertices is more detrimental to letter and word identification than is deleting midsegments of letters. These results converge with those of previous research on the role of vertices in object identification. Theoretical implications for early processing in reading are noted.

Most models of visual word recognition begin with a stage dubbed "feature processing" (e.g., Caramazza & Hillis, 1990; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; McClelland & Rumelhart, 1981; Paap, Newsome, McDonald, & Schvaneveldt, 1982; Perry, Ziegler, & Zorzi, 2007). In these models, activation of features leads to the activation of letters, which in turn activates word-level representations. Considerable evidence supports the idea that individual features represent the building blocks for letter and word recognition (e.g., Pelli, Burns, Farell, & Moore-Page, 2006; Rayner & Posnansky, 1978; Yap, Balota, Cortese, & Watson, 2006). In the present investigation, we assess the relative importance of different types of features in letter and word recognition.

Feature processing typically has been studied using confusion matrices generated from letter recognition experiments. Analysis of confusion matrices allows researchers to identify various features used in letter recognition (see Gervais, Harvey, & Roberts, 1984; Gibson, 1965; Gibson, Gibson, Pick, & Osser, 1962; Townsend, 1971; Townsend, Hu, & Kadlec, 1988). Such features typically include simple line segments of varying orientations or curvatures and intersections (Gibson, 1965, 1969; Gibson et al., 1962). Although confusion matrices provide an indication of which features are used in letter and word recognition, they are limited with respect to their ability to specify the relative importance of particular kinds of features (i.e., are some features more critical than others?).

To determine the relative importance of a given feature, various researchers have assessed the effect of altering that feature on recognition performance (e.g., Biederman, 1987; Fiset et al., 2008; Massaro & Hary, 1986; Naus & Shillman, 1976; Oden, 1979; Petit & Grainger, 2002). The relative importance of a given feature can be inferred by asking how its alteration affects the participant's performance relative to alterations of other features. Probably the best-known study that has used this approach is Biederman's work on object recognition. Biederman had participants identify objects with deletions at midsegments or vertices. The removal of vertices was more detrimental to object recognition than was the removal of midsegments. Previous research suggests that a similar result may occur in the context of letter and word recognition (e.g., Gibson, 1969; Gibson et al., 1962; Schomaker & Segers, 1999). For example, Schomaker and Segers demonstrated that participants were more likely to use "crossings" when trying to identify degraded handwritten words.

In the present investigation, we extend Biederman's (1987) results to letter and word recognition. Specifically, we set out to test, in the context of letter and word recognition, the relative importance of vertices versus midsegments. Most centrally, if feature processing in object recognition and in letter and word recognition is governed by the same principles, the deletion of vertices should be more detrimental to letter and word recognition than is the removal of midsegments.

EXPERIMENT 1
Letter Identification

Participants named single letters presented at the center of the screen. The letter was presented intact, with vertices removed, or with midsegments removed.

Method

Participants. Twenty-four undergraduate students received either $5 each or course credit for participating.

Apparatus. E-Prime experimental software (Schneider, Eschman, & Zuccolotto, 2002) controlled timing and presentation of stimuli and logged response time (RT) and accuracy. The stimuli

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Figure 1. Letter stimuli in Experiments 1–4 (intact vs. midsegment deletion vs. vertex deletion).

were presented on a 17-in. monitor with a 1,024 × 768 pixel resolution. Vocal RTs were recorded by a Plantronics microphone and a voice key.

Stimuli. The stimuli consisted of 23 letters. The letters *C*, *I*, *J*, *O*, *S*, and *U* were not used as experimental stimuli because they had no vertices in the Arial Narrow font. Three of these letters (*C*, *O*, and *S*) were used in the practice trials. Three versions of each letter were created: one without segment deletions, one with segment deletions at the vertices, and one with segment deletions at midsegments (see Figure 1). All vertices and all midsegments were removed from a letter across conditions.

Letters were created using Microsoft Paint. An equal number of pixels were removed in vertex and midsegment deletion conditions. Letters appeared in black on a white background in the center of the computer monitor. The letters appeared in a 27-point, Arial Narrow font. Each letter was 1.4 cm horizontal × 2.6 cm vertical.

