



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.

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 ($C2C_{err}$) 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 $C2C_{err}$ 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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Corresponding author: Cong Yu or Lei Liu.

Email: yucong@pku.edu.cn; liul7788@uab.edu.

Address: Department of Psychology, Peking University, Beijing, China; School of Optometry, University of Alabama, Birmingham, Alabama, USA.

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