Foveal target repetitions reduce crowding

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Abstract

Crowding is the limitation of peripheral vision by clutter. Objects that are easily identified when presented in isolation are hard to discriminate when presented flanked by similar close-by objects. It is often assumed that the signal of a crowded target is irretrievably lost because it is combined with the signals of the flankers. Here, we asked whether a target signal can be enhanced (or retrieved) by items presented far outside the crowding region. We investigated whether remote items matching a peripheral, crowded target enhanced discrimination compared to remote items not matching the target. In Experiment 1, we presented the remote item at different locations in the visual field and found that when presented in the fovea, a matching remote item improved target discrimination compared to a non-matching remote item. In Experiment 2, we varied stimulus onset asynchronies between target and remote items and found a strong effect when the remote item was presented simultaneously with the target. The effect diminished (or was absent) with increasing temporal separation. In Experiment 3, we asked whether semantic knowledge of a target was sufficient to improve target discrimination and found that this was not the case. We conclude that crowded target signals are not irretrievably lost. Rather, their accurate recognition is facilitated in the presence of remote items that match the target. We suggest that long-range grouping mechanisms underlie this “uncrowding” effect.

Introduction

To perceive and navigate in complex cluttered environments, humans rely strongly on information from the peripheral visual field. A severe limitation of peripheral vision is crowding – the inability to identify objects in clutter that are easily identified in isolation (Korte, 1923; Bouma, 1970; Andriessen & Bouma, 1976; Westheimer, Shimamura, & McKee, 1976). For example, a letter presented in the periphery that can be identified when presented alone is unrecognizable when flanked by close-by letters. Hence, crowding is not a limit of visual resolution but a process that combines, substitutes, or disrupts stimuli in some way. Explanations of crowding range from low level processes, such as spatial pooling (Wilkinson, Wilson, & Ellemberg, 1997; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001) and excessive feature integration (Pelli, Palomares, & Majaj, 2004), to higher level processes, such as substitution (Strasburger, Harvey, & Rentschler, 1991; Strasburger, 2005) and attentional resolution (He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001). Recently, it was proposed that crowding is not a unitary phenomenon but rather one that occurs at different stages in the visual system (Whitney & Levi, 2011).

While the exact mechanisms underlying crowding are unknown, a range of distinctive effects nonetheless provide a good characterization of crowding (see, e.g., Levi, 2008). For example, crowding only occurs when the flankers fall within a certain region around the target. This “crowding region” is often estimated to extend radially up to 0.5 times the eccentricity (also referred to as “Bouma’s law”) and tangentially about half that size (Toet & Levi, 1992). Other factors that strongly influence crowding are, for example, target-flanker similarity (Kooi, Toet, Tripathy, & Levi, 1994; Sayim, Westheimer, & Herzog, 2008; but see Greenwood, Sayim, & Cavanagh, 2014) and grouping (Banks & Prinzmetal, 1976; Banks & White, 1984; Livne & Sagi, 2007; Sayim, Westheimer, & Herzog, 2008, 2010; Saarela, Sayim, Westheimer, & Herzog, 2009) with more crowding when target and flankers are similar and when they group.

Interestingly, a number of studies have demonstrated that even when conscious access to a strongly crowded target is lost, the target's features are still processed by the visual system, influencing perception and behavior. For example, the target signal may become part of an average representation of the target and the flankers (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001) while still producing orientation-specific adaptation (He, Cavanagh, & Intriligator, 1996). Moreover, in a recent study, it was shown that crowded Chinese characters semantically primed observers in a (non-crowded) lexical decision task (Yeh, He, & Cavanagh, 2012). Other studies showed that crowded emotional facial expressions primed evaluation judgments (Kouider, Berthet, & Faivre, 2011) and crowded directional symbols primed action (Faivre & Kouider, 2011). Hence, the signal of a crowded target is often not entirely lost despite observers' inability to correctly report target identity.

A crowded target is more difficult to recognize not only because the target signal is suppressed by the crowding process but also because the target's appearance is altered, making it more similar to the surrounding flankers (Greenwood, Bex, & Dakin, 2010). Interestingly, this effect on appearance may also be induced by flankers that do not crowd the target themselves. In particular, we recently showed that items outside the crowding region imposed their identity on, i.e., assimilated, a crowded target when the items grouped with each other (Sayim & Cavanagh, 2013). These results showed the existence of "grouping" regions around targets that are larger than crowding regions. However, the size and the shape of these regions remain unclear, as does the nature of the influence from items outside the crowding region.

Here we asked whether items outside the crowding region can enhance the visibility of a crowded target to make it available for conscious report. In particular, we investigated whether remote items that matched the target, i.e. those with the same identity, enhanced target sensitivity compared to remote items that were different from the target. Previous experiments have demonstrated that additional matching items can improve target identification under crowded and non-crowded conditions alike (Geiger & Lettvin, 1986). However, these experiments did not separate sensitivity and bias, and did not investigate the temporal properties of the effect, leaving unclear whether the improvement was due to enhanced perception, response bias, or cueing.