Procedure. Each trial began with the presentation of a fixation cross (+) in the center of the screen for 500 msec. A letter was then presented at fixation and remained there until the participant made a vocal response, after which a blank screen was presented until the experimenter keyed in whether the response was accurate, at which time the fixation cross for the upcoming trial appeared.

Each participant received two blocks of trials following three practice trials. Each experimental block consisted of 60 letters. In each block, a letter was presented once intact, once with vertex deletions, and once with midsegment deletions. The stimuli within each block were randomized anew for each participant.

Results

Spoiled trials (e.g., those caused by microphone errors) were removed prior to analysis. RT analysis was conducted on trials in which the response was correct. These data were first subjected to a recursive trimming procedure that removed outliers on the basis of a cutoff criterion set independently for each participant in each condition by reference to the sample size in that condition (Van Selst & Jolicœur, 1994). The trimming procedure resulted in 1.6% of the RT data being discarded. Mean RT and percentage of error for each condition are presented in Figure 2. Correlated *t* tests for both participants and items tested the specific predictions regarding the role of vertices in letter recognition.

Relative to intact letters (465 msec), RTs were significantly slower in the midsegment deletion condition (476 msec) [$t_s(23) = 4.6$, $SE = 2.4$, $p = .001$; $t_i(19) = 4.44$, $SE = 2.54$, $p = .001$] and vertex deletion condition (483 msec) [$t_s(23) = 6.7$, $SE = 2.8$, $p = .001$; $t_i(19) =$

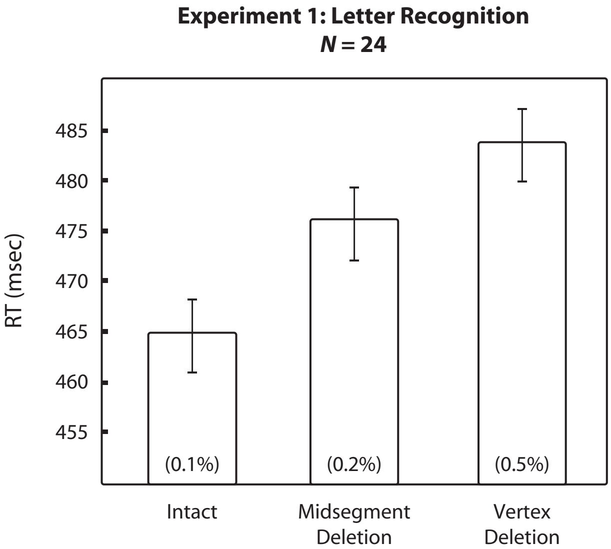

Figure 2. Response times (RTs, in milliseconds) and percentages of errors (in parentheses) as a function of letter type (intact vs. midsegment deletion vs. vertex deletion) in Experiment 1. Error bars represent the 95% confidence interval as defined by Masson and Loftus (2003).

5.82, $SE = 3.24$, $p = .001$]. Critically, RTs were significantly slower in the vertex deletion condition than in the midsegment deletion condition [$t_s(23) = 3.3$, $SE = 2.3$, $p = .003$; $t_i(19) = 2.28$, $SE = 3.33$, $p = .035$]. There were no significant effects in the error data (all ts < 1).

Discussion

The results of Experiment 1 demonstrate that removing vertices is more detrimental to letter recognition than is removing midsegments. This was true at both the participant and item levels. These results are consistent with Biederman's (1987) demonstration that the deletion of vertices is more detrimental than the deletion of midsegments in object recognition.

EXPERIMENT 2
Letter Identification With Brief Exposure

In Experiment 2, we again assessed the impact of removing vertices versus removing midsegments in letter identification, but, in an attempt to enhance the effect of removing vertices, the stimuli in Experiment 1 were presented briefly (50 msec). In Biederman's (1987) experiments the effect of vertex deletion *increased* as the presentation duration *decreased*.

Participants in Experiment 2 again named single letters presented at the center of the screen. The letter was presented intact, with vertices removed, or with midsegments removed. The critical difference between Experiment 2 and Experiment 1 was that the letter was now presented for 50 msec, rather than being response terminated.

Method

Participants. Twenty-four undergraduate students who had not taken part in the previous experiment participated in Experiment 2 for either $5 each or course credit.

