Whole report uncovers correctly identified but incorrectly placed target information under visual crowding

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Multiletter identification studies often find correctly identified letters being reported in wrong positions. However, how position uncertainty impacts crowding in peripheral vision is not fully understood. The observation of a flanker being reported as the central target cannot be taken as unequivocal evidence for position misperception because the observers could be biased to report a more identifiable flanker when failing to identify the central target. In addition, it has never been reported whether a correctly identified central target can be perceived at a flanker position under crowding. Empirical investigation into this possibility holds the key to demonstrating letter-level position uncertainty in crowding, because the position errors of the least identifiable central target cannot be attributed to response bias.

We asked normally-sighted observers to report either the central target of a trigram (partial report) or all three characters (whole report). The results showed that, for radially arranged trigrams, the rate of reporting the central target regardless of the reported position in the whole report was significantly higher than the partial report rate, and the extra target reports mostly ended up in flanker positions. Error analysis indicated that target-flanker position swapping and misalignment (lateral shift of the target and one flanker) underlay this target misplacement. Our results thus establish target misplacement as a source of crowding errors and ascertain the role of letter-level position uncertainty in crowding.

Introduction

It is well known that reporting the identity of an object in the visual periphery becomes difficult with the presence of flanking objects (Bouma, 1970; Levi, 2008; Stuart & Burian, 1962). This "crowding effect" is considered a bottleneck in peripheral visual recognition (Levi, 2008), as well as a challenge for persons who suffer from central field loss and have to rely on peripheral vision to perform daily visual tasks like reading (Chung & Legge, 2009;

Legge et al., 2007; Levi, 2008). Most crowding studies hypothesize that the identity of the target object is compromised by the flankers. One hypothesized cause of identity errors is wrongful feature pooling in which features of the flankers are pooled into the target when flankers and the target fall into a crowding zone (Greenwood, Bex, & Dakin, 2009, 2010; Levi, Hariharan, & Klein, 2002; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Pelli, Palomares, & Majaj, 2004). An alternative cause of identity errors under crowding is limited attentional resolution which hinders spatial details

from reaching perceptual awareness (He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001).

However, reporting errors under crowding may not always result from compromised identity of the central target. Studies of short-term memory using tachistoscopic multiletter stimuli with masking and/or bar-probe partial report reveal that a large portion of observed errors result from correctly identified letters being reported in wrong spatial positions (Di Lollo, 1977; Dick & Mewhort, 1967; Hagenzieker, Heijden, & Hagenaar, 1990; Mewhort, 1987; Mewhort, Campbell, Marchetti, & Campbell, 1981; Van der Heijden, 1987; Van der Heijden, Hagenaar, & Bloem, 1984). Studies of interactions between letter position and retinal eccentricity using horizontal letter strings straddling the fovea typically find that the letters near the fovea and the two ends of the letter string are more legible than those placed more peripheral and flanked by other letters on both sides, forming a "W-shaped" serial position curve (Di Lollo, 1977; Estes, Allmeyer, & Reder, 1976; Krumhansl, 1977; Townsend, Taylor, & Brown, 1971; Wolford, 1975). Again, a large portion of the observed errors are position errors.

Huckauf and Heller (2002) investigated whether the results from these studies could be generalized to crowding because stimuli used in these studies are long strings passing through the fovea, and the letter to be reported is indicated by a bar probe trial-by-trial, while stimuli used in crowding studies are typically short-letter strings (e.g., trigrams) presented in the periphery, and the target position is specified prior to the experiment. They studied position errors in crowding and found that flankers were reported as the target at a rate higher than chance. In addition, Huckauf and Heller (2002) compared results of partial report (reporting only the central letter as in a typical crowding experiment) and whole report (reporting all three letters) from two groups of observers. They compared how many left and right flankers were reported to the center in whole and partial reports, concluding that the observed flanker position errors resulted from position uncertainty in later rather than earlier visual processing. However, the observation that flankers are reported as the target may not provide unequivocal evidence that letter positions in a crowded stimulus are misperceived. Because the flankers are usually much more identifiable than the target (Bouma, 1973), an equally valid explanation, as discussed in Strasburger (2005), is that the observers were "just biased to respond in that manner when they are unable to identify the target." If this explanation is true, then reporting a flanker as the target may have little to do with misperceived position. We know of no crowding study that either disputes or proves this response bias explanation.

Relevant to our current experiments, Huckauf and Heller (2002) also compared the rates of correctly reporting the central target at the center of the response trigram in whole and partial reports, and their results showed that the whole report rate was higher than the partial report rate at 4° retinal eccentricity, but these rates were similar at 7° eccentricity. However, they did not further explore the implications of these results.

We believe that there is a fundamental difference between where the flankers are reported (Huckauf & Heller, 2002) and where the central target is reported in understanding position errors in crowding. As previously stated, reporting a flanker as the target may not necessarily lead to the conclusion of position uncertainty because of the response bias due to the drastic difference in target and flanker identifiability (Strasburger, 2005). However, if it can be shown that the central target can be correctly identified but reported in a flanker position, then the response bias explanation becomes inapplicable and a conclusion can be drawn that misperception of the positions of correctly identified letters indeed occurs in crowded stimuli.

In this study, we tested the target misplacement hypothesis that a correctly identified central target could be perceived at a flanker position under crowding. Because the typical partial report paradigm cannot be used to determine the fate of the central target when a response error occurs, a partial-versus-whole report experiment similar to that of Huckauf and Heller (2002) but with a within-subject design was conducted. More importantly, our data analysis was focused on whether the rate of reporting the central target regardless of the reported position in whole report was higher than the rate of reporting the central target in partial report, and if so, whether the extra target reports ended up at flanker positions. Our results demonstrated that a correctly identified central target was perceived at a flanker position at a higher-than-chance rate in whole report, thus supporting the target misplacement hypothesis.

Methods

Participants

Eight native Chinese speakers in their 20s with normal or corrected-to-normal vision participated in the study. Two participants were the first two authors. Others were new to psychophysical observations and naïve to the purpose of the study. All observers had at least a college education. Informed consent was obtained from each observer prior to testing. This study adhered to the Declaration of Helsinki.

