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The mechanism of word crowding

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ABSTRACT

Word reading speed in peripheral vision is slower when words are in close proximity of other words (Chung, 2004). This word crowding effect could arise as a consequence of interaction of low-level letter features between words, or the interaction between high-level holistic representations of words. We evaluated these two hypotheses by examining how word crowding changes for five configurations of flanking words: the control condition – flanking words were oriented upright; scrambled – letters in each flanking word were scrambled in order; horizontal-flip – each flanking word was the left–right mirror-image of the original; letter-flip – each letter of the flanking word was the left–right mirror-image of the original; and vertical-flip – each flanking word was the up–down mirror-image of the original. The low-level letter feature interaction hypothesis predicts similar word crowding effect for all the different flanker configurations, while the high-level holistic representation hypothesis predicts less word crowding effect for all the alternative flanker conditions, compared with the control condition. We found that oral reading speed for words flanked above and below by other words, measured at 10° eccentricity in the nasal field, showed the same dependence on the vertical separation between the target and its flanking words, for the various flanker configurations. The result was also similar when we rotated the flanking words by 90° to disrupt the periodic vertical pattern, which presumably is the main structure in words. The remarkably similar word crowding effect irrespective of the flanker configurations suggests that word crowding arises as a consequence of interactions of low-level letter features.

1. Introduction

Crowding refers to the increased difficulty in identifying targets due to the proximity of adjacent targets (Cline, Hofstetter, & Griffin, 1997; see Levi (2008) and Pelli, Palomares, and Majaj (2004) for review). Although the underlying mechanism of crowding is still under investigation, a common consensus is that crowding represents the failure of the object recognition process beyond the detection stage (e.g., Chung, 2010; Chung, Levi, & Legge, 2001; He, Cavanagh, & Intriligator, 1996; Levi, 2008; Levi, Hariharan, & Klein, 2002; Pelli, Palomares, & Majaj, 2004). It has been postulated that object recognition involves two stages: feature detection and feature integration (Neisser, 1967; Robson & Graham, 1981; Treisman & Gelade, 1980). Substantial evidence shows that the detection of a target is unaffected by the presence of nearby objects, implying that the perceptual errors in recognizing a target in the presence of nearby objects must occur at the second stage, or the feature integration stage, of the object recognition process (Chung, 2010; Levi, Hariharan, & Klein, 2002; Pelli, Palomares, & Majaj, 2004). At this stage where features are integrated to form a percept, features from nearby objects can influence how the features of the target are being represented or perceived. For instance, when the flankers are highly complex and contain lots of features, or when the flankers are similar to the target, the target would be less likely to be perceived veridically (Bernard & Chung, 2011). There is also recent evidence that the perceptual errors for the target could result from the compulsory averaging of features (e.g., Dakin et al., 2010; Greenwood, Bex, & Dakin, 2009; Parkes et al., 2001) or feature migration (Pelli, Palomares, & Majaj, 2004). Although the exact mechanism(s) by which flanker features cause the perceptual errors for the target is (are) still unclear, there is compelling evidence that crowding arises as a consequence of some interactions between target and flanker *features*.

Recently, Whitney and Levi (2011) suggested that crowding occurs at more than one stage in the visual hierarchy. In addition to the feature level, crowding could also occur at the higher level of visual processing where objects are represented holistically. Prominent evidence comes from studies on face identification. Like other objects, face recognition is highly susceptible to crowding (remember how difficult it is to pick out your friend from a crowd in a party?) Louie, Bressler, and Whitney (2007) reported that there was less crowding for identifying an upright face surrounded by inverted faces, compared with identifying the same upright face surrounded by other upright faces. It is commonly believed that the perception of faces is disrupted when faces are inverted because

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we cannot holistically process an inverted face. Similar results were also found for Mooney faces, two-tone monochrome photographs of real faces that have no recognizable features (Farzin, Rivera, & Whitney, 2009). The lack of recognizable features in Mooney faces implies that the perception of these images must rely on holistic processing. In general, crowding was found to be stronger when an upright Mooney face was surrounded by upright Mooney faces, and weaker when an upright Mooney face was surrounded by inverted Mooney faces (Farzin, Rivera, & Whitney, 2009). Given that crowding was diminished when holistic processing was disrupted, these studies provide evidence that crowding could also result from the interaction of high-level holistic representations of faces.

English words are composed of various numbers of letters that are each made up of a number of "features". To date, there is still no consensus as to what the actual basic features of letters are. Pixels, parts of or whole letter strokes, junctions between strokes have all been suggested as the "features" of letters. Nevertheless, it is generally agreed that the features, or components of words are letters (Pelli, Farell, & Moore, 2003). Previous studies have shown that crowding exists at both the letter level (e.g., Arditi, Knoblauch, & Grunwald, 1990; Bouma, 1970; Chung, 2002; Chung, Levi, & Legge, 2001; Latham & Whitaker, 1996; Liu & Arditi, 2000; Loomis, 1978; Toet & Levi, 1992; Whittaker, Rohrkaste, & Higgins, 1989; Yu et al., 2007) and the word level (Chung, 2004). Chung (2004) reported that word reading speed in peripheral vision suffered from crowding when target words were flanked by other words at a close distance. However, it remains unclear as to whether word crowding arises as a consequence of interactions of low-level features between words, such as letters or constituent letter parts, or the interactions between high-level holistic representations of words.