Apparatus, Stimuli, and Procedure. The apparatus, stimuli, and procedure were the same as those in Experiment 2, except that the fixation cross was now presented for 350 msec, followed by a blank screen for 150 msec, and then the letters were presented for 50 msec.

Results

Data analysis followed the same procedure as that used in the previous experiment and resulted in the elimination of 2.1% of the RT data. Mean RT and percentage of error for each condition are presented in Figure 3. Correlated t tests for both participants and items tested the specific predictions regarding the role of vertices in letter recognition.

Relative to intact letters (415 msec), RTs were significantly slower in the midsegment deletion condition (425 msec) [$t_s(23) = 2.34$, $SE = 4.04$, $p = .028$; $t_i(19) = 1.90$, $SE = 6.36$, $p = .073$] (marginally significant) and the vertex deletion condition (435 msec) [$t_s(23) = 3.20$, $SE = 6.11$, $p = .004$; $t_i(19) = 3.50$, $SE = 10.55$, $p = .002$]. Critically, RTs were again significantly slower in the vertex deletion condition than in the midsegment deletion condition [$t_s(23) = 2.20$, $SE = 4.58$, $p = .038$; $t_i(19) = 2.24$, $SE = 11.11$, $p = .037$]. More errors were made in the vertex deletion condition (1.8%) than in the midsegment

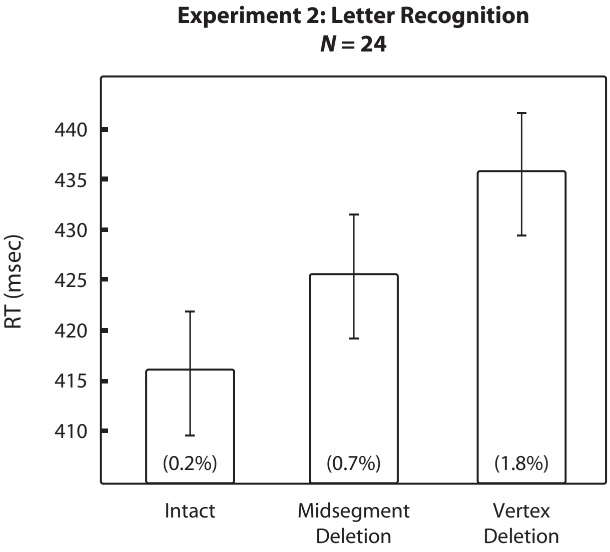

Figure 3. Response times (RTs, in milliseconds) and percentages of errors (in parentheses) as a function of letter type (intact vs. midsegment deletion vs. vertex deletion) in Experiment 2. Error bars represent the 95% confidence interval as defined by Masson and Loftus (2003).

deletion condition (0.7%) [$t_s(23) = 2.39$, $SE = 0.488$, $p = .025$; $t_i(19) = 2.56$, $SE = 0.67$, $p = .019$].

Discussion

Experiment 2 replicated Experiment 1 with letters presented briefly. Again, removing vertices from letters was more detrimental to naming letters aloud than was removing midsegments of letters. This effect was numerically larger than that in Experiment 1 and was significant in both RTs and errors, whereas the former was true only in Experiment 1. Again, the critical comparison between the midsegment and vertex deletion conditions was significant at the subject and item levels.

EXPERIMENT 3
Word Identification

In Experiment 3, we sought to extend the results in Experiments 1 and 2 to word recognition. Participants in Experiment 3 were asked to read aloud words presented at fixation. The words were composed of letters with either vertices or midsegments removed. The fact that a factor influences decontextualized letter identification does not imply that the same factor necessarily affects letter processing in the context of word identification. In word identification, there is contextual support in the form of feedback from the word level that may compensate for impaired letter-level processing (e.g., Massaro & Cowan, 1993; McClelland & Rumelhart, 1981).

Method

Participants. Thirty undergraduate students received either $5 or course credit for participating in Experiment 3.

