The word superiority effect overcomes crowding

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A B S T R A C T

Crowding and the word superiority effect are two perceptual phenomena that influence reading. The identification of the inner letters of a word can be hindered by crowding from adjacent letters, but it can be facilitated by the word context itself (the word superiority effect). In the present study, strings of four-letters (words and non-words) with different inter-letter spacings (ranging from an optimal spacing to produce crowding to a spacing too large to produce crowding) were presented briefly in the periphery and participants were asked to identify the third letter of the string. Each word had a partner word that was identical except for its third letter (e.g., COLD, CORD) so that guessing as the source of the improved performance for words could be ruled out. Unsurprisingly, letter identification accuracy for words was better than non-words. For non-words, it was lowest at closer spacings, confirming crowding. However, for words, accuracy remained high at all inter-letter spacings showing that crowding did not prevent identification of the inner letters. This result supports models of "holistic" word recognition where partial cues can lead to recognition without first identifying individual letters. Once the word is recognized, its inner letters can be recovered, despite their feature loss produced by crowding.

Crowding and the word superiority effect are two perceptual phenomena that influence reading. Crowding makes identifying a letter within a word difficult because it is surrounded by other letters (Pelli et al., 2007; Grainger et al., 2006). In contrast, the word superiority effect makes identifying a letter within a word easier: The word's shape and first and last letters may be sufficient to recognize the word and from that, its inner letters (Reicher, 1969; Wheeler, 1970). Here we examine the interaction between crowding and the word superiority effect.

In crowding, the identification of a target is degraded when it is surrounded by closely spaced distractors. This robust effect has been reported across a wide variety of tasks, including letter recognition (Levi, 2008). An example is given in Fig. 1. The strength of the crowding effect increases as the distance between the target and its distractors decreases (Bertoni et al., 2019; Levi, 2008; Toet & Levi, 1992; Whitney & Levi, 2011). The spatial extent over which crowding is seen increases with eccentricity and, depending on many factors, it is between one third to one half the eccentricity (Bouma, 1970; Coates, Ludowici, & Chung, 2021; Greenwood, Szinte, Sayim, & Cavanagh, 2017). As a result, letters within a word in typical text can be within the crowding range unless the gaze is within the word of interest (Pelli et al., 2007).

For example, in a four-letter word, with fixation on the first letter, the third and fourth letter are separated by 1/3 of the eccentricity to their midpoint, and so the third letter would be subject to some crowding. This crowding is one of the factors that limit the number of characters that can be read at each fixation to about 10 characters (visual span; Legge et al., 2001; Yu, Legge, Wagoner, & Chung, 2014). Accordingly, increasing the spacing between letters to reduce crowding improves performance in individuals with reading difficulties (e.g., Bertoni et al., 2019; Joo et al., 2018; Perea & Gomez, 2012; Yong et al., 2016; Zorzi et al., 2012).

While the recognition of letters can be hindered by crowding from adjacent characters, it can be facilitated if the letter string forms a word. The first and last letters, and the shape and length of words are often sufficient to identify the word or a set of likely words (Jordan et al., 1999; Rayner et al., 2006). This word context facilitates the recognition of the inner letters, an advantage known as the word superiority effect (Reicher, 1969; Wheeler, 1970). Importantly, this facilitation reveals an increased sensitivity to the features of the inner letters, not simply guessing. Reicher and Wheeler presented strings of four letters to form words or non-words. Each word had a partner word that differed only in the third letter (e.g., COLD and CORD) and for each test, participants

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Fig. 1. An illustration of crowding. Fixate the central "+" sign in red and try to identify the letter to the left (this is easy). Now fixate the "+" and try to identify the third letter on the right (located at the same eccentricity as the letter on the left). This is more difficult because of the crowding effect from two adjacent letters. Notice that, although it is at an even greater eccentricity, the fourth letter is easy to recognize as it has only one adjacent distractor and so is less crowded.

identified which of the two letters (e.g., L or R) was presented at the third position. Accuracy was higher for words than for non-words even though guessing was controlled by the two-alternative forced choice procedure. The advantage for the word context suggested that the outer letters had activated a set of likely words, which then facilitated the identification of the correct inner letter that completed the word (McClelland & Rumelhart, 1981). This advantage of words over non-words has been obtained for words in lowercase and uppercase type, and in a mixture of upper- and lowercase (Adams, 1979; McClelland, 1976).