Evidence abounds for both the low-level feature-based (e.g., Beckmann, Legge, & Luebker, 1991; Chung & Mansfield, 2009; Martelli, Majaj, & Pelli, 2005; Pelli, Farell, & Moore, 2003; Rayner et al., 2006) and the high-level holistic processing of words (e.g., Cattell, 1886; Grainger & Whitney, 2004; Pelli & Tillman, 2007; Perea, Duñabeitia, & Carreiras, 2008; Reicher, 1969; Wheeler, 1970; Wong et al., 2011), which fuels the ongoing controversy as to how words are perceived. Example evidence supporting the feature-based supposition includes the finding of Pelli, Farell, and Moore (2003) demonstrating that the efficiency for identifying a word is inversely proportional to its word length, and that the performance accuracy never exceeds the prediction based on a letter-by-letter model. Further, when words are comprised of letters of different contrast polarities, which presumably disrupt the grouping of letters to form a word, word recognition performance remains similar to that for recognizing words of a single contrast polarity (Beckmann, Legge, & Luebker, 1991; Chung & Mansfield, 2009). In contrast, the well-known word superiority effect (better performance for recognizing a letter in the context of a word than in isolation: Cattell, 1886; Martelli, Majaj, & Pelli, 2005; Reicher, 1969; Wheeler, 1970), and the examples of how reading is still possible even when some of the letters within a word are scrambled in order such that the word becomes a non-word, provide some strong evidence for the holistic processing of words. Very recently, Wong et al. (2011) adopted the composite paradigm (matching one-half of a word to a target word while the other half, either aligned or misaligned with the matching half, could be the same as the target word or not) that is widely used to demonstrate holistic processing of face recognition to English word recognition. They found that word recognition exhibits the same traits as those of face recognition using the composite paradigm, consistent with the notion of holistic processing of words. However, there is no reason why both a feature-based mechanism and one that depends on holistic processing cannot jointly contribute to word recognition. In their experiments designed to systematically knock out the contributions of letters, holistic representation based on the word shape and context effect on reading, Pelli and Tillman (2007) found that all three processes contribute to the reading process, and that each process always contributes the same reading speed (measured in words per minute), even when the other processes are not operating. This finding clearly demonstrated that both low-level and high-level processing are important for reading, but how do these two processes contribute to crowding among words? In this study, we evaluated the two hypotheses for word crowding – the low-level feature interaction vs. the high-level holistic representation – by examining how word crowding changes with different configurations of flanking words.

In this study, we used oral reading speed as the performance measurement. As expected based on Chung (2004), crowding causes a reduction in reading speed when the target words are closely flanked by other words. To evaluate our hypotheses, we manipulated the configuration of flanking words to selectively eliminate some levels of representation of the words or letters while keeping others. For example, in the *scrambled* flanker configuration, the letter order in each flanking word was scrambled, resulting in a non-word, while the letters and the letter features of the flankers remained the same. In the *horizontal-flip* and the *letter-flip* conditions, the flipped words were non-words, but the letters themselves, as well as the letter features were also flipped (left–right). In the *vertical-flip* flanker configuration, each flanking word was presented upside down, which impaired the holistic representation of the word, as well as changing the orientation of letter features. The low-level feature interaction hypothesis predicts that word crowding does not depend on flanker configuration, as long as the local letter features of the flankers remain the same. In contrast, the high-level holistic representation hypothesis predicts that word crowding is stronger when the flankers are perceived as whole words, and less when the flankers are not perceived as words despite the presence of identical local features. Therefore, compared with the *control* flanker configuration (upright real words), there would be a relief of the word crowding effect and an increase of reading speed for the other unconventional flanker configurations.

2. Methods

2.1. Observers

Twelve native English speakers aged between 18 and 28 participated in this study (six in Experiment 1, four in Experiment 2 and five in Experiment 3, some participated in more than one experiment). All observers had normal or corrected to normal vision. Protocols of the study were approved by the Committee for Protection of Human Subjects at the University of California, Berkeley. All observers gave written informed consent prior to the commencement of data collection. Each observer was tested monocularly using the left eye, with the right eye covered using an eye patch.

2.2. Stimuli and general methods

We used MATLAB (version 7.7.0) and Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) to generate the experimental stimuli and control the experiments. Stimuli were four-letter words with a contrast of 99%, presented as black-on-white (luminance: white = 126 cd/m^2; black = 1 cd/m^2), on a SONY color graphic display (model: Multiscan E540; refresh rate: 75 Hz; resolution: 1280 $\times$ 1024; dimensions: 39.3 cm $\times$ 29.4 cm) controlled by a Macintosh computer. The word stimuli were rendered in Courier, a fixed-width font, to ensure that the physical length of each word was identical.

Oral reading speed was measured using the rapid serial visual presentation (RSVP) paradigm. On each trial, six unrelated four-letter words were presented one at a time at 10° eccentricity in the nasal visual field, as in Chung (2004). We specified the eccentricity as the distance between the fixation target (a dot of 0.3° diameter) and the center of the target word (i.e., between the second and the third letter of the word). Testing was performed at 40 cm, using a print size of 2° (defined as *x*-height in lowercase). This print size exceeded the critical print size (the smallest print size for which reading is possible at maximum speed) of all observers (measured in preliminary testing) at the tested eccentricity. To induce crowding, each target word was flanked above and below by two different words (also four letters in length). The baseline-to-baseline separation between the target word and one of its flankers was referred to as the vertical word spacing. Given that crowding strongly depends on the separation between a target and its flanker, we tested several vertical word spacings to obtain a full function of how reading speed changes with spacing. The spacings tested varied among the three experiments and will be given in the sections below.

2.3. Experiment 1: main experiment

Four vertical word spacings, 0.7×, 1×, 1.5×, and 2× the standard word spacing (2.6× the *x*-height; Chung, 2004), were tested (see Fig. 1). These spacings correspond to 3.64°, 5.2°, 7.8°, and 10.4° of visual angle, respectively. The 0.7× spacing was the smallest spacing that we could test without the letters from the target and the flankers touching one another, which could induce overlap masking. For comparison, we also measured reading speed for single words (i.e., in the absence of flankers).

To determine if word crowding results from the interference of low-level features or high-level holistic representation of words, we tested five different flanker configurations. Fig. 2 shows these five flanker configurations: *control* – flanking words were oriented upright; *scrambled* – letters in each flanking word were scrambled in order; *horizontal-flip* – each flanking word was the left–right mirror-image of the original; *letter-flip* – each letter of the flanking word was the left–right mirror-image of the original; and *vertical-flip* – each flanking word was the up–down mirror-image of the original.