In three experiments, we presented a target item, either a letter or a number, eight degrees from fixation in the right peripheral visual field. Targets were crowded by two close-by flankers (letters and numbers). Additionally, we presented a remote item that was either the same as the target or different to the target. In Experiment 1, the remote item was presented in one of five positions (Figure 1A). We found that remote items presented at the foveal location reduced crowding when they matched the target compared to when they did not match the target. We call this the "uncrowding" effect. When the remote item was presented in any of the other four positions, crowding was not reduced.

In Experiment 2, we presented the remote item exclusively at the foveal location simultaneously with, before, or after the target. The results again showed a strong uncrowding effect for simultaneous presentation, as in Experiment 1. Uncrowding diminished when the remote item was presented more than 200 ms before the target and when it was presented after the target. In Experiment 3, we tested whether the advantage found for remote items that matched the target was based on semantic knowledge of the target rather than shape similarity between the target and the remote item. We separated shape and semantic content by using an upper case or lower case letter as the target and remote item. Uncrowding was found when the remote item matched the target shape but not when it was semantically the same but had a different shape, i.e., when the remote item was the same letter but of different case than the target.

Our results show that signals of strongly crowded targets can be enhanced by items well outside the traditional crowding zone, and that this uncrowding effect is not merely due to the cueing of semantic target identity but rather to a shape-specific enhancement of the target. Crowded targets are not irretrievably lost. We propose that our results are due to long-range grouping between the target and the remote item.

Experiment 1: Remote item positions

In Experiment 1, we examined the effects of presenting a remote item at different positions in the visual field. The remote item was either the same as or different to the crowded target. We asked whether crowding would be reduced when the remote item was the same as the target compared to when it was different from the target. The remote item was presented simultaneously with the target and the flankers, in one of five different positions. The five remote item positions were chosen to cover a broad range, including the same and the opposite hemifield as the target. Specifically, the positions were (1) in the opposite hemifield of the target at the same eccentricity, (2) in the opposite hemifield at half the eccentricity as the target, (3) at the fovea, (4) in the same hemifield as the target at half its eccentricity, and (5) on the vertical midline at the same eccentricity as the target in the lower visual field (Figure 1A).

Method

Participants

Five experienced psychophysical observers, including one of the authors, participated in the experiment (two females, three males). All observers, except the author, were naive as to the purpose of the experiment. All observers reported normal or corrected-to-normal visual acuity.

Apparatus

Stimuli were presented on a 22'' Formac ProNitron 22800 CRT monitor driven by a standard accelerated graphics card. The screen resolution of the CRT was set to 1056 by 792 pixels. Observers were supported by a chin and head rest and viewed the monitor from a distance of 65 cm. The experimental room was dimly illuminated. Responses were recorded using a standard keyboard. MATLAB 7.5 (Mathworks, Natick Massachusetts, USA) in combination with the Psychophysics toolbox (Brainard, 1997) was used for stimulus presentation and data collection.

Stimuli

Stimuli consisted of numbers and capital letters of Arial font, drawn from the two sets “2, 3, 4, 5, 6, 7, 8, 9” and “A, B, F, G, K, P, R, Y”. In half of the trials, the target was a letter and in the other half a number, randomly drawn from each set. The target was presented at a horizontal distance of 8 degrees to the right of a central fixation dot. All items were black with a luminance of 1.0 cd/m^2 and were presented on a gray background (9.5 cd/m^2). Letters and numbers were 1.0 degree high (slightly varying in width depending on the item). The target was flanked by two items (flankers), one to the left and one to the right, presented at a center-to-center distance of 1.2 degrees from the target (the innermost item at 6.8 degrees, the outermost at 9.2 degrees from fixation). The two flankers always consisted of one number and one letter. In half of the trials, the letter was presented at the innermost and the number at the outermost position (and vice versa in the other half of the trials, in random order). The target was never the same as either of the flankers. Additionally, a single remote item was drawn from the letter and number sets and presented at one of the five positions (Figure 1A). The remote item was either the same as the target (this is the “Matched” condition; e.g., remote item = 2 and target = 2) or different from the target. When the remote item and the target were different, they were either from the same category, i.e. both were numbers or letters (“Unmatched-Same” condition; e.g., remote item = 2 and target = 4, or remote item = B and target = G) or from different categories, i.e. the remote item was a number when the target was a letter and vice versa (“Unmatched-Different” condition; e.g., remote item = 2 and target = K, or remote item = B and target = 3). The remote item was never the same as any of the flankers. The Matched condition and the Unmatched-Same condition each comprised 25% of the trials. The Unmatched-Different condition comprised the remaining 50%

of the trials. This distribution ensured that the remote item was not informative about the target identity or category (i.e. whether the target was a number or a letter). Importantly, the Matched and Unmatched-Same condition are equivalent in terms of their potential to observe a category influence from the remote item (e.g., if observers were to respond with the category of the remote, clearly seen item when the target category is difficult to identify) because responses in line with the remote item were correct in both conditions.