This ability to read words based on their first and last letters and their length has been demonstrated by scrambling the internal letters of words in a text (e.g., "Cmabirgde Uinervtisy", Grainger & Whitney, 2004; Rayner et al., 2006). These modified words could be read despite the inappropriate positions of the inner letters. The word context from the first and last letters and the word length can also fill in internal letters that are not even there. Jordan et al. (1999) replaced the inner letters with meaningless texture patches and showed that if the inappropriate patches were small enough, the word context could perceptually fill in letters that completed the word (See Fig. 2).

If the word context facilitates the identification of the inner letters of a word, while crowding impedes it, which wins? This question was addressed in two articles by Fine (2001, 2004). Participants were asked to identify the middle letter in three-letter words and non-words that were presented rapidly in the peripheral visual field with letter spacing that ensured crowding of the inner letter. The middle letter was identified better (Fine, 2001) and faster (Fine, 2004) when presented in words than in non-words. Although these results show that the word context improved letter identification, the improvement could be due to guessing in these conditions. In addition, since the letter spacing was not varied, it was not possible to establish whether the word context had just reduced the effect of crowding or eliminated it.

Here, to overcome these issues, letter identification from words and non-words is compared while varying inter-letter spacing and controlling for guessing. Four-letter words and non-words were presented peripherally with four different inter-letter spacings and participants identified the third letter (e.g., 'R' when 'CORD' was presented). The non-words were scrambled versions of each word that retained the target letter in the third location. The inclusion of non-word stimuli with different letters spacings allowed the degree of crowding to be assessed

without a word context. This served as a baseline to evaluate the extent of crowding seen with words.

Controls for guessing were implemented two ways. First, two lists of "partner" words were created: Each word in the first list had a partner in the second that differed in only the third (target) letter (e.g., COLD and CORD). The higher frequency word in each pair was assigned to one list and the lower frequency word to another list. If guessing were the source of a word advantage, the words from the higher frequency list should have a higher rate of correct responses as those words would be more likely to be guessed correctly than the words from the lower frequency list. Second, the letters given as responses were recorded in the letter identification task so that the types of errors could be analyzed. Of particular interest are the errors made by responding with the third letter of the "partner word" because these errors estimate the frequency with which participants guess correctly based on the word context. Moreover, comparing this estimate to the advantage of words over the errors for non-words also indicates whether the advantage is due to guessing or to an increased sensitivity to the target letter in the word context.

1. Method

1.1. Participants

Participants were three authors and 34 undergraduate students, all from Glendon College of York University, Toronto, Canada. There were 29 females and eight males (age range: 18–76, mean and S.D.: 23 ± 11). Other than the authors, all participants were naive to the purpose of the study and had normal or corrected-to-normal vision. The undergraduate students earned $15 for their participation. Each participant gave their written, informed consent prior to their experimental sessions. The study was approved by the Human Participants Review Sub-Committee of York University's Ethics Review Board; it was carried out in accordance with the declaration of Helsinki guidelines and regulations (2003).

1.2. Apparatus

Stimuli were generated an Apple Macintosh G4 computer with custom software written in C using the Vision Shell Graphics Libraries (Comtois, 2003). Head movements and the viewing distance (57 cm) were controlled with a chin rest. The stimuli were presented on an Optix MPG341CQR monitor with 1800R curvature. The display area measured 60.0 cm × 33.5 cm, had a resolution of 1920 × 1080 pixels, and a frame rate of 60 Hz.

1.3. Stimuli

Black upper-case letters were presented on white background. Single letters, four-letter words, and four-letter non-words were presented in
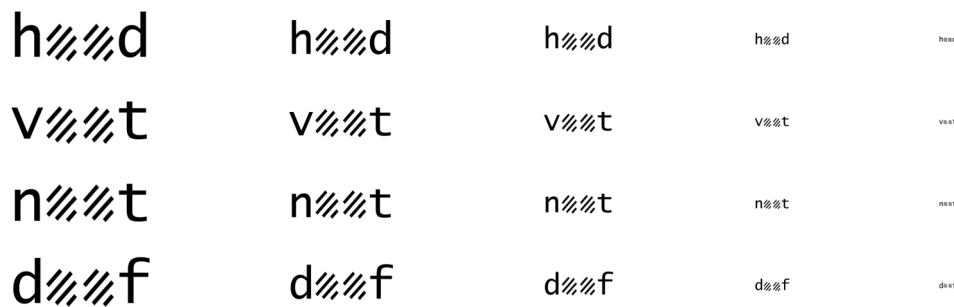