All the words used in this experiment were four-letter words that appeared frequently in normal English usage. We adopted the word list originally developed by Legge, Mansfield, and Chung (2001), and expanded it to include a total of 913 words by adding more commonly used four-letter words. All observers previewed the word list and none of them reported difficulty in recognizing any of the words. Over the course of the experiment, each word was presented to each observer five or six times as the target word, with a total of approximately 5000 presentations of target words. Target words were selected randomly from the word list without replacement until all the words were presented, before

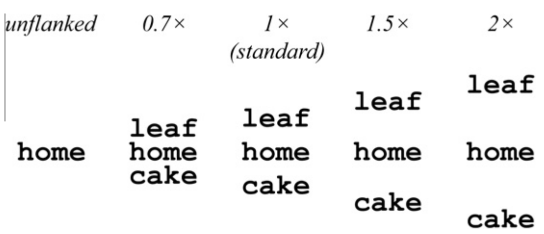

Fig. 1. Samples of the target word "home" presented in the unflanked condition and flanked conditions for the *control* condition where the flanking words were oriented upright. The numbers on the top row of the figure refer to the nominal word spacing between each pair of vertically adjacent words.

we repeated the word list again. On each trial, the flanking words were selected randomly from the same four-letter word list with replacement, with the only constraint that the two flanking words were different from each other and different from the target word.

There were a total of 21 testing conditions derived from all possible combinations of the flanker configurations and vertical word spacings (1 unflanked condition + 5 flanker configurations × 4 vertical word spacings). For a given testing condition, we used the Method of Constant Stimuli to present words at six RSVP word exposure durations that spanned approximately 1 log unit, with a total of six trials per duration (six target words per trial). Observers were instructed to read the target words aloud as accurately as possible, while fixating a fixation dot. An experimenter scored the number of words read correctly after each trial. Word identification was scored as correct on the condition that the observers reported the word correctly, regardless of the reporting sequence. We also recorded observers' responses as digital audio files for later analysis to determine if there was any consistent pattern in the response errors. Such an analysis on a random sample of trials (756 trials for each of two observers) showed that observers' response errors were largely random, with no clear evidence that observers reported one of the flanking words as the target (mislocation errors). For each testing condition (flanker configuration × vertical word spacing), we fit the set of data relating performance and word exposure duration with a cumulative Gaussian curve to construct a psychometric function, from which we derived the word exposure duration that yielded 80% accuracy. This word exposure duration was then converted to reading speed in words per minute (wpm). Fig. 3 shows sample psychometric functions for the five flanker configurations and for two word spacings, all obtained from a randomly chosen observer. During testing, eye movements of observers were monitored by the experimenter. A trial was discarded when eye movements away from fixation were detected (estimated accuracy of 1.5°). On average, approximately 2.4% of the trials were discarded.

For each observer, testing consisted of three sessions with 21 blocks (one for each condition) per session. There were 12 trials in each block, with two trials tested for each of the six durations. The block sequence was pseudo-randomized and counterbalanced across sessions and observers to minimize any sequencing effects. Before the actual testing, observers were given practice on all conditions. Data from the practice trials were not included in the data analysis.

A repeated measures ANOVA was used to analyze the data. The two within-subject factors were flanker configuration and vertical word spacing. Post-hoc tests were performed as needed.

2.4. Experiment 2: the 0.42× spacing

According to "Bouma's law", crowding exists when a flanker is within a distance equivalent to half the target eccentricity from the target (Bouma, 1970). Pelli (2008) illustrated that Bouma's law is observed for a variety of objects and is not limited to letters, as Bouma originally studied. To date, there is no evidence showing that word crowding observes Bouma's law (Pelli did not test word recognition). However, if we assume that word crowding follows Bouma's law, then among the different vertical word spacings that were tested in Experiment 1, only the smallest one (0.7× spacing, equivalent to a separation of 3.64°) would yield crowding. As we shall see later (Section 3), this was indeed the case. To ascertain that our finding of an invariant shape of the reading speed vs. word spacing function for all flanker configurations would still hold for an even smaller word spacing, where reading speed should be even lower due to more crowding, we tested four additional observers (none of them participated in Experiment 1) using similar experimental paradigm as in Experiment 1, with the following

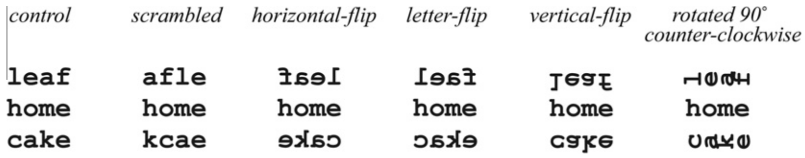

Fig. 2. Examples of the six flanker configurations. *Control*, *scrambled*, *horizontal-flip*, *letter-flip* and *vertical-flip* were the flanker configurations tested in Experiment 1. The *90° rotated* condition was tested in Experiment 3. See text for a detailed description of each of these flanker configurations. The vertical word spacing shown here was 1× standard word spacing.