Apparatus

The stimuli were generated by a PC-based WinVis program (Neurometrics Institute, Oakland, CA) and

were presented on a 21-inch Sony G520 color monitor (2048 × 1536 resolution, 0.189 mm × 0.189 mm pixel size, 75 Hz frame rate, 50 cd/m^2 mean luminance) at a viewing distance of 0.8 m. An Eyelink II eye tracker (SR Research, Kanata, Ontario, Canada) was used to monitor eye movement in half of the observers in Experiments I and II and in all observers in Experiment III. A chin-and-head rest helped stabilize the head of the observer. Experiments were run in a dimly lit room. Viewing was monocular.

Stimuli

The test stimulus (Figure 1a) was a meaningless three-character string of equally sized, equally spaced Chinese characters arranged in a horizontal or vertical orientation. The three characters were randomly selected without repetition from a group of 10 (Figure 1a) that had a similar number of strokes (two to four strokes) and legibility (Zhang, Zhang, Xue, Liu, & Yu, 2007). These 10 characters were similar to the Sloan letters in terms of the mean stroke frequency (2.22 versus 2.02 strokes/letter; Zhang et al., 2007) and crowding characteristics (nearly identical identification threshold versus eccentricity functions; Zhang, Zhang, Xue, Liu, & Yu, 2009). Font type bold Heiti (black font) was used because of its relatively uniform stroke width. Six to eight stimulus angular sizes were tested for each observer under each condition to produce a psychometric function covering a wide range of crowding strength. The edge-to-edge separation between characters was always one character width, which could produce severe crowding without stimulus overlapping and could produce crowding-free stimuli without widely separating the characters. These were important experimental design concerns because our study required robust reporting of all three stimulus characters over the full range of crowding. Although the stimulus size and spacing covaried here, there have been reports that crowding is limited by center-to-center stimulus spacing, not the stimulus size (Tripathy & Cavanagh, 2002). The black character string was presented on a full-screen, full-luminance white background. The central target character was always presented at 10° retinal eccentricity, either on the horizontal meridian in the right visual field or on the vertical meridian in the lower visual field.

Procedure

The observer was asked to fixate at a constant fixation cross before pressing a key to start a 200-ms (Figures 1 and 2) or 1600-ms (Figure 3) stimulus presentation. The task was to report the central target

from a list of the 10 characters (10 alternative, forced-choice trials) in a partial report task, or all three characters from left to right for a horizontal trigram or from top to bottom for a vertical trigram in a whole report task. Reporting was made by pressing number keys (0 through 9) corresponding to the characters. A 30-minute practice session was given to each observer prior to data collection. An auditory feedback was provided when a wrong character at the central position was reported in both partial report and whole report (after all characters were reported). Partial and whole report conditions were run in alternating blocks of trials in several daily sessions, each lasting 1.5 to 2 hours. Each block consisted of 60 to 80 trials for 6 to 8 character sizes, 10 per character size. Each data point in the following figures (report rate) was based on 60 or 120 trials completed in 6 or 12 blocks (observers with eye movements monitored completed six blocks). Observers were informed that there were no repeated characters in a stimulus and were warned not to report the same character more than once in any whole report trial. Trials with repeated characters (0.5% ± 0.2% of total trials) were excluded from data analysis.

Data fitting

Data were fitted with a Weibull function: $P = 1 - (1 - \gamma)e^{-(x/th)^{\beta}}$, where P was the percent correct, γ was the guessing rate (0.1 with partial report and 0.3 with whole report for 10AFC trials), x was the stimulus angular size, β was the slope of the psychometric function, and th was the threshold character size for identification at a 66.9% correct rate.

Permutation test

To test the differences between whole report data and whole report prediction based on partial report rates (see Results), a permutation test was conducted on all the prediction/data pairs collected from all subjects under a given crowding condition (Hesterberg, Moore, Monaghan, Clipson, & Epstein, 2006). The statistic in this test was the mean of pair-wise differences (prediction-data) of the N prediction/data pairs obtained under an experimental condition. The null hypothesis to be tested was that the mean of pair-wise differences was zero. A sampling distribution for this null hypothesis was then constructed by resampling the prediction/data pairs 10,000 times. The resampling that was consistent with this null hypothesis was to randomly assign one of the two values in each prediction/data pair to "data" and to assign the other value to "prediction." This resampling resulted

in N new pairs, each of which had the same two numbers as the original but had either the same or the opposite "prediction" and "data" order. The mean of the pair-wise differences of the resampled N pairs was then calculated. This resampling procedure was repeated 10,000 times and resulted in a 0-mean normal distribution of means of pair-wise differences. The location of the observed mean of pair-wise differences in this distribution could then be determined. If the observed value fell into the main body of the null hypothesis distribution, the observed difference between data and prediction could happen just by chance. If the observed value fell on the tail of the distribution, evidence existed that the difference was caused by something other than chance. The probability that the observed value belonged to the null-hypothesis distribution was calculated by counting the number of resampled pairs that produced means of pair-wise differences that were larger than the observed value and dividing this number by the total number of resamples. This probability was compared with the α (0.05) to determine if the difference between prediction and data was significant.

Eye movement monitoring

For observers whose eye movements were monitored, trials were excluded from data analysis if eye positions deviated from the fixation point by more than $1°$ before stimuli offset. Only $0.4 \pm 0.1\%$ of the trials on the average were excluded with the 200-ms condition (Figures 1 and 2). Under the long stimulus duration condition (1600 ms, Figure 3), $4.3 \pm 0.7\%$ of the trials were excluded.