Fig. 2. Example of the stimuli created by Jordan et al. (1999). Try reading the words in the right-hand column (or the next one to the left if those are too small to see). These words may appear to be complete with actual letters in the middle two positions, perhaps "head" at the top. In fact, as is obvious in the leftmost columns, the two positions show only textured patches. The letters seen in the smallest words are perceptually filled in from the word context.

upper case in the Courier font. This font was chosen because of its constant inter-letter spacing and similar individual letter width. The height of the letters was 1.37° and the width varied from 1.0° (the letter I) to 1.5° (M). For the four-letter words and non-words, the third letter was the target letter, and it was flanked by two letters to the left and one to the right. The target letter was located horizontally at 9.25° to the left or right of the fixation point. Four different inter-letter spacings were used: 1.85°, 2.47°, 3.08°, and 3.70° which corresponded to 0.20, 0.27, 0.33, and 0.40 times the target eccentricity. The tightest spacing (1.85°) corresponds to that used in normally printed text for Courier font letters of this height. The largest spacing (3.70°) is greater than one third of the eccentricity (Greenwood et al., 2017) which is the critical limit spacing of crowing (here 3.08°).

A total of 96 pairs of four-letter words were selected from Norvig's compilation of 97,565 distinct English words (https://norvig.com/mayzner.html) across the sample of 743,842,922,321 English words found in the Google books Ngrams (from all English books scanned by Google only including words with more than 100,000 instances). Each of the 96 selected four-letter words had a paired word that differed only in the third letter: for example, "COLD" and "CORD". All the selected words were from the 1150 most frequent English four-letter words in the Norvig list. Non-words were generated by changing the order of the word's letters from 1-2-3-4 to 4-1-3-2 (e.g., CORD became DCRO). The non-words had the same four letters as the source word while keeping third (target) letter at the same position. None of the selected words produced another word when changing the order of the letters.

Two list of words were created based on the frequency of the words in each pair (lists are in the Supplementary Materials). The first list contained the more frequent word in each pair (e.g., COLD) and the second, the less frequent word (e.g., CORD). The higher frequency list had an average frequency ranking of 298 (SD = 23) from the Norvig lists of four-letter English words, and the lower frequency list had an average frequency ranking of 592 (SD = 30). These two lists of corresponding words of different frequency provided a check for guessing the identity of the target letter of words. In addition, a list of controlled non-words was generated from each word list. This control provided a check for the equivalence of the target letters of the two lists. For the non-words, the two lists differed only in the relative frequencies of the different target letters while the non-target letters were all matched. The target letter sets for the two lists are presented at the end of the Supplementary Materials.

1.4. Procedure

The first testing block included 24 trials showing a single letter, followed by two blocks of 96 trials, one presenting words (48 from the higher frequency list, and 48 from the lower frequency list), and one presenting non-words (48 of the corresponding non-words generated from the higher frequency list, and 48 from the corresponding lower frequency list). The words and non-words blocks were presented in counterbalanced order across participants. Within each block, the 96 words (or non-words) were assigned to all combinations of the two Lists (higher and lower frequency), four Spacings (1.85°, 2.47°, 3.08°, and 3.70°), and two Sides (left and right) with six repetitions of these 16 conditions. The resulting 96 trials were presented in a random order. The words assigned to these 16 conditions varied systematically so that across participants, each word (and corresponding non-word) was tested at all spacings and both sides. Participants never saw the same word twice. They saw only one word from each partner pair (higher or lower frequency list) and their corresponding non-words. For example, if a participant saw COLD, they never saw CORD, and the matching non-word would be DCLO. The presentation side and spacing location of the corresponding words and non-words were matched for each participant. For example, if a participant saw COLD on the left with spacing 3.08°, they also saw DCLO on the left with spacing 3.08°. A total of 16 participants were required for all words and non-words to be tested

at all Spacings, Lists, and Sides.

Participants were informed that letters would be briefly presented to the left or right of the central fixation dot and that they should maintain their gaze on the fixation until they made their response. To begin a trial, a beep sounded and after 1500 ms, the target letter appeared on the left or right-hand side of the screen for 200 ms. Participants then used the keyboard to press the key corresponding to the letter that they saw. This response letter was displayed on the monitor so participants could verify their choice. They could press other letters to change their response if they wished. Once satisfied with their choice, they pressed the space bar and initiated the next trial. Participants could take breaks as needed by pausing before pressing the space bar. Fig. 3 illustrates a trial sequence.