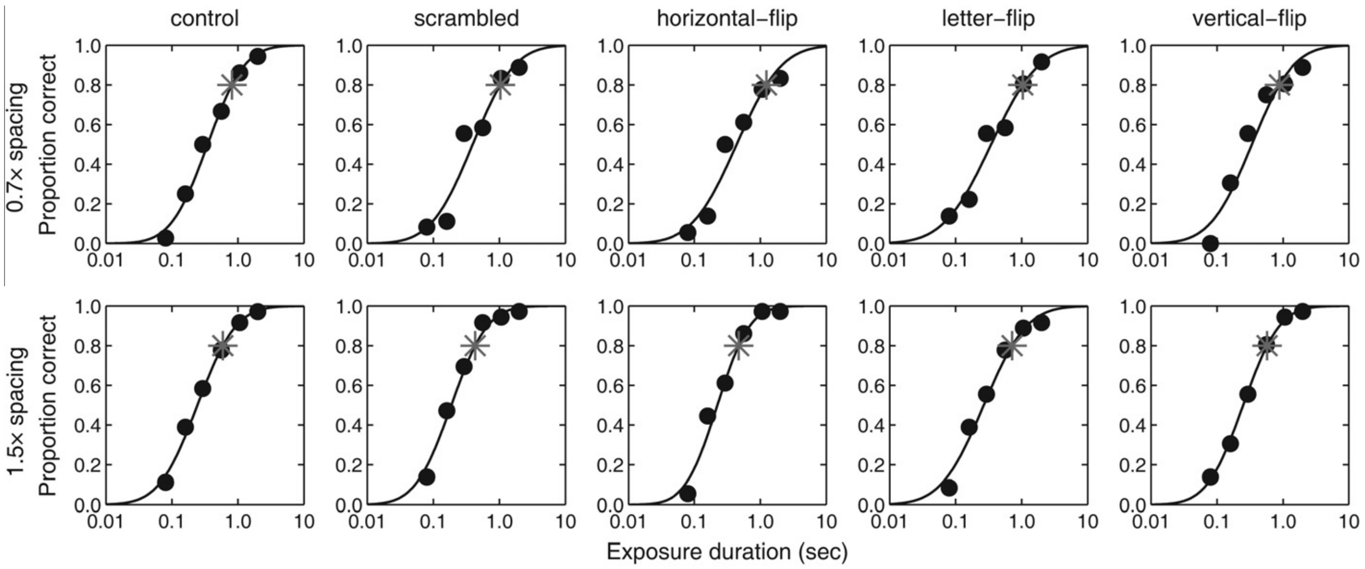

Fig. 3. Sample psychometric functions relating proportion correct of word recognition with word exposure duration (s) are shown for two vertical spacings (0.7× and 1.5× standard spacings) and for all flanker configurations. All psychometric functions were obtained from observer S3. The gray asterisk in each panel represents the exposure duration that yielded 80% accuracy of word reading, which was subsequently converted to reading speed in words per minute (wpm).

exceptions. For each flanker configuration, we tested two vertical word spacings that were tested in Experiment 1 (0.7× and 2× standard word spacing), as well as the unflanked condition, using the same word list as in Experiment 1. These conditions were simply for replicating the same conditions in Experiment 1. In addition, we tested two new conditions – 0.42× standard word spacing (equivalent to a separation of 2.18°) and the unflanked condition, using a modified word list that contained only a subset of the original words used in Experiment 1. In Experiment 1, the 0.7× spacing was the smallest spacing that we could use without the letters from the target and the flankers touching one another. To further reduce spacing while ensuring no overlapping between the target and flankers, we used only words that did not have ascenders or descenders as target words. Flankers were also selected such that the upper flankers had no descenders and the lower flankers had no ascenders (see Fig. 4 for an example). With these criteria for selecting the target and flanking words, the 0.42× spacing became the smallest spacing that we could test without any overlapping

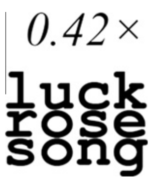

Fig. 4. An example of the target word "rose" presented in the presence of two upright flankers (the *control* condition), at a 0.42× spacing, the smallest spacing used in Experiment 2.

between the target and flankers. A total of 90, 654 and 169 words satisfied the criteria to be considered as the target, upper flanker and lower flanker, respectively. A repeated measures ANOVA was used to analyze the data. The two within-subject factors were flanker configuration and vertical word spacing. Post-hoc tests were performed as needed.

2.5. Experiment 3: 90° rotated letters

As we shall see later in Section 3, the various flanker configurations tested in Experiment 1 produced similar crowding effects. One explanation for this finding is that the periodic vertical pattern, the main structure of printed words according to Watt and Dakin (2010), was present in all five flanker configurations, thus yielding similar word crowding effects. This explanation predicts that by rotating the letters in the flanking words by 90°, the encoding of each flanking word would be made more difficult. Thus if word crowding occurs at or after the stage at which the main structure of words (the periodic vertical pattern) is extracted, then there should be less crowding for these 90° rotated flanking words. Of course, the reduction in crowding for this condition could also be explained as a disruption of the word shape, which could be important for the holistic representation of words, and the unconventional orientation of the letters or the letter features present in the flanking words. To evaluate our prediction, we tested five observers (three of them also participated in Experiment 1) using a similar experimental paradigm as in Experiment 1, with the exception that each letter of the flanking word was rotated 90° counter-clockwise (see Fig. 2). Consequently, letters with ascender or descender in the flankers occupied more horizontal space. To minimize crowding within the flanking word itself, we excluded words with overlapping letters or with at least three letters touching one another. This yielded a total of 729 usable words. In addition to the vertical word spacings tested in Experiment 1 (unflanked condition, 0.7×, 1×, 1.5×, and 2× standard word spacing), we tested an even smaller separation, 0.64× spacing, the smallest spacing that did not have any overlapping between the 90° rotated letters and the target word. A repeated measures ANOVA was used to analyze these data. The within-subject factor was vertical word spacing. Post-hoc tests were performed as needed.

3. Results

3.1. Experiment 1: main experiment

Reading speed in words per minute (wpm), plotted as a function of vertical word spacing for the five flanker configurations, and for each observer who participated in Experiment 1, is shown in Fig. 5. The unflanked reading speed for the six observers ranged between 46.4 wpm and 236.7 wpm (the geometric mean was 94.1 ± 52.9 [SD] wpm). Despite the individual variability, there is a consistent trend that reading speed decreased with smaller word spacing, for all five flanker configurations.