Design and procedure

Observers fixated on the fixation dot in the center of the screen. After 800 ms the stimulus array -- target, flankers, and remote item -- was presented for 200 ms. The next trial started 800 ms after the observers' response. Matched, Unmatched-Same and Unmatched-Different conditions were randomly intermixed within a block. The remote item was presented in one of five positions (Figure 1A), each measured in separate blocks. Before each block, the locations of the remote item and the target were indicated by two black circles. When the remote item was presented at fixation, the fixation dot disappeared for 200 ms during stimulus presentation. In the other remote item position conditions, the fixation dot remained on the screen.

Observers performed two tasks on each trial. In the first, *category* task, observers indicated by keyboard press whether the target was a number or a letter. In half of the trials, the target was a letter, in the other half a number. Number and letter trials were randomly interleaved. In the second, *identity match* task, observers indicated whether the remote item and the target were the same or not. This task was included solely to ensure attention to both the remote item and the target, though observers were not told of this. The category response was given first, followed by the identity response. Auditory feedback was given when observers failed to respond in this order. In the baseline condition, no remote item was presented -- observers only indicated whether the target was a letter or a number. Observers completed 2 blocks per condition with 160 trials per block.

Results and discussion

Before proceeding to our analysis of sensitivity, we first evaluated whether the category of the remote item was determining the responses. Specifically, when the target category is hard to identify, participants might simply respond with the category of the easily seen remote item. To address this, we examined the responses when the remote item did not have the same identity as the target (Unmatched conditions) and compared performance when the remote item was from the same category as the target (Unmatched-Same condition: same category, different identity), e.g. a remote item "2" with a target "4", to performance when the remote item was from the different category (Unmatched-Different condition: different category, different identity), e.g. a remote item "5" with a target "B". On average, 75.8% of the responses in the Unmatched-Same condition were correct, compared to only 62.6% in the Unmatched-Different condition ($p < 0.01$, paired t-test). This difference shows that participants' responses were influenced by the category of the remote item, even when it did not match the target. This influence may reflect a tendency to respond with the category of the visible remote item when the identity of the target is unavailable.

To determine the effect of the identity of the remote item independently of the effect of the remote category, we now compare sensitivities only in the conditions where the remote item's category always matches that of the target: Matched (same category, same identity) versus Unmatched-Same (same category, different identity). In these analyses, the tendency to respond with the category of the visible remote item is held constant as the remote item always has the same category as the target. To calculate sensitivity (d') and bias, we defined letters as "signal" and numbers as "noise". Hence, correctly reporting a letter was a hit and correctly reporting a number was a correct rejection. d' thus indicates the sensitivity of discriminating letters from numbers, while bias values indicate a preference to report the target as a number (positive bias) or a letter (negative bias). These values were computed separately for trials where the remote item matched the target and for trials where the remote item did not match the target. The results are shown in Figure 1B. The main finding is that a remote item presented at the foveal location with the same identity as the target increased sensitivity compared to a non-matching remote item.

The data were analyzed with a repeated measures ANOVA with the two factors Match (two levels: Matched and Unmatched-Same) and Position (five levels: the five different positions of the remote item). Separate ANOVAs were calculated for sensitivity and bias. Comparing sensitivities, we found a main effect of Match ($F(1,4) = 7.951$, $p < 0.05$). Sensitivity was lower in the Unmatched-Same condition ($d'=1.55$; $SE=0.07$) compared to the Matched condition ($d'=2.16$, $SE=0.20$). The main effect of Position did not reach significance ($F(4,16) = 2.620$, $p = 0.074$) and there was no interaction ($F4,16) = 1.286$, $p = 0.317$). As we were interested in a remote item position that would be the best choice for the remote effect in the following experiments, we conducted planned comparisons separately for each of the five positions. We used Bonferroni correction for multiple comparisons with an adjusted alpha level of 0.01 (0.05/5). When the remote item was presented at the fovea (position P3 in Figure 1A), sensitivity was higher in the Matched than in the Unmatched-Same condition (P3: $F(1, 36) = 12.875$, $p < 0.001$). In the remaining four positions, sensitivities did not differ significantly for Matched and Unmatched-Same conditions (P1: $F(1, 36) = 1.286$, $p = 0.264$; P2: $F(1, 36) = 2.374$, $p = 0.132$; P4: $F(1, 36) = 1.654$, $p = 0.207$; P5: $F(1, 36) = 0.579$, $p = 0.452$).

Concerning biases, there was no main effect of Match ($F(1,4)=1.738$, $p = 0.258$), no main effect of Position ($F(4,16) = 2.078$, $p = 0.131$), but an interaction between Match and Position ($F(4,16) = 4.161$, $p < 0.05$, results not shown).