Eye movements were not monitored but were controlled by presenting the letter strings for only 200 ms and randomly to the left or right, and by asking participants to report whether they moved their eyes towards the target during a trial. The duration of 200 ms was chosen to prevent eye movements as the average time for an 9.25° eye movement to land on its target is about 230 ms [around 190 ms latency (Darrien et al., 2001), and 40 ms from initiation to landing for this amplitude (Bahill, Clark & Stark, 1975)] by which time the stimulus would no longer be present on the display. The random presentation to the left or right also prevented shifting gaze to the target letter. If a participant knowingly moved their eyes towards the target, they were asked to report it by pressing any non-letter key; the response was not recorded, and the trial not replaced. Participants were excluded if they reported eye movement in more than 80% of the trials in any condition, or if they obtained nearly perfect accuracy in the non-word conditions which would require eye movements that landed near the target letter.

To evaluate the visibility of single letters at the eccentricity at which the targets are presented (9.25°), and to get used to the procedure, a block of 24 single letter trials was presented first. Participants needed to have greater than 85% correct responses to continue with the word and non-word blocks. All participants exceeded this threshold.

In the word and non-word blocks, the third letter of a 4-letter strings was the target letter; it was always presented at the eccentricity of 9.25° and flanked by two letters on its left and one on its right (Fig. 4). The letter string appeared on the left or right-hand side of the screen for a duration of 200 ms.

After completing the single letter block, participants were informed beforehand whether each block presented words or non-words. The three blocks took approximately one-half hour to complete.

2. Results

2.1. Eye movements

The validity of the tests for crowding depends on reliable fixation at the display center to maintain the appropriate eccentricity for the letter strings. The results of five participants (out of 37) were excluded due to poor fixation. One participant reported multiple eye movements and had several trials with no data, and four had near perfect responses in the non-word trials implying that they had made eye movements but did not report them. Across the remaining 32 participants, an average of 2.4% (SE = 0.5) of the trials were excluded because of mis-fixations. There were more mis-fixations at closer spacings but no differences between the left and right side and between words and non-words.

For the remaining 32 participants, the accuracy for reporting single letters was above 85%. On average, it was 97.7% (SE = 0.7) with no significant difference between the left or right side, $t(31) = 0.069$, $p = 0.95$.

2.2. Letter identification accuracy

The percent of correct responses (accuracy) for the word and non-word blocks was calculated and analysed with a repeated-measures analysis of variance (2x2x2x4) with the independent variables Word
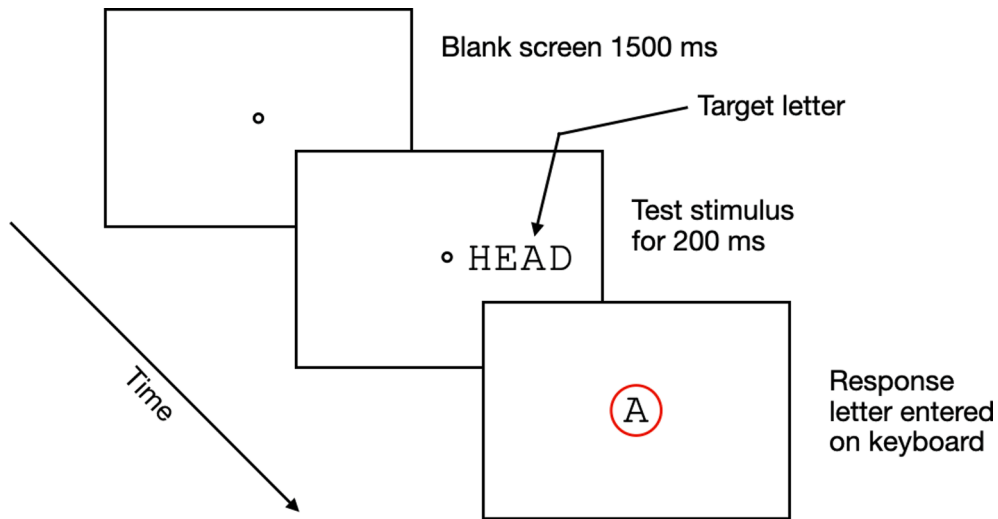
Fig. 3. Trial sequence. A trial started with a short tone and the fixation was present alone on a blank screen for 1.5 s. The stimuli (words, non-words, or single letter) followed, randomly on the left or right for 200 ms. The 3rd letter of words and non-words was the target, and it was always at 9.25° eccentricity. The participant then entered their response choice on the keyboard, and it was displayed at the center of the screen. They could revise their choice by pressing another letter key or by entering a non-letter key to indicate that they had made an eye movement. When the participant was satisfied with their response, they pressed the space bar to end the trial and begin the next.