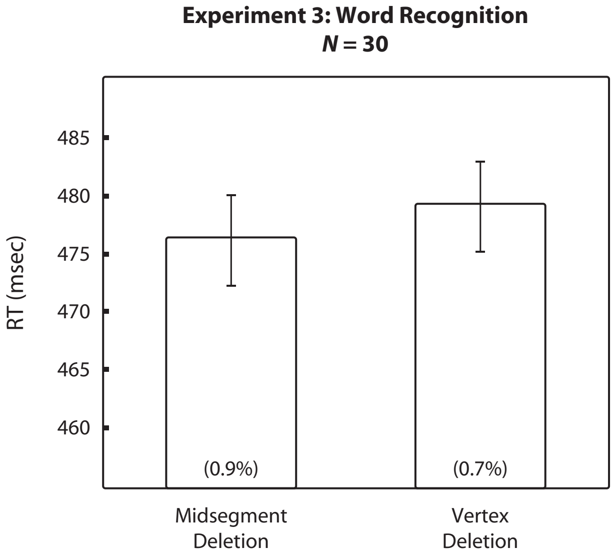

Figure 4. Response times (RTs, in milliseconds) and percentages of errors (in parentheses) as a function of letter type (midsegment deletion vs. vertex deletion) in Experiment 3. Error bars represent the 95% confidence interval as defined by Masson and Loftus (2003).

Apparatus. The same apparatus as that used in Experiments 1 and 2 was used in Experiment 3.

Stimuli. The experimental stimuli consisted of 80 four-letter words with Kučera–Francis (1967) word frequencies of 10–100. A different set of 8 words was used in the practice trials.

The words were created using the letters with vertex and midsegment deletions from Experiments 1 and 2. There were two conditions: letters with vertex segment deletions and letters with midsegment deletions. The 80 words were split into two 40-word lists, one for each condition. These lists were counterbalanced across participants, so that each word appeared only once in each condition. Each word therefore appeared only once for each participant during the experiment. Each word was approximately 6.4 cm horizontal $\times$ 2.6 cm vertical.

Procedure. Each trial began with the presentation of a fixation cross for 500 msec. The word was presented immediately after the fixation ended and was displayed until the participant made a vocal response, after which a blank screen appeared. The experimenter keyed in response accuracy, after which the fixation cross for the upcoming trial appeared.

The experiment consisted of two blocks of trials: an 8-trial practice block followed by the 80-trial experimental block. The entire experiment lasted approximately 5 min.

Results

Data analysis followed the same procedure as those in Experiments 1 and 2. Outlier elimination resulted in the removal of 1.7% of the RT data. Mean RTs and percentage of errors for each condition are presented in Figure 4. Correlated *t* tests for both participants and items tested the specific predictions regarding the role of vertices in word recognition.

RTs did not differ between the vertex deletion condition (479 msec) and the midsegment deletion condition (476 msec) [$t_s(29) = 1.1$, $SE = 2.7$, $p = .294$; $t_i(79) = 0.22$, $SE = 0.03$, $p = .828$]. Nor was there a significant difference in the error data (all ts < 1).

Discussion

In Experiment 3, the removal of vertices from individual letters was no more detrimental to word recognition than was the removal of midsegments of letters. This result stands in contrast to the results of Experiments 1 and 2, which demonstrated, under the same conditions, that isolated letter recognition was more affected by the deletion of vertices than was the deletion of midsegments. The results from Experiment 3 are consistent with the idea that contextual support available at the word level can reduce the effect of a letter-level degradation manipulation. The effect of removing vertices was small in the context of isolated letter recognition (7 msec), and the added contextual support provided by a word's representation may render the effect small enough to be difficult to detect statistically in the present context (3 msec). This interpretation is consistent with previous research (e.g., Massaro & Cowan, 1993; McClelland & Rumelhart, 1981).

EXPERIMENT 4
Word Identification With Brief Exposure

In Experiment 4, we again assessed the impact of removing vertices versus removing midsegments on word identification. The stimuli in Experiment 4 were presented briefly (50 msec, as in Experiment 2) in an attempt to enhance the effect of removing vertices. Thus, participants in Experiment 4 again read words aloud in which letters had vertices or midsegments deleted. The critical difference between Experiments 3 and 4 was that the words in Experiment 4 were presented only for 50 msec.

Method

Participants. Thirty undergraduate students who had not taken part in any of the previous experiments participated in Experiment 4 for either $5 each or course credit.