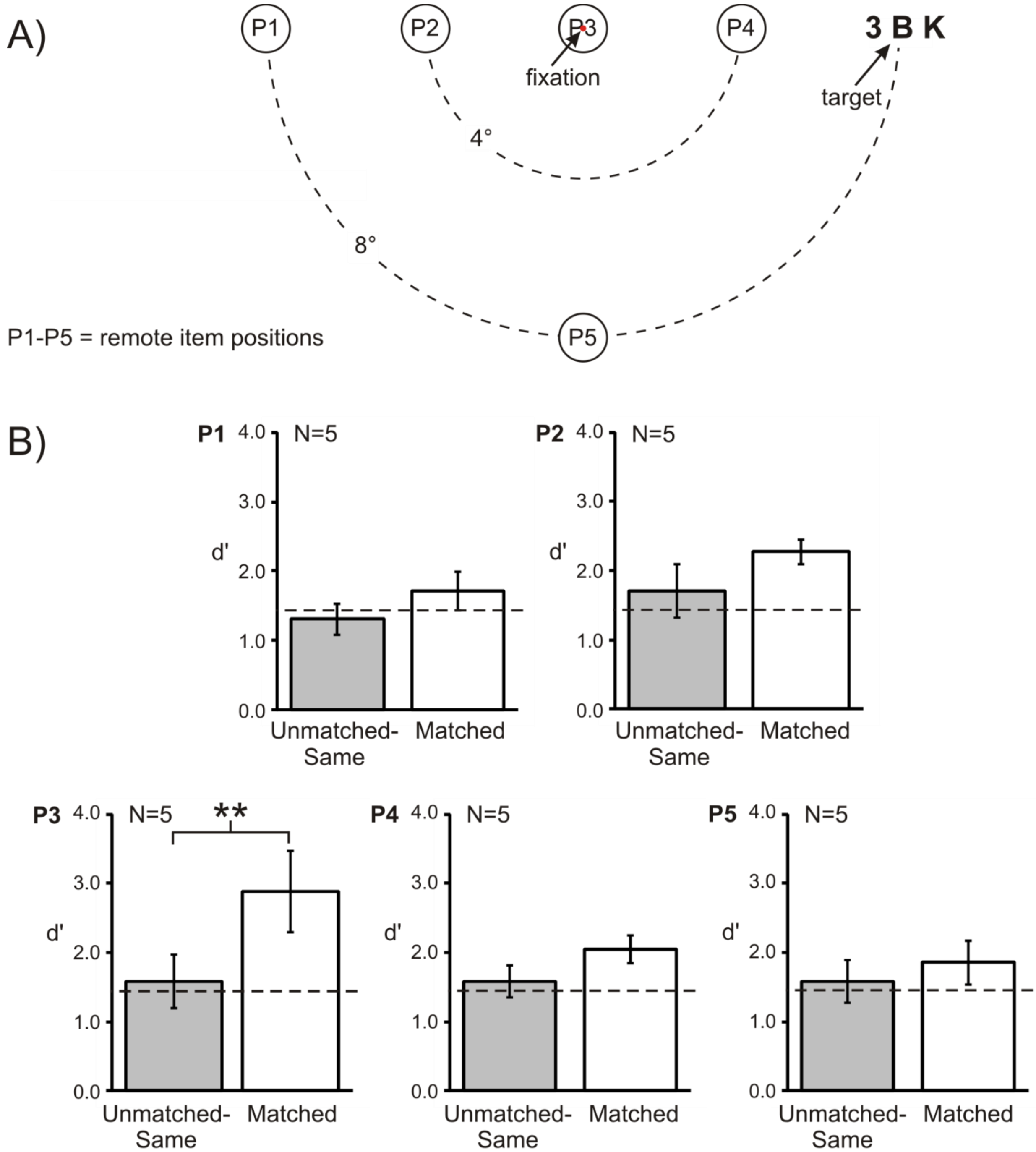

Figure 1: A) Positions of the remote item in Experiment 1. A target ("B") with two flankers ("3" and "K") is shown on the right. The remote item was presented simultaneously with the target and the flankers in one of the five positions indicated by the black circles (P1 - P5). Remote item positions were in the opposite hemifield of the target at the same eccentricity (P1), at half the eccentricity (P2), at the fovea (P3), in the same hemifield as the target at half its eccentricity (P4), and on the vertical midline at the same eccentricity as the target in the lower visual field (P5). The two dashed half circles show the eccentricity and half the eccentricity of the target. The

small red disc indicates the fixation dot. B) Results of Experiment 1. In condition P3 (remote item presented at the fovea), d′ in the Matched condition was significantly higher than in the Unmatched-Same condition (indicated by the asterisks). In the other positions, no difference between the Matched and Unmatched-Same conditions was observed, despite a trend in the same direction in all conditions. Error bars indicate standard errors of the mean. The dashed line shows sensitivity in the baseline condition where no remote item was presented.