Results

Experiment 1: target misplacement under crowding revealed by partial-whole report comparison

In the first experiment, the stimulus was a horizontal trigram of Chinese characters centered at $10°$ retinal eccentricity in the right visual field (Figure 1a). Six to eight character sizes (21.5–120 arcmin) were tested in each observer to induce crowding effects from severe to insignificant based on the partial report correct rates. The character sizes used by each observer were individually determined. The partial report rates of each observer (red solid circles, Figure 1b) were used to predict his/her whole report rates (green curves, Figure 1b), with the assumption that the partial report rate reflected the true identifiability of

the central target, and that when characters at all three perceived positions could be reported in whole report, the central target was reported to flanker positions purely by chance. These predictions were calculated using the thresholds and slopes of the partial-report Weibull-fitting functions and a chance level of 0.3 instead of 0.1 to signify the central target being randomly reported at any one of the three positions. The baseline data for identification of isolated characters and the Weibull fittings were also plotted (black solid circles, Figure 1b). Overall, the Weibull function provided a satisfactory fit of the partial- and whole-report functions, with the $R^2 = 0.91 \pm 0.02$.

A permutation test indicated that the empirical whole-report rates (blue circles, Figure 1b) were significantly higher than predictions made from partial report rates ($p < 0.001$). To further characterize this effect, the empirical and predicted whole-report rates at stimulus sizes that resulted in 0.2, 0.4, 0.6, and 0.8 partial-report rates were calculated on the basis of Weibull fittings (Figure 1c). A repeated measures ANOVA confirmed a higher-than-chance rate of reporting the central target in whole report ($F_{1,7} = 12.582$, $p = 0.009$). This effect was stronger at lower partial-report rates (interaction between report type and partial-report rate $F_{3,21} = 19.44$, $p < 0.001$). For example, when the partial-report rate was 0.2 (very severe crowding), the mean whole-report rate of the central target was 0.52, substantially ($\sim 40\%$) higher than the predicted rate of 0.38. However, the difference vanished at the 0.8 partial-report rate where crowding started to diminish. In addition, the eye movement monitored and unmonitored observers showed similar amount of the target misplacement effect ($F_{1,6} = 0.60$, $p = 0.47$). It is worth mentioning that, at the 0.2 partial-report rate, the lower bound of our data analysis, the corresponding identification rate for isolated characters (at the same stimulus sizes) was at $91.6\% \pm 4.0\%$. Therefore, the target misplacement effect observed here was not much affected by the visual acuity.

A higher whole report rate, however, did not automatically lead to the conclusion that the central target was sometimes misperceived at a flanker position. There was previous report that the rate of reporting the central target at the central position (C2C) in whole report could somehow be higher than the partial-report rate (Huckauf & Heller, 2002). This, however, was not the case here. The whole report C2C rates predicted from Weibull fittings (Figure 1b, dashed red curves) did not differ significantly from the corresponding 0.2 to 0.8 partial-report rates ($F_{1,7} = 1.68$, $p = 0.236$; Figure 1d), similar to what Huckauf and Heller (2002) found at $7°$ retinal eccentricity. Therefore, an extra number of central targets were indeed reported to one of the flanker positions in
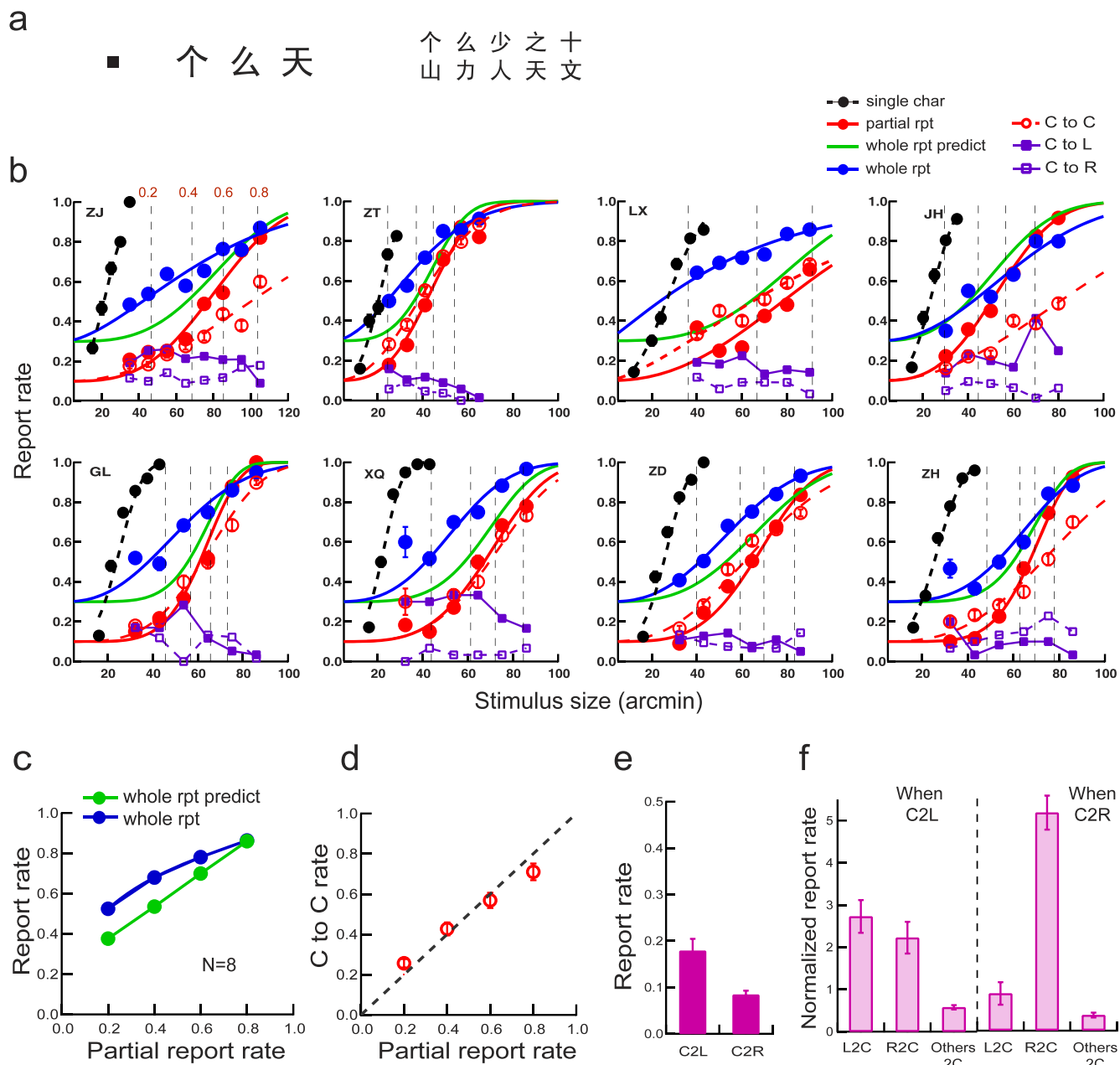
Figure 1. Partial- and whole-report data. (a) Stimuli. Left: A horizontal three-character string presented in the right visual field. Right: The 10 Chinese characters used in the study. (b) Individual results. Solid red circles represent the partial-report rates of correctly reporting the central target at various character sizes, and solid red curves are Weibull fittings. The green curves are the predicted whole-report rate based on partial-report data, assuming the central target being identified at the same rate in partial and whole reports. The blue circles are the rates of the central target being reported, regardless of its position in the reported trigram, and the blue curves are the Weibull fitting. The whole-report rates are further divided into those reported at the central position (C2C, for Central-to-Central, red empty circles and dashed curves), left-flanker position (C2L, for Central-to-Left, purple filled squares and solid curves), and right-flanker position (C2R, for Central-to-Right, purple empty squares and dashed curves). The black circles are the baseline data for identification of isolated characters. The vertical dash lines represent the stimulus sizes that resulted in 0.2, 0.4, 0.6, and 0.8 partial-report rates, respectively, as predicted from Weibull fittings. Results from observers whose fixation was monitored are in the upper row. Error bars when invisible are smaller than the symbol size. (c) The mean predicted (green circles) and empirical (blue circles) whole-report rates at 0.2 to 0.8 partial-report rates, all calculated from data fitting. (d) A comparison of the mean whole-report rates of the central target at the center position (C2C) and the corresponding partial-report rates. (e) The rates of the central target being reported to the left-flanker position (C2L) and the right-flanker position (C2R) with whole report. (f) The conditional rates of the left-flanker (L2C), right-flanker (R2C), and nonstimulus stimulus (others2C) being reported to the center position when the central target was reported to the left-flanker position (C2L, left panel) and to the right-flanker position (C2R, right panel). These conditional rates are normalized by the corresponding chance rates.