To facilitate the comparison of how reading speed was affected by the flankers for different flanker configurations, we normalized each observer's reading speed measured with flankers to that for unflanked words (i.e., dividing each reading speed by the reading speed for the unflanked condition). Fig. 6 shows the normalized reading speeds averaged across the six observers, plotted as a function of the vertical word spacing for the five flanker configurations. In general, reading speed increased with word spacing until the critical word spacing, beyond which reading speed became independent of word spacing. Therefore, it was of no surprise that we found a significant main effect of vertical word spacing on normalized reading speed ($F(3,15) = 16.36$, $p < 0.0005$). Post-hoc pairwise comparisons showed that reading speed was unaffected by the presence of flanking words until the word spacing was smaller than 1× spacing. In other words, crowding was found only when word separation was smaller than the standard word spacing. At the 0.7× spacing, the geometric mean reading speed was 60.7 ± 40.3 wpm, representing a 35.5% reduction from the unflanked reading speed (94.1 ± 52.9 wpm). The important issue, however, was whether or not the change in reading speed with word spacing varied with flanker configuration. Across observers, the main effect of flanker configuration on normalized reading speed was not significant ($F(4,20) = 0.38$, $p = 0.82$). The interaction between flanker configuration and vertical word spacing was also not significant ($F(12,60) = 1.86$, $p = 0.06$). These results imply that the changes in reading speed with word spacing were similar for the five flanker configurations. In addition, paired *t*-tests revealed that reading speeds for the five flanker configurations at the 0.7× spacing condition were not statistically different from one another (for all pairs, $p > 0.05$), further confirming that the word crowding effects were similar across the five flanker configurations.

To quantitatively compare the changes of reading speed with word spacing for the five flanker configurations, we fit each data set of normalized reading speed vs. the logarithm of vertical word spacing with a bilinear function which has been previously used to obtain the critical value of independent parameter (e.g., print size, letter spacing and word spacing) that could affect reading performance (Chung, 2002, 2004; Chung, Mansfield, & Legge, 1998; Mansfield, Legge, & Bane, 1996). The parameter of interest in the present study was the *critical vertical word spacing*, the spacing beyond which the reading speed measured with flankers reached that of the unflanked condition (normalized reading speed = 1). During the curve fitting, we constrained the maximum normalized reading speed to 1 and the slope of the second line to 0. The only variable parameters in the bilinear function are the critical vertical word spacing and the slope of the first line. The critical vertical word spacings estimated from the averaged data were 1.02×, 1.10×, 1.09×, 1.02×, and 1.07× the standard spacing for the control, scrambled, horizontal-flip, letter-flip, and vertical-flip flanker configurations, respectively. These values were not different from one another ($F(4,20) = 0.98$, $p = 0.44$), nor were the slope of the first line ($F(4,20) = 0.61$, $p = 0.66$) estimated for each individual observer. For the five flanker configurations in the order listed above, the slopes estimated from the averaged data were 0.90, 0.80, 0.60, 0.94, and 0.92, respectively. The similar values obtained for the critical vertical word spacing and the slope of the first line of the bilinear fit imply that the functions of normalized reading speed vs. vertical word spacing were similar for the five flanker configurations.

3.2. Experiment 2: the 0.42× spacing

Fig. 7 shows reading speed for individual observers as a function of vertical word spacing for the five flanker configurations tested in Experiment 2. Using the original word list (the one used in Experiment 1), the geometric reading speeds were 56.8 ± 13.8 wpm, 98.0 ± 27.9 wpm and 96.5 ± 29.8 wpm for the 0.7× spacing, 2× spacing and the unflanked condition, respectively. These values are very similar to those obtained for the same conditions in Experiment 1, even though different observers participated in the two experiments. Using the modified word list, the geometric reading speeds were 32.9 ± 4.5 wpm and 77.6 ± 18.1 wpm for 0.42× spacing and the unflanked condition, respectively. Across all observers, reading speed decreased with smaller word spacing, for all five flanker configurations. For the unflanked condition, observers' reading speed was on average, 20% slower when reading words

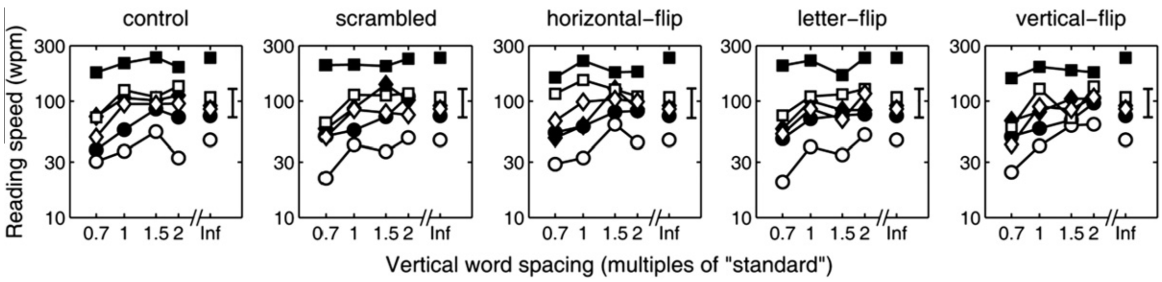

Fig. 5. Reading speed (wpm) is plotted as a function of vertical word spacing for the five flanker configurations. The unflanked condition is equivalent to having an infinite vertical word spacing ("Inf" on the *x*-axes). Each panel shows the data from all six observers (represented by different symbols) who participated in Experiment 1. We used bootstrapping with 5000 resamplings to estimate the 95% confidence intervals. Error bars represent the averaged 95% confidence intervals for each flanker configuration and are given near the right ordinate in each panel.

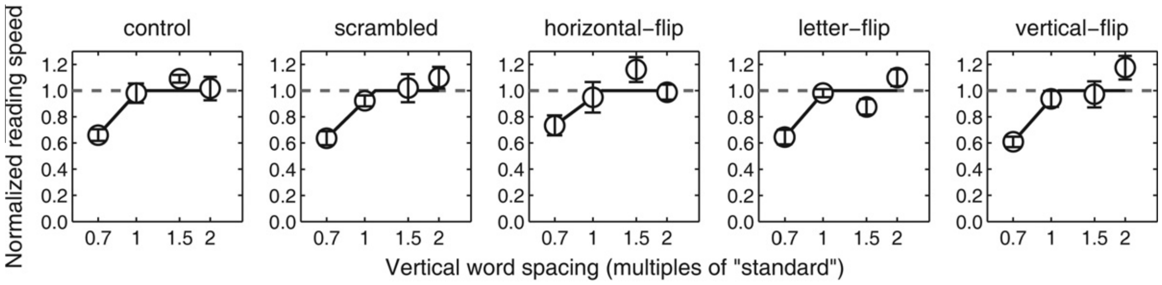

Fig. 6. Normalized reading speed, averaged across all six observers who participated in Experiment 1, is plotted as a function of vertical word spacing for the five flanker configurations. Normalized reading speed refers to the ratio of reading speed for the flanked to unflanked condition. Error bars represent ±1 SEM.