While there was higher sensitivity when data from all five remote item locations were averaged, the planned comparisons for each individual location showed that this was significant only for the foveal location. It is possible that a high degree of remote item visibility -- as is the case in the fovea – might be necessary for a clear uncrowding effect (but see Geiger & Lettvin, 1986). Additionally, foveal items have an attentional advantage compared to peripheral locations (Wolfe, O'Neill, & Bennett, 1998), presumably contributing to the effect. Pilot experiments showed that focusing attention on both positions, target and remote item, was mandatory for uncrowding. Interestingly, using a slightly different paradigm, we also found uncrowding when the remote item was presented in the mirrored target location on the opposite side of fixation (position P1 in Figure 1A; results not reported here), though sensitivity did not differ significantly here in the present study.

Overall, the results of Experiment 1 show that a crowded target signal can be enhanced from far outside the crowding region by an additional item that matches the target compared to an item that does not match the target.

Experiment 2: Temporal properties

In Experiment 1, we investigated whether a remote item increased sensitivity when it matched the target (relative to a non-matching remote item) at five positions in the visual field. We found spatial specificity – a matching remote item presented at the fovea but not at other positions increased sensitivity compared to a non-matching remote item. In Experiment 2, we investigated the temporal properties of this uncrowding effect. This allowed us to consider alternative explanations for our results. For instance, if the uncrowding effect depends upon the cueing of target identity (by the clearly visible remote item), then in addition to a benefit in the Matched condition when the target and the remote item are presented simultaneously, there should also be an advantage when the remote item is presented before the target. There should not be any difference between the two conditions when the remote item is presented after the target. Grouping processes, in contrast, predict that benefits should only arise from presentations of the target and remote item that are more-or-less simultaneous.

Method

Experiment 2 was the same as Experiment 1 with the following exceptions. The remote item was exclusively presented in the fovea (at position P3; Figure 1A) where we found an advantage in the Matched compared to the Unmatched-Same condition in Experiment 1. The remote item was presented either before, simultaneously with, or after the target. Seven different stimulus onset asynchronies (SOAs) were used: -600, -400, -200, 0, 200, 400, and 600 ms. Negative values indicate that the remote item was presented before the target, 0 ms indicates simultaneous presentation, and positive values indicate that the remote item was presented after the target. A Chinese character of Yung font (Pelli, Burns, Farell, & Moore-Page, 2006) was presented immediately after the remote item as a mask and remained on the screen until observers responded. Three of the observers who participated in Experiment 1, including one of the authors, and two new observers participated in the experiment (5 males).

Results and discussion

As in Experiment 1, we first examined the influence of the remote item's category and found a higher percentage of correct responses, 72.7%, when the remote item category matched that of the target (Unmatched-Same: different identity, same category) compared to 56.6% for the Unmatched-Different condition (different identity, different category). This again indicates that when participants could not report the target category, they had a significant tendency to respond with the category of the clearly visible remote item. As in Experiment 1, our main analysis compared only Matched (same identity, same category) to Unmatched-Same (different identity, same category). Since we used only trials when the remote item had the same category as the target we can determine the effect of identity independently of this large category influence.

Figure 2 shows the results of Experiment 2. As in Experiment 1, we calculated sensitivity (d′) and bias in the number versus letter category task. We will see that sensitivity in the Matched condition (same identity, same category) was again higher compared to the Unmatched-Same (different identity, same category) condition, and that the temporal order between the target and the remote item influenced sensitivity.

The sensitivity data were analyzed with a repeated measures ANOVA with the two factors Match (two levels: Matched and Unmatched-Same) and SOA (the seven SOA levels). Separate ANOVAs were calculated for sensitivity and bias. Comparing d′ values, we found a main effect of Match ($F(1,4) = 45.158$, $p < 0.005$), a main effect of SOA ($F(6,24) = 3.851$, $p < 0.01$), and no interaction between Match and SOA ($F(6, 24) = 1.895$, $p = 0.123$). The main effect of SOA showed that sensitivity decreased from negative to positive SOAs, indicating that there was a general benefit when remote items were presented before the target, possibly because of an advantage due to cueing of target onset. As expected, sensitivity was lower in the Unmatched-Same condition (d′=1.40; SE=0.09) compared to the Matched condition (d′=1.93, SE=0.15).