whole report. We took this as evidence that the central target was more identifiable than what was revealed by the partial-report rate. It was underreported because it was sometimes identified but misperceived as occupying a flanker position.

To understand the characteristics of target misplacement, we pooled all data points at stimulus sizes that resulted in 0.2 to 0.6 partial-report rates in each observer for an error analysis (blue points between the first and third vertical dash lines in each panel of Figure 1b). Beyond the 0.6 rate, there would be not much crowding, and the full-report advantage diminished. First, the error analysis showed that target misplacement, including the central target being reported to the left flanker position (C2L, for Central-to-Left) and the right flanker position (C2R, for Central-to-Right), accounted for $26.3\% \pm 2.2\%$ of total errors ($p < 0.001$), in which the C2L rate was 2.1-times as often as the C2R rate (Figure 1e, $p = 0.025$, two-tailed paired t-test). This asymmetry might result from the difference in flanker identifiability at the inner and outer positions. The left (inner) flanker is known to be less identifiable than the right (outer) flanker (Bouma, 1973) and thus might be less likely to hold its place.

Second, we were particularly interested in which character was reported at the center when the central target was reported to a flanker position. Whole-report errors were classified into three categories based on the single operation that could bring the central character into one of the flanker positions in the response: a flanker swapping position with the target (position swapping); a flanker and the target keeping their correct relative order, but being perceived as one position shifted to the left or right (misalignment); and a nonstimulus character being reported to the center (intrusion). For example, if [L C R] were the three stimulus characters, and X was one of the nonstimulus characters, whole reports [C L R] and [C L X] were classified as position swapping between the target and the left-flanker, and [L R C] and [X R C] was position swapping between the target and the right-flanker; [C R L] and [C R X] were misalignment to the left, and [R L C] and [X L C] were misalignment to the right; and a nonstimulus character occupying a center position, i.e., [C X R] , [C X L] , [C X X], [L X C], [R X C], and [X X C], were classified as intrusions. Error analysis indicated that, when the central target was reported to the left flanker position (C2L) (Figure 1f, left panel), the normalized rates of target-flanker swapping (L2C) and misalignment (R2C) (divided by a chance rate of 1/9) were 2.73 ± 0.39 and 2.22 ± 0.37, respectively, significantly higher than the chance rate of 1.0 ($p = 0.004$ and 0.018, respectively). These two processes occurred nearly equally ($p = 0.50$). However, the normalized rate of intrusion (by a chance rate of 7/9) was 0.58 ± 0.05, significantly lower than the chance rate ($p < 0.001$). When the central target was reported to the right-flanker position (C2R) (Figure 1f, right panel), target-flanker swapping (R2C) was predominant at a normalized rate of 4.90 ± 0.37, significantly higher than 1 ($p < 0.001$). The normalized rate of stimulus misalignment was 0.91 ± 0.25, not significantly different from chance ($p = 0.76$), and the normalized rate of intrusion was 0.44 ± 0.05, significantly lower than chance ($p < 0.001$).

Experiment 2: target misplacement at radial versus tangential stimulus orientations

The stimulus used in the first experiment had a radial orientation with respect to the fovea (Figure 1a). In this trigram, the three characters had different retinal eccentricities. The combined effect of retinal eccentricity and crowding made the outer flanker most legible, the target least legible, and the inner flanker somewhere in between (Bouma, 1970, 1973). Such a profile of uneven identifiabilities, plus other factors such as different position coding accuracy across the retinal eccentricity (White, Levi, & Aitsebaomo, 1992), might not provide a reliable cue for coding the relative position of the target. Could this be the cause of target misplacement we observed? A straightforward answer may come from testing tangential trigrams, where the two flankers had the same retinal eccentricity and were equally more identifiable than the target.