Fig. 4. Sample words and non-words presented on left and right of the fixation point at the four different spacings.

Type (words and non-words), Side (left and right), List (higher and lower frequency source words), and Spacings (1.85°, 2.47°, 3.08°, and 3.70°). The results (combining data from left and right sides) are plotted in Fig. 5.

The analysis of variance showed the expected advantage of words over non-words (main effect of Word Type, $F(1,31) = 79.90, p < 0.001$, $\eta p^2 = 0.72$): the average accuracy was significantly better for words (M = 79.2%, SE = 1.6) than non-words (M = 63.5%, SE = 2.3). In addition, there was a significant interaction of Spacing and Word Type ($F(3,93) = 4.19, p = 0.008, \eta p^2 = 0.12$): As illustrated in Fig. 5, the correct responses increased linearly with increased letter spacings for non-words, $F(3, 93) = 7.50, p < 0.001$) but not for words, $F(3,93) = 0.11, p = 0.995$, showing effects of crowding for non-words, but none for words. (The strong crowding effect for the non-words argues that fixation was reliably maintained.)

The analysis also showed a significant interaction of Side $\times$ Word Type ($F(1,31 = 33.59, p < 0.001, \eta p^2 = 0.52$): The advantage with words over non-words was larger on the right than on the left (Fig. 6). The three-way interaction of Word Type $\times$ Side $\times$ Spacing was not significant ($F(3,93) = 1.85, p = 0.144, \eta p^2 = 0.06$) indicating that the interaction between Spacing and Word Type was similar on both sides: As spacing increased, the accuracy increased for non-words, but remained constant for words.
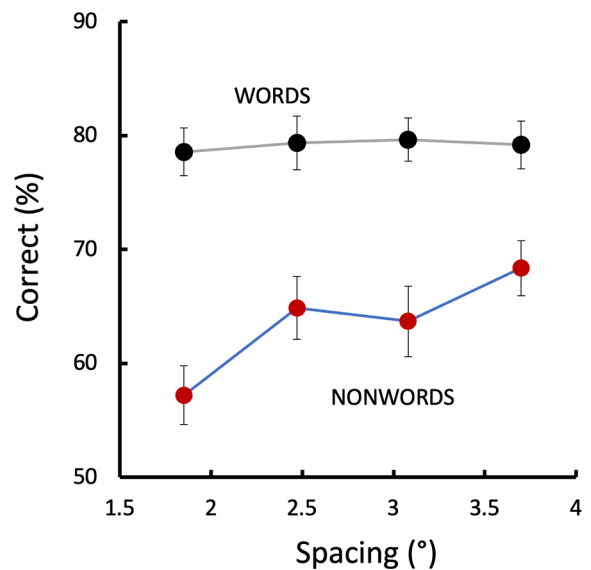

Fig. 5. Average percent correct responses in reporting the target (3rd) letter as a function of Spacing for Words and Non-words (combining Sides and Lists). One vertical error bar corresponds to ±1 SE.

2.3. Guessing as the source of word advantage

If guessing were an important contributor to the word advantage, there should be a higher rate of correct responses for the higher frequency words list where the guesses would be more likely to be correct, and, for the lower frequency words list, the letters reported when errors occurred should be more often the third letters of the corresponding higher frequency words. Thus, to rule out guessing, the correct responses between the higher and lower frequency words lists were compared and the types of errors were analyzed.