To examine the precise SOAs where the Matched and Unmatched-Same conditions differed, we conducted planned comparisons for each of the seven SOAs, using Bonferroni correction for multiple comparisons with an adjusted alpha level of 0.007 (0.05/7). As in Experiment 1, sensitivity in the Matched condition was higher compared to the Unmatched-Same condition when the remote item was presented simultaneously with the target (SOA = 0 ms: $F(1,52) = 13.77$, $p < 0.001$). Sensitivity was also higher in the Matched condition when the remote item was presented 200 ms before (-200 ms: $F(1,52) = 8.64$, $p < 0.007$) but not when it was presented 400 ms (-400 ms: $F(1,52) = 5.18$, $p = 0.027$) or 600 ms before the target (-600 ms: $F(1,52) = 3.48$, $p = 0.068$). When the remote item was presented after the target, there was no difference between the two conditions (200 ms: $F(1,52) = 0.62$, $p = 0.435$; 400 ms: $F(1,52) = 4.10$, $p = 0.048$; 600 ms $F(1,52) = 0.09$, $p = 0.765$). Because the Bonferroni correction is rather conservative, and the two "preview" conditions, -600 ms and -400 ms, seem by eye to show an advantage in the Matched condition, we performed additional tests. First, when using the (less conservative) sequentially rejective Bonferroni test (Holm, 1979), again only -200 ms and 0 ms showed significant differences. Second, when comparing the average advantages (d' Matched minus d' Unmatched-Same) of the three negative vs three positive SOAs, the difference was not significant ($p = 0.36$).

There was no tendency to report letters in favor of numbers or vice versa: the bias values showed no significant effects (no main effect of SOA: $F(6,24) = 0.734$, $p = 0.627$; no main effect of Match: $F(1,4) = 0.232$, $p = 0.655$; no interaction: $F(6,24) = 0.128$, $p = 0.992$; results not shown).

These results show a clear temporal specificity of the uncrowding effect. We expected a cueing benefit in the Matched condition when the remote item was presented before the target. Given the preview of the remote item, observers could then scrutinize the crowded stimulus for a matching shape at the target position (as was required for performing the secondary task). The observed advantage in the Matched condition compared to the Unmatched-Same condition when remote items were presented 200 ms before the target could be due to this cueing benefit where the remote item readies a search process based on its identity. However, an advantage in the Matched condition was observed with simultaneous presentation of the remote item and the target, arguing against cueing as the only source for the advantage. Typically, maximum cueing efficiency occurs with a preceding cue and is reduced at simultaneous presentation (see, for example, Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). The lack of benefit when the remote item preceded the target with long SOAs also argues against some form of cueing.

An alternative explanation is that rather than looking for a shape match, observers judged the similarity between the remote item and the degraded features of the crowded target. Again, this should favor the presentation of the remote item prior to the crowded target as the unidentified cluster of degraded target features will decay rapidly whereas the remote item's identity is easily encoded and retained for comparison to a later crowded target. The results show that performance is better in the Matched condition for simultaneous presentation or a slight precedence of the remote item, consistent with the persistence of the decaying features of the crowded item in iconic memory.

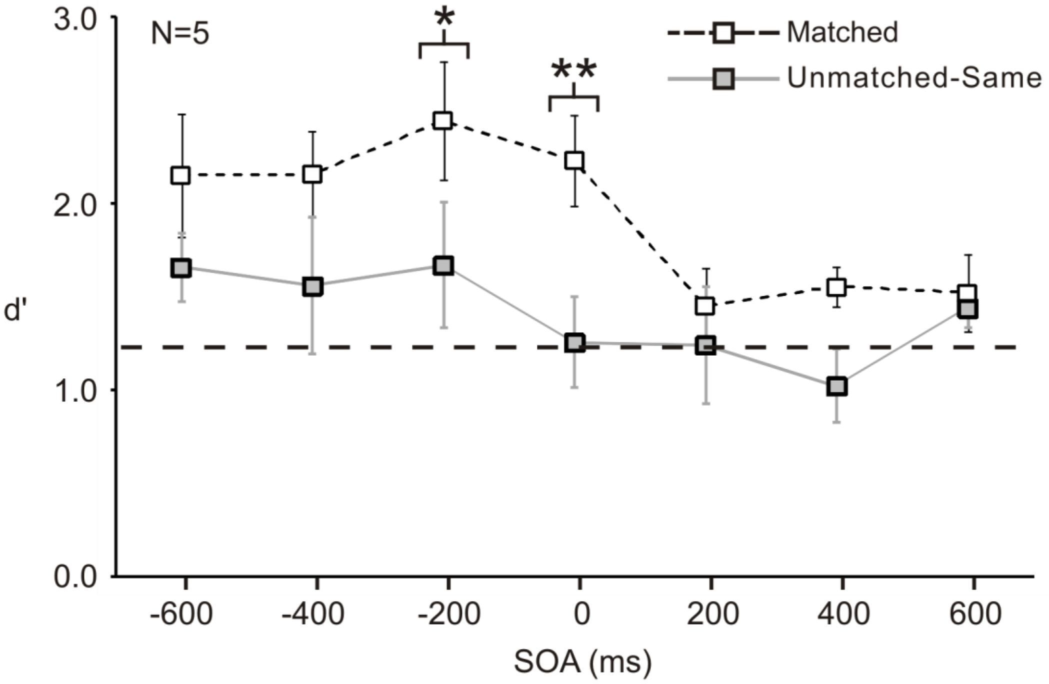

Figure 2: Results of Experiment 2. The remote item was presented before (negative SOAs), simultaneous with (SOA = 0), or after (positive SOAs) the crowded target. Sensitivity was higher in the Matched compared to the Unmatched-Same condition. Planned comparisons revealed higher sensitivity when the remote item was presented before (at -200 ms) or simultaneously with the target. Asterisks indicate statistical significance. Error bars indicate standard errors of the mean. The dashed line shows sensitivity in the baseline condition where no remote item was presented.