We repeated the partial- and whole-report experiments on six of the observers of Experiment 1 with three new conditions in random blocks of trials: radial orientation in the lower field (vertical trigrams, Figure 2a), tangential orientation in the lower field (horizontal trigrams, Figure 2b), and tangential orientation in the right visual field (vertical trigrams, Figure 2c). This design also guarded against the radial and tangential orientations being confounded with horizontal and vertical stimulus configurations, as well as with the vertical and horizontal reading directions. (The dominant direction is from left to right in modern Chinese.) Besides the permutation tests, the predicted and empirical whole report rates were again calculated at the 0.2 to 0.8 partial-report rates on the basis of Weibull fittings to characterize the whole-report effects, and were combined with those from Figure 1 for a complete ANOVA analysis. At the 0.2 partial-report rate, the corresponding identification rate for isolated characters in the lower visual field was also at a suprathreshold level at $92.2\% \pm 2.8\%$, so the data analysis here was not much affected by the visual acuity.
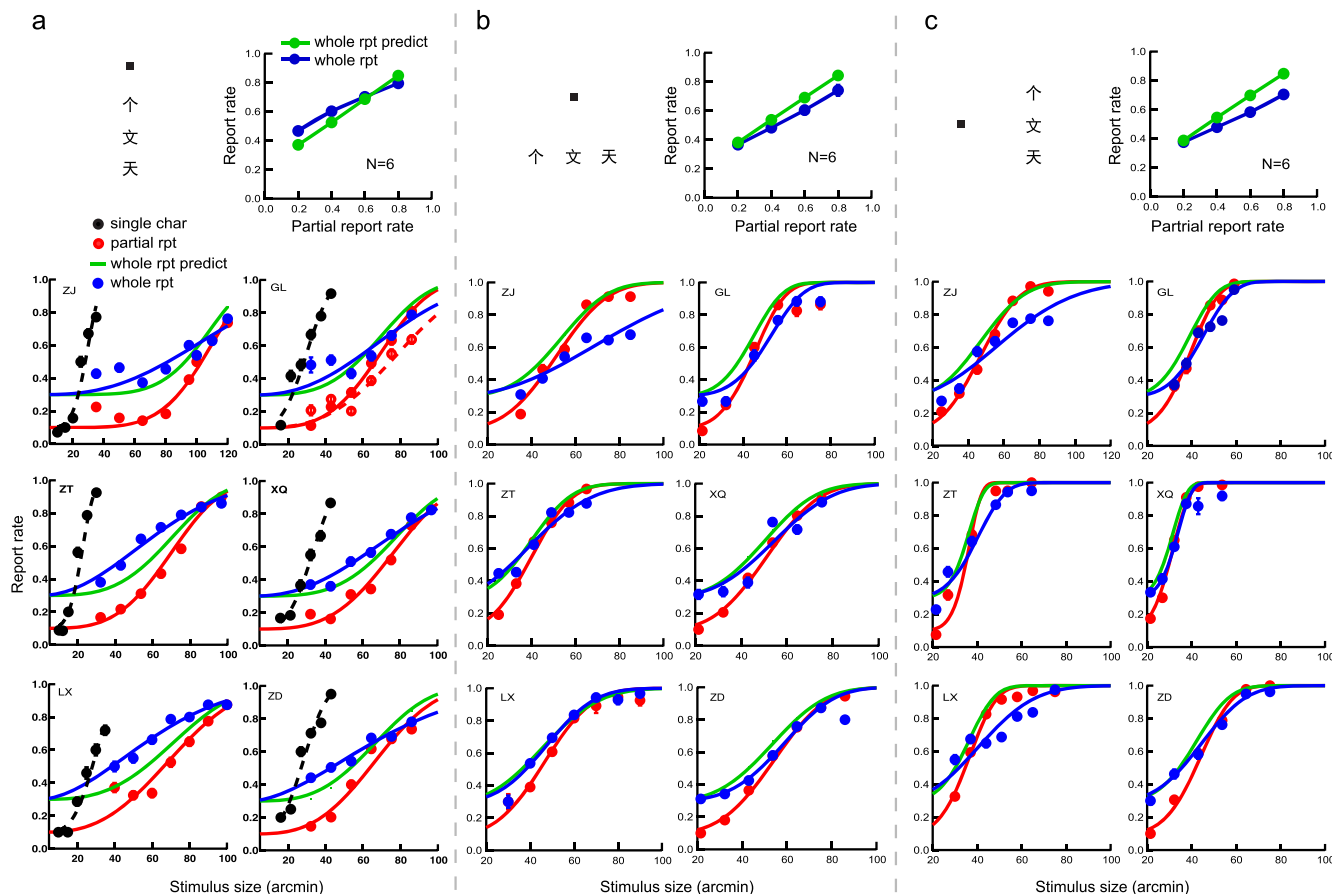
Figure 2. A comparison of the target misplacement effect at radial and tangential stimulus orientations. (a) Radial vertical strings in the lower visual field. (b) Tangential horizontal strings in the lower visual field. (c) Tangential vertical strings in the right visual field. For each subfigure, the top row, left panel shows the stimulus configuration, and the top row, right panel shows the predicted and empirical whole-report rates at ~0.2 to 0.8 partial report rates. The bottom rows show individual results of partial-report rates, predicted and empirical whole-report rates against various stimulus sizes. Baseline data for identification of isolated characters in the lower visual field were also plotted in panel (a).

Overall crowding (solid red circles, Figures 1b and 2) was stronger in radial than in tangential orientation. Mean threshold character sizes for partial report were 79.8 ± 5.5 arcmin and 47.9 ± 2.4 arcmin, respectively ($F_{1,5} = 59.1$, $p = 0.001$), but the slopes of the psychometric functions were not significantly different

($F_{1,5} = 0.53$, $p = 0.50$), confirming the known radial-tangential crowding anisotropy (Toet & Levi, 1992).