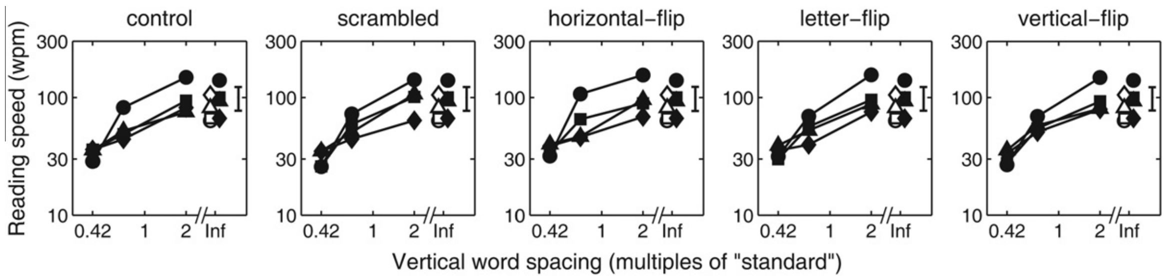

Fig. 7. Reading speed (wpm) is plotted as a function of vertical word spacing for the five flanker configurations. The unflanked condition is equivalent to having an infinite vertical word spacing ("Inf" on the *x*-axes). Each panel shows the data from all four observers (represented by different symbols) who participated in Experiment 2. Open symbols represent the unflanked reading speeds measured with the modified word list. We used bootstrapping with 5000 resamplings to estimate the 95% confidence intervals. Error bars represent the averaged 95% confidence intervals for each flanker configuration and are given close to the right ordinate in each panel.

without ascenders and descenders. Therefore, we normalized each observer's flanked reading speed to the corresponding unflanked reading speed measured with the same word list. The group-averaged normalized reading speeds are shown in Fig. 8. For comparison, we included the data from Experiment 1, replotted from Fig. 6. The normalized reading speeds at 0.7× and 2× spacing obtained in this experiment were highly similar to those obtained in Experiment 1, implying that our results are replicable.

For the data obtained in Experiment 2, we found a significant main effect of vertical word spacing on normalized reading speed ($F(2,6) = 68.4$, $p < 0.0005$). As shown in Fig. 8, reading speed was reduced dramatically at 0.42× (an average reduction of 58% compared with the unflanked reading speed; $p < 0.01$ for all one-sample *t*-tests) and 0.7× spacing (41% reduction; $p < 0.01$) for all flanker configurations. Across observers, we did not find a significant effect of flanker configuration ($F(4,12) = 0.61$, $p = 0.66$) or any interaction between flanker configuration and vertical word spacing ($F(8,24) = 0.55$, $p = 0.81$). These results, consistent with the findings of Experiment 1, confirmed that the changes in reading speed with word spacing were similar for the five flanker configurations.

3.3. Experiment 3: 90° rotated letters

Results from Experiment 3 are summarized in Fig. 9. The left panel plots individual observers' reading speed, while the right panel plots the group-averaged normalized reading speed, as a function of vertical word spacing for the 90° rotated flanker configuration. As expected, a significant main effect of vertical word spacing on reading speed was found ($F(4,16) = 4.03$, $p = 0.02$). Averaged across observers, there was a reduction in reading speed of 21% for 0.7× spacing and 36% for 0.64× spacing, compared with the unflanked reading speed. The geometric mean reading speed was 80.9 ± 30.6 wpm for 0.64× spacing, 100.0 ± 45.4 wpm for 0.7× spacing, and 128.4 ± 46.7 wpm for the unflanked condition. We also fit the normalized reading speed data using the bilinear fit as described in Experiment 1. As shown in the right panel of Fig. 9, normalized reading speed increased with vertical word spac-

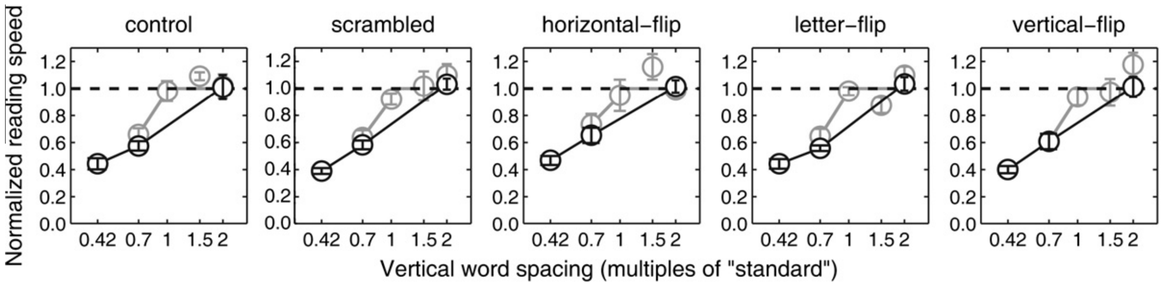

Fig. 8. Normalized reading speed, averaged across the four observers who participated in Experiment 2, is plotted as a function of vertical word spacing for the five flanker configurations. Normalized reading speed refers to the ratio of reading speed between the flanked and unflanked conditions as measured using the same word list. Error bars represent ±1 SEM. For comparison, data obtained for Experiment 1 are included in gray (replotted from Fig. 6).