The main ANOVA results of correct answers show that no main effect of List ($F(1,31) = 3.88, p = 0.058, \eta p^2 = 0.11$), and no interaction of List by Word Type ($F(1,31) = 0.162, p = 0.199, \eta p^2 = 0.005$). The results showed no accuracy difference between the two word lists (80.1%, SE = 1.7 vs 78.3%, SE = 1.7, for higher and lower frequency lists,
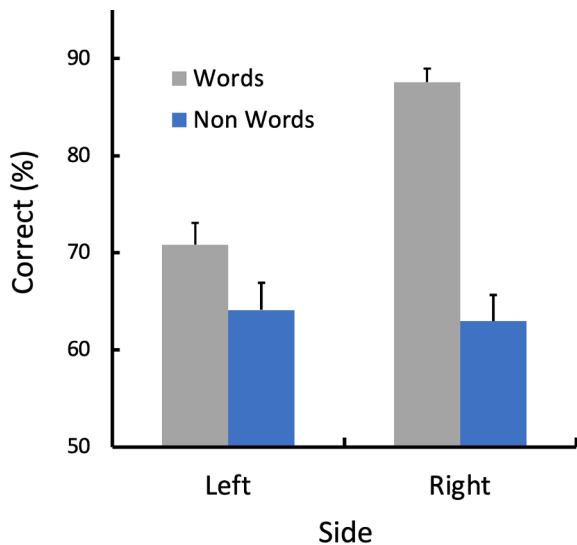
Fig. 6. Percent correct in reporting the target (3rd) letter as a function of left vs. right side presentation, for Words and Non-words. One error bar corresponds to +1 SE.

Fig. 7. Percent of trials for words and non-words of partner word errors, another word error, an adjacent letter error, or another error that was in none of these categories. Vertical bars show +1.0 SE.

Fig. 8. Partner Word Percent Error for words and non-words from the higher frequency words list (blue) and the lower frequency words list (orange). Vertical bars show +1.0 SE.

respectively), $F(1,31) = 1.723$, $p = 0.199$, showing that accuracy was not better when the target letter was more likely to be guessed. There was also no difference in accuracy between the two lists of non-words (64.9%, SE = 2.4 vs 62.2%, SE = 2.5 for higher and lower frequency source word lists, respectively), $F(1,31) = 2.045$, $p = 0.163$. This result was expected as the two non-words lists differed only in the relative frequencies of the different target letters while the non-target letters were all matched.

Finally, the errors were analyzed to determine more precisely the level of word-based guessing for the words. Errors were classified as "partner word errors", "other word errors", "adjacent letter errors" or "none." An error was a partner word errors when the response was the third letter of the paired word. For example, if the word CASE was presented and the participant responded "M", their response was classified as a "partner word error" because its paired word CAME had "M" as the target letter. For an "other word error," the response letter made a word that was not the partner word. For example, varying the third letter of CASE could lead to CAPE, CAKE, CANE — words which were not the partner word CAME. Adjacent letter errors were responses that were one of the other three letters in the letter strings. For example, an "A" response for CASE was an adjacent letter error. Any other response letter was classified as "none." (Note these categories are not mutually exclusive. A response could be an adjacent letter error and another word error; for example, with BARS, the error response S is both an adjacent letter and it makes another word: BASS.)

Fig. 7 shows the mean percent error rates for each of the four error types. The most frequent types of errors were adjacent letters and "none" for both words and non-words. For words, the rate of responding with a letter that made a word, other than the partner word, was the third most frequent type of error. Importantly, for both words and non-words, the rate of responding with the partner word's letter was the least frequent type of errors. These errors estimate the rate of correct guessing. The percent partner word error was 1.75% for the higher frequency word list and 2.15% for the lower frequency word list (Fig. 8). Correct guesses based on the word context could therefore explain about 2% of the correct responses for the words. However, correct responses for words showed an average of 15% advantage over non-words.