The whole-report rates for reporting the central target (blue circles) were significantly higher than predicted (green curve) for the radial orientation in the lower field (vertical trigrams, Figure 2a; $p = 0.001$,
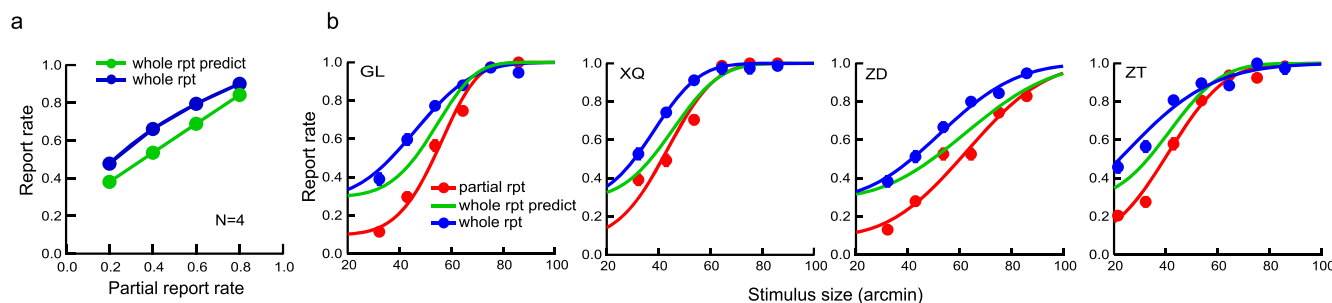

Figure 3. Partial- and whole-report data with extended stimulus duration (1600 ms). (a) The mean predicted (green circles) and empirical (blue circles) whole-report rates at 0.2 to 0.8 partial-report rates. (b) Individual results of partial-report rates and predicted and empirical whole-report rates.

permutation test). At the 0.2 to 0.8 partial-report rates, the overall whole-report effect was significant for both right-horizontal and lower-vertical radial orientations ($F_{1,5} = 32.5$, $p = 0.002$; Figures 1b and 2a). Again, this effect was more evident at lower partial report rates, showing a significant interaction ($F_{3,15} = 25.9$, $p < 0.001$).

On the other hand, there was no evidence for higher-than-predicted whole report rates for tangential trigrams, suggesting a radial-tangential anisotropy. This result is consistent with our conjecture that the uneven character legibility and the resultant relative position uncertainty in the radially orientated trigram may contribute significantly to target misplacement. The whole-report rates in tangential orientation were actually lower than predicted (right-vertical: $p < 0.001$; lower-horizontal: $p < 0.001$; permutation tests). At the 0.2 to 0.8 partial-report rates, the overall effect was significant for both right-vertical and lower-horizontal trigrams ($F_{1,5} = 27.78$, $p = 0.003$, Figure 2b and c, second right panels), especially at the higher 0.6 to 0.8 partial-report rates (Figure 2b and c; a significant interaction with $F_{4,20} = 8.99$, $p = 0.001$).

Experiment 3: target misplacement with extended stimulus duration

Most peripheral crowding studies, including ours, use ≤ 200 ms stimulus duration to discourage eye movements. Therefore, the target misplacement we observed in the first experiment might be alternatively explained by insufficient processing time or short-term memory decay. Four observers from previous experiments redid the partial- and whole-report experiments with horizontal trigrams in the right visual field (Figure 1a) but with a 1600-ms duration. A response was made only after the stimulus presentation completed. An eye tracker was used to monitor the eye fixation during stimulus display.

The partial report curves (Figure 3) showed significant crowding. The size threshold for the central character at a 66.9% correct rate was 56.5 ± 5.6 arcmin. Although we did not measure the single character threshold at the 1600-ms duration, because of the temporal summation, the threshold should be equal to or smaller than the 26.0 ± 1.2 arcmin single-character threshold for the same four observers at 200-ms duration (Figure 1).

The results also showed a higher-than-predicted whole-report rate ($p < 0.001$, permutation test) at the 1600-ms duration (Figure 3), which was confirmed by data at the 0.2 to 0.8 partial-report rates ($F_{1,3} = 771.7$, $p < 0.001$). A comparison of target misplacement effects at 200-ms versus 1600-ms duration conditions at the 0.2 to 0.8 partial-report rates indicated no significant

duration main effect ($F_{1,3} = 5.64$, $p = 0.098$, repeated measures ANOVA). However, there was a significant interaction between duration and partial-report rate ($F_{3,9} = 22.2$, $p < 0.001$) due to stronger higher-than-predicted whole-report rates at higher partial-report rates (i.e., 0.6 and 0.8) at 1600 ms (Figure 3a). Here, the actual stimulus size that corresponded to 0.6 and 0.8 partial-report rates were 53.2 ± 5.3 arcmin and 63.5 ± 6.3 arcmin at 1600 ms, respectively, about equal to the stimulus sizes corresponding to 0.4 and 0.6 partial-report rates at 53.6 ± 5.6 arcmin and 63.4 ± 6.1 arcmin at 200 ms, respectively. Therefore, the higher-than-predicted whole-report rates at higher partial-report rates at 1600 ms were likely caused by relatively smaller stimulus sizes and intercharacter gaps, and thus were less demanding for the brain to attend to all three characters.

The 1600-ms data indicates that target misplacement observed in this study were caused by genuine target-flanker interactions, not the result of insufficient stimulus persistence and/or fast memory decay (Townsend et al., 1971). The preponderance of position errors in tachistoscopic display of multiple-item stimulus was usually explained by the different rates of decay for identity and position information in short-term memory (Dick, 1969). Our current data excluded such an explanation.

Discussion

This study demonstrates that the central target in a crowded stimulus is not always rendered unidentifiable by flankers. It is in many cases correctly identified but misperceived as occupying one of the flanker positions due to target-flanker position swapping or misalignment when the stimuli are presented in the radial orientation. Therefore, the study establishes target misplacement as an additional source of crowding errors besides identity errors and provides evidence for the existence of letter-level position uncertainty in crowding. Such evidence cannot be derived from previous studies where only the reported positions of the flankers were considered.