Apparatus, Stimuli, and Procedure. The apparatus, stimuli, and procedure were the same as those in Experiment 3, except that the words were now presented for 50 msec, followed by a blank screen.

Results

Data analysis followed the same procedure as those used in the previous experiments and resulted in the elimination of 4.5% of the RT data. Mean RT and percentage of error for each condition are presented in Figure 5. Correlated *t* tests for both participants and items tested the specific predictions regarding the role of vertices in word recognition.

RTs were significantly slower in the vertex deletion condition (483 msec) than in the midsegment deletion condition (476 msec) [$t_s(29) = 2.7$, $SE = 2.7$, $p = .012$; $t_i(79) = 2.14$, $SE = 3.54$, $p = .035$]. More errors were also made in the vertex deletion condition (1.7%) than in the midsegment deletion condition (0.5%) [$t_i(29) = 2.2$, $SE = 0.005$, $p = .035$; $t_i(79) = 2.09$, $SE = 0.004$, $p = .04$].

Discussion

Experiment 4 demonstrates that removing vertices from letters is more detrimental to word recognition than is removing midsegments of letters when presentation time is limited.

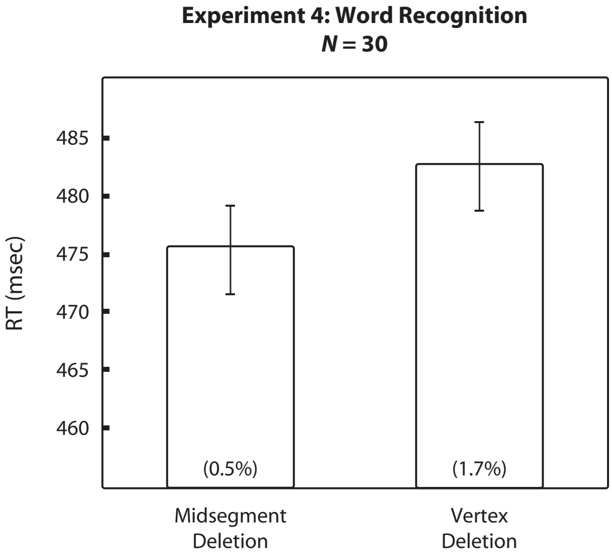

Figure 5. Response times (RTs, in milliseconds) and percentages of errors (in parentheses) as a function of letter type (midsegment deletion vs. vertex deletion) in Experiment 4. Error bars represent the 95% confidence interval as defined by Masson and Loftus (2003).

Effect size. Across experiments, the differences in performance between the midsegment and vertex deletion conditions were numerically small. In terms of Cohen's *d*, the reported effects (i.e., the significant RT effects in Experiments 1, 2, and 4) ranged from .3 to .7, averaging approximately .5. Thus, the effects are medium sized, according to Cohen's *d*, which is certainly well within the range of effect sizes in cognitive psychology. The difference between the midsegment and vertex deletion conditions is clearly replicable, suggesting that, although numerically small, the effect is robust.

GENERAL DISCUSSION

The present study demonstrates that removing the vertices in letters is more detrimental to letter and word recognition than is removing the midsegments of letters. These results are consistent with Biederman's (1987) results in the context of object recognition. This similarity across words and objects suggests that similar principles may operate in both domains.

The present results are consistent with many previous observations in other paradigms. For example, in the context of confusion matrices, intersections are often identified as a distinctive feature used in letter recognition (Gibson, 1965, 1969; Gibson et al., 1962). Research on handwriting also suggests that vertices may play an important role in the recognition of letters and words (Schomaker & Segers, 1999). This convergence across different paradigms suggests that vertices provide important information in the recognition of linguistic material.