We attribute the advantage in the Matched condition to long-range grouping between the remote item and the target, similar to grouping processes proposed to play a role when detecting repeated elements (Butcher & Cavanagh, 2008, 2012), and when targets are assimilated by grouped flankers (Sayim & Cavanagh, 2013). When the target and the remote item are presented simultaneously, we suggest that they become grouped and that it is this grouping that makes the target stand out from the flankers, and increases sensitivity.

Experiment 3: Semantic Control

In Experiment 1, we found that remote items reduced crowding when they matched the target compared to when they did not match the target. In Experiment 2, we showed that this effect was strong when the remote item was presented simultaneously with the target or in the 200 ms preceding the target, and weak (or absent) when it was presented with large SOAs before, or after the target. We also observed, in each case, a tendency for observers to report the target as having the same category as the remote item. We suspect that this arises due to observers' uncertainty regarding the target, and a tendency to report the category of the clearly visible remote item in its place. Importantly, our observed effects on d′ occur only for identity matches, and not simply for category matches, demonstrating that the advantage derived from remote items can occur even in the presence of this category bias. However, it could still be the case that cueing the category of the target facilitates its recognition. In order to control for this semantic knowledge, i.e., that performance could be facilitated through knowledge of the target's category but not its shape, we performed Experiment 3 where we independently varied the semantic identity (the letter name) and shape identity (the letter case) of both the remote item and the target.

Method

Experiment 3 was the same as Experiment 1 with the following changes. Instead of numbers and letters, the stimuli consisted of capital and lower case letters of Lucida Handwriting font, drawn from the two sets “a, b, e, h, n, r, t” and “A, B, E, H, N, R, T”, selected to match in curvature and complexity between the upper case and lower case letters (see Figure 3A). The maximum vertical extent of the letters was set to 1.0 degree (the height of the small lower case letters “a, e, n, r” was adjusted to match this height; the width varied slightly depending on the item). The remote item was always presented at the fovea.

The experiment was a balanced, 2 x 2 repeated measures design with two variables, Case and Name. The Case variable determined whether the remote item and the target were the same or different in case (e.g., same: AB or aa vs. different: Ab or aA), and the Name variable determined whether the remote item and target were the same or different in name (e.g. same AA or Aa vs different AB or aB). In the conditions with the same case, half of the trials were lower case and the other half upper case letters. In the conditions with different cases, the remote item was an upper case letter and the target a lower case letter in half of the trials, and vice versa in the other half of the trials. Neither the remote item nor the target ever shared the same identity as either of the flankers. The two flankers always consisted of one upper case and one lower case letter.

Observers performed two tasks. In the first task, they indicated whether the target was an upper or lower case letter – the *category* task. In the second, *name match* task, observers indicated whether the remote item and the target were the same letter or not (asked to respond “same” when the remote item and the target had the same name regardless of the case, e.g. A and a, or B and B). Observers completed 2 blocks with 160 trials per block. Four observers who participated in Experiment 2, including one of the authors, and one new observer participated in the experiment (5 males).

Results and discussion

Figure 3B plots the results of the category task of Experiment 3. To calculate sensitivity (d′) and bias, we defined upper case letters as “signal” and lower case letters as “noise”. Separate ANOVAs were calculated for sensitivity and bias. Comparing sensitivities, we found a main effect of Name ($F(1,4) = 10.359$, $p < 0.05$). Sensitivity was higher when the name of the remote item and the target were the same (d′=1.78; SE=0.19) compared to when they were different (d′=1.29, SE=0.18). There was no main effect of Case ($F(1,4) = 4.076$, $p = 0.114$), while the interaction approached but did not reach significance ($F(1,4) = 6.159$, $p = 0.068$).

Looking at the effect of Name for each value of Case, planned comparisons (with Bonferroni corrected alpha level of 0.017 (0.05/3)) showed that the same name advantage only held when the remote item and target also had the same case (Same-Name-Same-Case condition versus Different-Name-Same-Case condition; ($F(1,12) = 8.60$, $p < 0.017$)). In this condition, the remote item and target were physically identical. In contrast, there was no significant advantage for a name match when the cases did not match (i.e., no semantic, name effect in the absence of a physical match: Same-Name-Different-Case versus Different-Name-Different-Case; ($F(1,12) = 0.70$, $p = 0.419$)). The comparison between the two Same-Name conditions also revealed a clear advantage when the remote item and target were of the same case (Same-Name-Same-Case versus Same-Name-Different-Case; $F(1,12) = 10.30$, $p < 0.017$), where again they were physically matched.