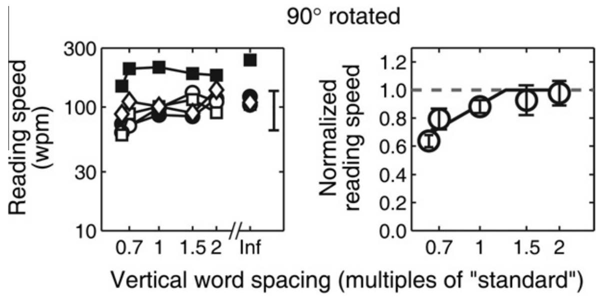

Fig. 9. Reading speed for individual observers (left panel) and the group-averaged normalized reading speed (right panel) is plotted as a function of vertical word spacing for the 90° rotated flanker configuration. Each symbol in the left panel represents data obtained from a single observer. Error bars in the left panel represent averaged 95% confidence intervals. Error bars in the right panel represent ±1 SEM.

ing (slope = 0.47) until it reached the critical vertical word spacing of 1.25× the standard spacing. Compared with the parameters estimated in Experiment 1, the critical vertical word spacing for the 90° rotated condition was slightly larger, which was due to the shallower slope (0.47) of the first fitted line. When we constrained the slope of the first fitted line at 0.83 (average of the slopes estimated from the averaged data for the five flanker configurations in the main experiment), the critical vertical word spacing for the 90° rotated condition was 1.01, similar to the critical vertical word spacings estimated for the other five flanker configurations in Experiment 1.

4. Discussion

Consistent with the findings of Chung (2004), the present study demonstrated that crowding occurs between vertically adjacent words and can be reduced with increasing vertical word spacing. The novel result of this study is that the word crowding effect induced by the flanking words is invariant across the various flanker configurations tested.

Martelli, Majaj, and Pelli (2005) investigated whether words and faces are recognized as a whole or by their parts. They found internal crowding for both words and faces, and suggested that both objects are recognized by parts (i.e., letters or facial features) and the parts are recognized holistically. Likewise, a study examining the legibility of Chinese characters (each has its basic meaning and sometimes can stand alone as a word) also indicated that internal crowding exists (Zhang et al., 2009). While faces and words have internal crowding arising from the interaction among the internal features within them, they also suffer from external crowding induced by surrounding objects. Previously, using faces as target and flanking stimuli, Louie, Bressler, and Whitney (2007) and Farzin, Rivera, and Whitney (2009) found a weaker crowding effect for identifying upright faces surrounded by inverted faces, compared with identifying upright faces surrounded by other upright faces. These results suggest that face crowding not only occurs between low-level features in face images, but also arises between holistic representations of faces. This raises the question of whether the same applies to words. In the present paper, we did not find any alleviation of crowding at small word spacings when upright target words were flanked by upside-down words, which presumably impaired the holistic representation of the flanking words. In fact, all our other flanker configurations disrupted the holistic representation of words, in addition to disrupting other "features" in the word stimuli, and the lack of an alleviation of crowding at small word spacings was consistent across the different flanker configurations. Based on these results, we conclude that word crowding occurs at a stage before words are represented holistically, and is likely due to an interaction of low-level features.

What then, are these "low-level features"? As mentioned in the Introduction, to date, there is no consensus as to what are the basic features of letters. However, based on previous studies, some likely candidates include whole letters (e.g., Pelli, Farell, & Moore, 2003), letter strokes (e.g., Fiset et al., 2008; Geyer & Dewald, 1973; Gibson, 1963), or even junctions between letter strokes (e.g., Fiset et al., 2008, 2009; Lanthier et al., 2009). Our *scrambled* condition was the only flanker configuration in which whole letters were preserved (only the letter order within the word was scrambled). We did not find an alleviation of crowding at small word spacings for this condition. For the *horizontal-flip* and *letter-flip* conditions, in addition to the disruption of word form, letters were rendered as the left–right mirror-images of the original. Therefore, if word crowding requires the proper representations of letters, in other words, letter-strokes have to be presented in the correct orientations (oblique strokes are most affected by these manipulations) and different letter strokes have to maintain proper spatial relationships with one another (junctions are most affected by these manipulations), then these flanker configurations should have caused a reduction of crowding at small spacings. This did not happen. Likewise, when we rotated each letter of the flanker by 90° (the *90° rotated* condition), the representation of each letter in the flankers changed (orientations of letter strokes and the junctions of letter strokes were all rotated by 90°). Further, this manipulation disrupted the periodic vertical pattern that is present in word stimuli, which presumably forms the main structure of printed words (Watt & Dakin, 2010). Yet, this condition, like all others, did not alleviate crowding at small letter spacings. These findings suggest that the manifestation of word crowding does not require (1) the flankers to be real words; (2) the flankers to comprise real letters (letters of proper orientations); and (3) letter strokes to be oriented correctly and maintain the proper relationships with one another. The remarkably similar word crowding effect observed, irrespective of the flanker configurations, points toward an early stage before letter strokes are properly represented, as the substrate at which word crowding occurs. Can word crowding occur at an even earlier stage? The way to test this is to disrupt the flankers at even more basic "feature" levels, such as scrambling letter strokes, deleting random pixels or scrambling the phase spectrum of the flanker words. Previously, He and Tjan (2004) showed that for *letter crowding*, patches of letter noise (created by scrambling the phase spectrum of a letter but retaining its power spectral density) are just as effective as real letters as flankers. For *word crowding*, we do not yet know if a string of letter noise patches, or a string of randomly scrambled letter strokes would be equally effective as real word or word-like flankers. We are currently investigating this possibility.

Our results place constraints on the possible neural site for word crowding. The site is likely to be beyond V1 as the V1 neurons are widely believed to be orientation-tuned, and that our results showed that the word crowding effect is not sensitive to the orientation information of the "features". The site is also likely to be before words are represented in the putative "visual word form area" (VWFA), the putative neural site for visual word recognition (e.g., Cohen et al., 2000; McCandliss, Cohen, & Dehaene, 2003), as a recent paper showed that the neural responses of this area are similar for words and non-word consonant letter strings (Baker et al., 2007).