Petit and Grainger (2002) reported results seemingly inconsistent with the relative importance of vertices over midsegments in letter identification. Using a masked priming paradigm, they found that letter primes with vertex deletions produced *greater* priming than did letter primes with midsegment deletions. Given that letters with vertex deletions typically are recognized *more slowly* than are letters with midsegment deletions, the greater priming afforded by the former seems surprising. Although it is counterintuitive, this pattern has been observed previously in studies of priming in object and word recognition. The perceptual closure effect refers to the observation that moderately degraded images produce greater priming effects than do less degraded images, despite the fact that the latter are recognized faster than the former (Snodgrass & Feenan, 1990; Snodgrass & Kinjo, 1998). According to Snodgrass and Kinjo, moderately degraded images may activate the optimal amount of top-down and bottom-up processes, thus enhancing the perceptual representation of the image. A similar explanation may be used to explain Petit and Grainger's finding that letter primes with vertex deletions (i.e., moderately degraded primes) produce *greater* priming than do letter primes with midsegment deletions (i.e., less degraded primes).

In a similar vein, Emrich, Ruppel, and Ferber (2008) found that objects with vertex deletions formed more persistent representations than did objects with midsegment deletions, even though the former objects were recognized more slowly than the latter. They hypothesized that the additional elaborative processing (see Craik & Tulving, 1975) required to make objects with vertex deletions recognizable also makes representations of these objects more persistent. The additional persistence of the more degraded object may result in more priming. Thus, although Petit and Grainger's (2002) results are counterintuitive at first blush, other research provides support for the idea that some forms of degradation can harm identification but enhance priming effects.

Why Are Vertices Important?

The importance of vertices, relative to midsegments, may stem from a number of factors. Vertices carry information regarding the relations among different features, whereas midsegments carry information regarding a single feature. In addition, vertices occur at discontinuities (e.g., line terminations; see Fiset et al., 2008) and thus may be more difficult to "infer" from remaining information than a midsegment (Biederman, 1987; Binford, 1981). For a midsegment, the line is simply extended through the deletion, and the point of line termination is predetermined. With vertices, two or more lines must be extended through the deletion, and the point of line termination must be inferred. Thus, when a vertex is removed, it may be harder to recover the missing information than when a midsegment is removed.

Regardless of the underlying cause of the differences between vertex and midsegment deletions in the context of letter and word recognition, the manipulation introduced here provides an opportunity to further our understanding of early processes in visual word recognition.

This manipulation provides a unique window into the interactions across feature-, letter-, and word-level processing. Future work combining vertex and midsegment deletions with other psycholinguistic variables (e.g., word frequency) may shed additional light on early processing in reading.

Implications for Models of Letter and Word Recognition

The introduction noted that many extant computational models of reading include a feature-processing level. The features in these models (e.g., DRC, CDP+) typically consist of simple line segments (e.g., / | \) and therefore do not offer an account of the present results. That said, these models have focused largely on the influence of linguistic-level factors (e.g., word frequency, neighborhood density). Nonetheless, computational models will need to accommodate the present findings in order to accurately describe the full course of visual word recognition. Currently, at least in existing word recognition models, individual features are equipotent in activating letter representations.

Feature processing is typically better explicated in models of letter recognition than in models of word recognition. In the classic pandemonium model, a hierarchy of demons are activated by specific features in a letter (see also Jacobs & Grainger, 1991; Petit, Midgley, Holcomb, & Grainger, 2006; Selfridge & Neisser, 1960). The model contains feature demons for line segments of various orientations. Critically, some features are weighted more heavily than others. The present results could be accounted for by assuming that "vertex demons" are weighted more heavily than other line segment demons. The idea that a vertex functions as a basic feature that is more "important" than other features in letter recognition could also be accounted for in the context of the fuzzy logical model of perception (see also Oden, 1979; Oden & Massaro, 1978).

An alternative computational perspective views a vertex as a complex feature composed of more basic features (e.g., oriented line segments and terminations). For example, in Hummel and Biederman's (1992) neural net model of shape recognition, the first layer of cells responds to the presence of simple features (e.g., oriented line segments). These cells feed forward to the second layer of vertex detector cells, which uses the signals from the first layer to determine conjunctions of simple features. In this context, vertices are more complex features that define how more basic features relate to each other. When vertices are removed, as in the present experiments, defining relations between features is more difficult, which delays recognition.

Conclusion

The deletion of vertices is more detrimental to letter and word recognition than is the deletion of midsegments, suggesting that vertices are an important feature. Future research involving manipulations of other psycholinguistic variables, in conjunction with the present manipulation of feature processing, may yield a more comprehensive understanding of early processing in reading.

AUTHOR NOTE

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