3. Discussion

The interaction between crowding and the word superiority effect was studied by measuring at the accuracy of reporting the third letter
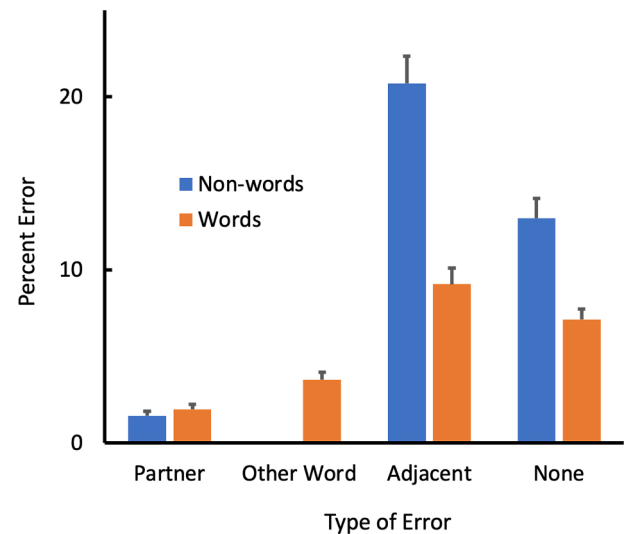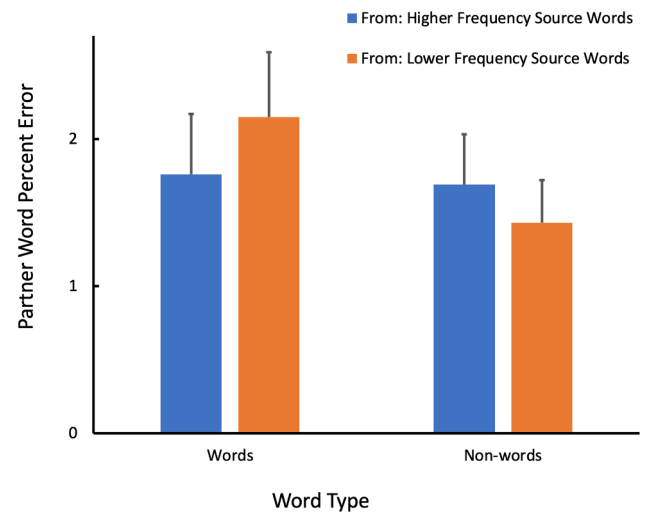
within 4-letter words and matched non-words presented at different inter-letter spacings. Letter identification accuracy was reduced by crowding for non-words, but not for words. These results show that the word context facilitates identification of letters within words even when the perceptual conditions impose crowding. While finding that word context helps letter identification is not novel (e.g., Grainger & Whitney, 2004; Rayner et al., 2006; Reicher, 1969; Wheeler, 1970) or surprising, showing that word context completely overcomes crowding is.

Fine (2001, 2004) had previously demonstrated a word advantage when 3-letter words were presented in the periphery with inter-letter spacings within the crowding range. However, the inter-letter spacing was not varied and so the presence or absence of crowding for the words could not be established. Moreover, there was no explicit control for guessing. Out of the total of 57 words presented, 29 had alternate words with other middle letters (e.g., ode, one, ore, owe) and 25% of the letter recognition errors in words corresponded to the second letter of one of these alternate words (Fine, 2001). This indicates that when the first and last letter matched only one word, there would be a high probability of

guessing that word and responding correctly even if there was no encoding of any features from the middle letter. The advantage of 24% accuracy for words over nonwords in Fine's experiments (2001) may therefore have been due primarily to guessing.

Our method varied the inter-letter spacing to assess crowding and controlled for word-based guessing. The effect of letter spacings on accuracy clearly showed the expected, strong crowding for non-words; however, surprisingly, this crowding did not affect accuracy for the letter identification in words. The control for guessing is critical for claiming that the word context facilitated the recovery of the target letter within words and the experiment had two tests for the contribution of guessing to the word advantage. First, if there were significant word-based guessing when words were incompletely encoded, the most likely guess should be a higher frequency word. In this case, the accuracy should be higher for words from the higher frequency list than for words from the lower frequency list. However, there was no difference between these lists (80.3% vs 78.3%, respectively). Second, partner word errors are a clear index of the rate of word-based, correct guessing. For example, with the partner words LAND and LARD, responding "N" when the stimulus was LARD is a partner word error. The rate of these errors should mirror the rate of correct word guessing, so when LAND is incompletely encoded (LA—D), the rate of guessing "N" should be the same, but now it is correct. Critically, the partner word error rate, averaged over both lists (2%), was far lower than the word advantage that it would have to explain (15%) if guessing were the only source of the advantage. Overall, the evidence suggests that the word advantage comes from an increase in accurate identification of the third letter supported by the word context.

How did the word context facilitate the retrieval of the third letter? A holistic strategy of word recognition is the likely the source of this advantage (e.g., Nischal & Behrmann, 2023; Samuels, LaBerge, & Bremer, 1978; Ventura, et al., 2020, although see Grainger, 2008; Pelli, Farell, & Moore, 2003). Specifically, partial information from the letters is sufficient to activate the representations of candidate words (McClelland & Rumelhart, 1981) without having to first identify each letter. Indeed, a glance at the words in Fig. 9 gives the impression of degraded third letter (in LAND or LARD) as expected from crowding, but the word context takes account of the weak cues from the third letter to retrieve it. Accordingly, letter identification in words was accurate and constant across all spacings tested. Crowding might become evident with closer letter spacing but the tightest spacing used corresponded to typical reading material. In contrast, for non-words, the degraded third letter had no word context to facilitate its identification and performance dropped as closer letter spacing imposed more crowding.