The demonstration of target misplacement allows us to reach a more comprehensive and quantitative understanding of crowding. For a radial letter trigram presented in the right visual periphery (Figure 1), within the range of 0.2 to 0.6 partial-report rates where strong crowding occurs, the overall C2C rate in whole report is 35.2%, and the error rate of not reporting the target at the central position (C2C$_{\mathrm{err}}$) is $100\% - 35.2\% = 64.8\%$. Among these errors, the sum of C2L and C2R rates is 26.3%, which is 40.1% of total errors. As Figure 1b indicates, the C2C rate increases and the related C2C$_{\mathrm{err}}$ rate decreases with the partial report

rate, but the C2L and C2R rates do not correlate to the partial-report rate. A simulation of pseudorandom guessing at the 35.2% C2C rate showed that pure guessing could produce 14.2% C2L and C2R responses. Therefore, the observed target misplacement rate is 12.1% above pure guessing. The rest of the errors, $C2C_{err}$ − 12.1% = 52.7%, are true identity errors. Therefore, target misplacement accounts for about 20% of total errors, and the identity errors accounts for 80%.

Our results also provide insights into the observed errors of a flanker being reported as the target in partial report (Huckauf & Heller, 2002). In the case of Figure 1, the rate of flanker-report errors upon target misplacement is 15.4% (corresponding normalized rate was shown in Figure 1f). A simulation showed that random guessing could produce 3.2% of such errors. Therefore, the real rate of flanker report errors upon target misplacement is 15.4% − 3.2% = 12.2% above chance, demonstrating position swapping between the target and flankers. Meanwhile, the rate of flanker-report errors with no central target reported at all is 13.7%, as calculated from observers' raw data. Because random guessing could produce 11.1% of such errors, the actual rate was only 2.6% above pure guessing. The sum of two types of flanker-report errors is 14.8% in whole report. However, the rate of flanker-report errors in partial report within the same partial-report rate range is 47.0%, or 33.0% after discounting the chance rate of 14.0% when the overall partial-report rate is 37.1%. Therefore, the rate of flanker-report errors in partial report is more than twice the summed rate of flanker-report errors in whole report, suggesting that more than half the flanker-report errors observed in partial report may not result from position errors, but likely from the response bias due to uneven target-flanker identifiabilities discussed in Strasburger (2005).

The finding that target misplacement occurs mainly in the radial orientation indicates that such position errors are at least partially responsible for the known radial/tangential anisotropy of crowding (Toet & Levi, 1992). This is because correctly identified but misplaced targets in the radial orientation are considered errors in Toet and Levi's partial-report experiment. This finding also suggests a method to emphasize position or identity errors associated with crowding. For example, studies of the effect of crowding on letter identification may consider using tangential configurations, which produces fewer position errors. A potentially more potent method to reduce position errors, even in a radial stimulus string, is to draw the target and the flankers from different character groups and make it known to the observers. This method has been shown to greatly reduce position errors but still produces a significant number of identity errors (Zhang et al., 2009). In this experimental design, target misplacement is not permitted because the target is the only reportable character no matter at what position it is perceived. However, the remaining identity errors indicate that those processes responsible for impairing target identification are still effective.

Although our experimental materials are Chinese characters, the fact that the trigrams are made of simple, unrelated characters makes it possible to generalize the findings to understanding visual identification of alphabetic words. Letter transposition has been a routine stimulus manipulation in studying the mechanisms underlying visual word identification. Transposing interior letters of a word only has a moderate impact on identification speed and accuracy and only causes a small reduction (11%) in reading speed (Johnson, Perea, & Rayner, 2007; Rayner & Kaiser, 1975; Rayner, White, Johnson, & Liversedge, 2006). In contrast, the effect of transposing the exterior (first and last) letters of a word is devastating (Rayner & Kaiser, 1975). Our findings indicate that letter transposition can occur naturally under crowded conditions in the visual periphery and may involve exterior letters (flankers). Studies are being conducted to quantify the relative prevalence of exterior and interior position errors associated with crowding and how they may affect peripheral reading. It will be interesting to see how naturally occurring letter transposition can account for up to a factor of 4.4 reduction of reading speed (Chung, Mansfield, & Legge, 1998). Chung and Mansfield (2009) reported that assigning opposite contrast polarities to the target and flankers of a trigram improved identification of a crowded central target but assigning opposite contrast polarities to alternate letters in text did not improve reading. They explained that this effect was due to the "task difference" between identifying one letter and multiple letters. The task difference may be specific to opposite contrast polarity and may not apply to our speculation that perceived letter position errors in crowded words may affect reading. This is because we showed that position errors did occur in whole report (identifying multiple letters) and that our whole-report and partial-report stimuli were equally crowded (same C2C rates).

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References

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226*(5241), 177–178.

Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research, 13*(4), 767–782.

Chung, S. T., & Legge, G. E. (2009). Precision of position signals for letters. *Vision Research, 49*(15), 1948–1960.

Chung, S. T., & Mansfield, J. S. (2009). Contrast polarity differences reduce crowding but do not benefit reading performance in peripheral vision. *Vision Research, 49*(23), 2782–2789.

Chung, S. T., Mansfield, J. S., & Legge, G. E. (1998). Psychophysics of reading. XVIII. The effect of print size on reading speed in normal peripheral vision. *Vision Research, 38*(19), 2949–2962.

Di Lollo, V. (1977). On the spatio-temporal interactions of brief visual displays. In Day, R. H. & Stanley, G. V. (Eds.), *Studies of Perception* (pp. 39–55). Claremont, Western Australia: University of Western Australia Press.

Dick, A. O. (1969). Relations between the sensory register and short-term storage in tachistoscopic recognition. *Journal of Experimental Psychology, 82*(2), 279–284.

Dick, A. O., & Mewhort, D. J. (1967). Order of report and processing in tachistoscopic recognition. *Perception & Psychophysics, 2*(2), 573–576.

Estes, W. K., Allmeyer, D. H., & Reder, S. M. (1976). Serial position functions for letter identification at brief and extended exposure durations. *Perception & Psychophysics, 19*(1), 1–15.