For the 90° rotated flanker configuration, because of the shorter dimension in letter width than height, the smallest non-overlapping vertical word spacing was 0.64× spacing. Note that the edge-to-edge spacing between a target word and its flankers was the same for the 0.64× spacing for the 90° rotated flanker configuration and the 0.7× spacing for other flanker configurations used in Experiments 1 and 2. Once the edge-to-edge spacing was equated,[1] the reduction in reading speed (the crowding effect) at the smallest non-overlapping vertical word spacing was comparable across all flanker configurations. In addition, the critical word spacing was similar between the 90° rotated flanker condition and the other five flanker configurations used in Experiment 1, once the rate of change of reading speed vs. vertical word spacing (the slope of the first line in the bilinear fit) was equated, again, implying that the crowding effect was not different among these various flanker configurations. When we allowed the slope of the first fitted line free to vary, we found that the slope was shallower and the critical vertical word spacing was larger for the 90° rotated condition compared with the other flanker configurations. These results indicate that although the magnitude of crowding at the 0.7× spacing was smaller, the size of the crowding zone was larger for the 90° rotated condition compared with the other flanker configurations. However, the larger crowding zone should not distract from the main finding that we did not find a reduction of crowding at small spacings for the 90° rotated flanker configuration.

In our experiments, we only found crowding at the 0.42× and 0.7× spacings, which correspond to crowding extents of 2.18° and 3.64°. According to Bouma's law (Bouma, 1970; Pelli, 2008), crowding extends to approximately half the target eccentricity, but this only applies to the configuration in which the target and flankers are presented along the radial meridian from the fovea. The crowding extent is even smaller (~0.1× the eccentricity; see Table 1 in Chung, Levi, and Legge (2001)) when the target and flankers are presented along the tangential meridian with respect to the fovea. In our experiments, the target word was always flanked above and below by other words, and when tested at 10° in the nasal visual field, the target and flankers lied along a tangential meridian with respect to the fovea. This tangential arrangement of the target and flankers might explain why we only found crowding at spacings smaller than the standard vertical word spacing. Clearly, one way to obtain a larger crowding effect was to perform our testing in the lower or upper vertical field instead, as in Chung (2004). In fact, we originally tested at 10° lower field in our pilot experiment, but we chose to test at 10° nasal field for the experiments reported here for the following reasons. First, consistent with Chung (2004), in our pilot experiment, reading speed in the presence of flankers, even at 2× the standard spacing, was only 75–80% of the unflanked reading speed. However, we were unable to test spacings larger than 2× spacing, because at 2× spacing, the upper flanker was already at a distance of 10.4° from the testing eccentricity. Spacings larger than the 2× spacing would place the upper flanker above fixation in the upper field. Second, even for vertical spacings smaller than 2× spacing, when the upper flanker came very close to the fixation target, observers found it difficult to keep their fixation steady. Consequently, testing was very tedious (we had to abort or discard many trials) and the data were very noisy. Nevertheless, despite the difference in the magnitude of crowding obtained in the nasal vs. the lower field, the main finding remains the same – that the functions relating reading speed with word spacing were invariant across the different flanker configurations.

Words are processed at multiple stages in the visual system. Besides letters, the holistic information of words and even sentence context also contribute to word reading (Pelli & Tillman, 2007). It is possible that word crowding occurs at several levels with domination of one over the others. For instance, the interaction of high-level holistic representations of words may be too weak to be expressed in the presence of strong interactions of low-level letter features. Indeed, Pelli and Tillman (2007) showed that the information provided by the low-level letter features accounted for approximately 62% of the normal reading speed, compared with the 16% contribution from the holistic word form information. It remains possible that the effect of flanker configuration might emerge if the performance measurement targets other levels of word processing, such as comprehension or contextual effects, instead of word recognition or reading speed.

In daily reading, words in text are normally aligned horizontally and more often closely flanked on the left and right sides. Moreover, within a word, there is more uncertainty along the horizontal direction (i.e., number of letters in word) than the vertical direction (letter/word height). Although it might appear that word crowding along the horizontal dimension deserves more attention, such a crowding effect was not measured in the present study for two reasons. First, it is not possible to present the target word with two flanking words on the left and right sides at 10° in the nasal visual field without extending the stimulus to the fixation point and the temporal visual field. Second, even the minimal non-overlapping spacing would place the target word within the so-called uncrowded window (the region where target–flanker spacing exceeds the critical spacing required to prevent crowding; Pelli & Tillman, 2008). Although these problems would not exist if we used one- or two-letter words, we chose to use four-letter words as stimuli to keep the word complexity at a moderate level and the word length close to the standard word length in printed text (six characters including spaces and punctuation marks; four or five characters if only letters were counted; Carver, 1976, 1990).

This study provides a new insight in the mechanism of word crowding. We found that the word crowding effect remains the same regardless of the variations in flanker configuration, supporting the hypothesis that word crowding arises as a consequence of the interaction of low-level letter features.

[1] Recently, Levi and Carney (2009) showed that the magnitude of crowding depends on the distance between the centroid of the flanking elements and the target, instead of the edge-to-edge separation between the flankers and the target. Their targets were Gabor patches and the flankers were sine-wave gratings windowed by different two-dimensional shapes. Therefore, specifying the centroid of each of the flanker was easy. In our study, we specified the target–flanker spacing as the edge-to-edge separation instead of one that depends on the centroid of the flanking word because of the following reasons. First, our word stimuli are made up of black letter strokes surrounded by white spaces. Unlike grating patches, it is unclear that the perception of the centroid of a word for our list of four-letter words would be shifted significantly depending on the letter composition, when we considered the many trials and thus, combinations of letters, that we tested. Second, for the 13 lowercase letters that do not have ascenders and descenders, the centroid of the letter is unlikely to change significantly when the letter is rotated by 90°. For the other 13 lowercase letters that have an ascender or a descender, rotating the letter by 90° would have shifted the centroid horizontally rather than vertically, and would not have affected our specification of the target–flanker separation. Although we acknowledge that crowding could depend on the centroid-to-centroid, instead of edge-to-edge, separation between a target and a flanker, in our case of word stimuli, we do not think that the difference in how the separation was specified would have a significant effect on our conclusions, but merely a modulation of the magnitude of crowding.

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