Holistic recognition does not require the identification of individual letters but only that the available features constrain the recognition to the target word. These features can be low-level curvatures and junctions of individual letters, to some extent independent of their exact location in the word. This type of recognition would be relatively immune to crowding, a process that may integrate the features of target letters with those of the adjacent distractors (Levi, 2008; Pelli, Palomares, & Majaj, 2004). It is not the case that crowding has no influence on the letter features in words, it is more likely that the word context can overcome the loss leading to successful recognition based on what remains. Although crowding is a formidable enemy of independent letter identification, it is not of word recognition.

There are many proposals for the source of crowding, including lateral interactions within a zone of feature pooling (e.g., Pelli, 2008), attentional resolution (e.g., Intriligator & Cavanagh, 2001), position

uncertainty (e.g., Strasburger & Malania, 2013), and others (see reviews: Agaoglu & Chung, 2016; Herzog & Sayim, 2022; and, Whitney & Levi, 2011). In our task, position uncertainty appears to be an important contributing factor as there were many errors from adjacent letters in the non-word trials (Fig. 7).

Crowding has been shown to be affected by in-out asymmetry (Chakravarthi, Rubruck, Kipling, & Clarke, 2021) where crowding is enhanced when stimuli are presented on the left hemifield with more flankers presented on the peripheral position from the target ("out", here left side) than on the inner position between the target and the fixation point ("in" side of the target). This in-out asymmetry was not found here —there was no difference in the performance of the non-words whether presented on the left or right side, despite the in-out asymmetry.

While the non-words did not reveal anything novel about crowding, the word stimuli did. Importantly, performance with words was unaffected by the inter-letter spacing (an absence of any measurable crowding effect), indicating that crowding must occur at or beyond the level where the word context is extracted. This outcome is at odds with models proposing a low-level mechanism (Balas, Nakano, & Rosenholtz, 2009; Greenwood, Bex, & Dakin, 2010; Harrison & Bex, 2017; Rosenholtz, Yu, & Keshvari, 2019). Instead, it supports models where crowding occurs across multiple stages (Manassi & Whitney, 2018) and/or is influenced by the semantic information of the stimuli (Kouider, Berthet, & Faivre, 2011; Yeh, He, & Cavanagh, 2012). Interestingly, the word advantage was larger when presented on the right than the left side which may result from having the first two letters of the word nearer fixation when the stimulus is on the right rather than on the left. Despite the difference in the word advantage between presentation on the left and right side, the absence of crowding was maintained on both sides.

The absence of crowding was found using the monospaced Courier font which might limit the generalization of the results. However, since inter-letter spacing was not a factor for words, it is likely that the result would hold for fonts with variable inter-letter spacing (proportional spacing) as well.

The finding that words overcome crowding may also have implications for reading. Our stimuli did not correspond to typical reading conditions as the target letters were quite far in the periphery and the font size and letter spacing were large. However, if scaled proportion-ately to more typical text sizes, our stimuli would fall within the visual span —a range that encompasses about 5 letters to the left and right of fixation that contribute to reading (Legge et al., 2001; Yu et al., 2014). Since letter spacings did not influence letter recognition with words, it appears that word context provides protection from crowding in typical reading conditions. This result is consistent with the idea that, with standard spacing, individuals with reading difficulties have a reduced ability to use word context to overcome crowding and the increased inter-letter spacing helps by reducing the crowding (e.g., Bertoni et al., 2019; Joo et al., 2018; Perea & Gomez, 2012; Yong et al., 2016; Zorzi et al., 2012).

Our results show that when the word context is available, crowding is overcome. Interestingly, we now show that crowding is suppressed with words, and Grainger and colleagues showed that it is reduced with letters compared to symbols. They have proposed that letters benefit from specialized processing via modified receptive fields that reduce the effects of crowding for letters in non-word strings (Chanceaux & Grainger, 2012; Grainger et al., 2010; Tydgat & Grainger, 2009). Our results suggest that the word superiority effect may recruit more holistic analyses that not only reduce but completely overcome the effects of crowding when the letter string forms a word.

Data and code

Available at: https://osf.io/d4yue/.

Fig. 9. Sample words and non-words on left and right at the closest spacing.

CRediT authorship contribution statement

June Cutler: Project administration, Investigation, Formal analysis, Data curation. **Alexandre Bodet:** Writing – original draft, Methodology, Investigation, Conceptualization. **Josée Rivest:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Patrick Cavanagh:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The link to our data is https://osf.io/d4yue/.

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.visres.2024.108436.

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