Greenwood, J. A., Bex, P. J., & Dakin, S. C. (2009). Positional averaging explains crowding with letter-like stimuli. *Proceedings of the National Academy of Sciences USA, 106*(31), 13130–13135.

Greenwood, J. A., Bex, P. J., & Dakin, S. C. (2010). Crowding changes appearance. *Current Biology, 20*(6), 496–501.

Hagenzieker, M. P., Heijden, A. H. C., & Hagenaar, R. (1990). Time courses in visual-information processing: Some empirical evidence for inhibition. *Psychological Research, 52*(1), 13–21.

He, S., Cavanagh, P., & Intriligator, J. (1996).

Attentional resolution and the locus of visual awareness. *Nature, 383*(6598), 334–337.

Hesterberg, T., Moore, D. S., Monaghan, S., Clipson, A., & Epstein, R. (2006). Bootstrap methods and permutation tests. In Moore, D. S. & McCabe, G. P. (Eds.), *Introduction to the Practice of Statistics (Fifth Edition)*. New York, NY, USA: W. H. Freeman. pp. 1–70.

Huckauf, A., & Heller, D. (2002). What various kinds of errors tell us about lateral masking effect. *Visual Cognition, 9*(7), 889–910.

Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology, 43*(3), 171–216.

Johnson, R. L., Perea, M., & Rayner, K. (2007). Transposed-letter effects in reading: evidence from eye movements and parafoveal preview. *The Journal of Experimental Psychology: Human Perception and Performance, 33*(1), 209–229.

Krumhansl, C. L. (1977). Naming and locating simultaneously and sequentially presented letters. *Perception & Psychophysics, 22*(3), 293–302.

Legge, G. E., Cheung, S. H., Yu, D., Chung, S. T., Lee, H. W., & Owens, D. P. (2007). The case for the visual span as a sensory bottleneck in reading. *Journal of Vision, 7*(2):9, 1–15, http://www.journalofvision.org/content/7/2/9, doi:10.1167/7.2.9. [PubMed] [Article]

Levi, D. M. (2008). Crowding-An essential bottleneck for object recognition: A mini-review. *Vision Research, 48*(5), 635–654.

Levi, D. M., Hariharan, S., & Klein, S. A. (2002). Suppressive and facilitatory spatial interactions in peripheral vision: peripheral crowding is neither size invariant nor simple contrast masking. *Journal of Vision, 2*(2):3, 167–177, http://www.journalofvision.org/content/2/2/3, doi:10.1167/2.2.3. [PubMed] [Article]

Mewhort, D. J. (1987). Information stores and mechanisms: Early stages of visual processing. In Heuer, H. & Sanders, A. F. (Eds.), *Perspectives on Perception and Action*. Hillsdale, NJ: Lawrence Erlbaum Associates, Publishers. pp. 335–357.

Mewhort, D. J., Campbell, A. J., Marchetti, F. M., & Campbell, J. I. (1981). Identification, localization, and "iconic memory": an evaluation of the bar-probe task. *Memory & Cognition, 9*(1), 50–67.

Parkes, L., Lund, J., Angelucci, A., Solomon, J. A., & Morgan, M. (2001). Compulsory averaging of crowded orientation signals in human vision. *Natural Neuroscience, 4*(7), 739–744.

Pelli, D. G., Palomares, M., & Majaj, N. J. (2004).

Crowding is unlike ordinary masking: distinguishing feature integration from detection. *Journal of Vision, 4*(12):12, 1136–1169, http://www.journalofvision.org/content/4/12/12, doi:10.1167/4.12.12. [PubMed] [Article]

Rayner, K., & Kaiser, J. S. (1975). Reading mutilated text. *Journal of Educational Psychology, 67*(2), 301–306.

Rayner, K., White, S. J., Johnson, R. L., & Liversedge, S. P. (2006). Raeding wrods with jubmled lettres: there is a cost. *Psychological Science, 17*(3), 192–193.

Strasburger, H. (2005). Unfocussed spatial attention underlies the crowding effect in indirect form vision. *Journal of Vision, 5*(11):8, 1024–1037, http://www.journalofvision.org/content/5/11/8, doi:10.1167/5.11.8. [PubMed] [Article]

Stuart, J. A., & Burian, H. M. (1962). A study of separation difficulty. Its relationship to visual acuity in normal and amblyopic eyes. *American Journal of Ophthalmology, 53*, 471–477.

Toet, A., & Levi, D. M. (1992). The two-dimensional shape of spatial interaction zones in the parafovea. *Vision Research, 32*(7), 1349–1357.

Townsend, J. T., Taylor, S. G., & Brown, D. R. (1971). Lateral masking for letters with unlimited viewing time. *Perception & Psychophysics, 10*, 375–378.

Tripathy, S. P., & Cavanagh, P. (2002). The extent of crowding in peripheral vision does not scale with target size. *Vision Research, 42*(20), 2357–2369.

Van der Heijden, A. H. C. (1987). Central selection in vision. In Heuer, H. & Sanders, A. F. (Eds.), *Perspectives on Perception and Action.* Hillsdale, NJ: Lawrence Erlbaum Associates, Publishers. pp. 421–446.

Van der Heijden, A. H. C., Hagenaar, R., & Bloem, W. (1984). Two stages in postcategorical filtering and selection. *Memory & Cognition, 12*, 458–469.

White, J. M., Levi, D. M., & Aitsebaomo, A. P. (1992). Spatial localization without visual references. *Vision Research, 32*(3), 513–526.

Wolford, G. (1975). Perturbation model for letter identification. *Psychological Review, 82*, 184–199.

Zhang, J. Y., Zhang, T., Xue, F., Liu, L., & Yu, C. (2007). Legibility of Chinese characters and its implications for visual acuity measurement in Chinese reading population. *Investigative Ophthalmology & Visual Science, 48*(5): 2383–2390, http://www.iovs.org/content/48/5/2383. [PubMed] [Article]

Zhang, J. Y., Zhang, T., Xue, F., Liu, L., & Yu, C. (2009). Legibility of Chinese characters in peripheral vision and the top-down influences on crowding. *Vision Research, 49*(1), 44–53.