Concerning biases, there was no main effect of Case ($F(1,4)=1.761$, $p = 0.255$), no main effect of Name ($F(1,4) = 3.025$, $p = 0.157$), and no interaction ($F(1,4) = 0.310$, $p = 0.608$, results not shown).

These results show that it is the physical match (same name, same case) that generates the remote item benefit and not the semantic match (same name) on its own. Importantly, in the secondary task, observers reported whether the remote item and the target were of the same (or different) name. Hence, although observers scrutinized the target location for a particular letter name independently of case, same case letters yielded an advantage compared to different case letters.

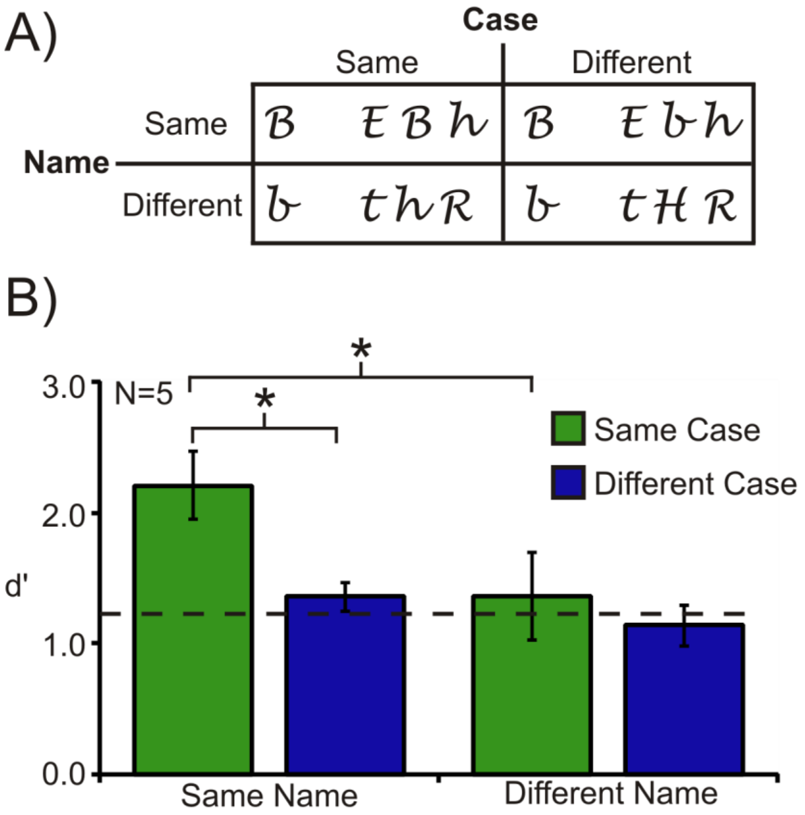

Figure 3: A) Stimuli of Experiment 3. For each of the four conditions, one example is shown in each field. The remote item is shown on the left and the target on the right between two flankers. B) Results of Experiment 3. The Same-Name-Same-Case condition yielded higher sensitivity than the Same-Name-Different-Case condition and the Different-Name-Same-Case condition (indicated by the asterisks). The dashed line indicates baseline sensitivity. Error bars indicate standard errors of the mean.

General discussion

Crowding is a fundamental limit to visual perception -- objects that are easily identified in isolation are unidentifiable when presented in clutter. Understanding the underlying mechanisms of crowding will help to understand how the brain integrates information and ultimately how objects are perceived. A central question in crowding is what happens to the target signal. Different accounts of crowding propose that target features are mixed with flanker features through processes such as averaging (Parkes et al., 2001), or regularization (Greenwood et al., 2010; Freeman & Simoncelli, 2011), or that flankers are wholly substituted for targets (Strasburger, Harvey, & Rentschler, 1991; though cf. Greenwood, Bex, & Dakin, 2009; Freeman, Chakravarthi, & Pelli, 2012). We know that the target signal is weakened in some way by the flankers – as shown by the reduced performance with crowded compared to uncrowded targets. However, many studies have shown that even though a target cannot be discriminated, it is still processed by the visual system to an extent where it can influence perception and behavior.

Here, we investigated whether a target weakened by crowding can be enhanced by matching items that are located far outside the crowding region, and showed that this was indeed the case. We suggest that the target signal is not irretrievably degraded by crowding, but can be enhanced or protected by shape-specific mechanisms from outside the crowding region. It needs to be shown whether such enhancement in the Matched compared to the Unmatched-Same condition is due to the remote helper boosting a weak signal or preventing the typical weakening caused by crowding. Importantly, we found in a pilot experiment that the enhancement was only seen if the observers were forced to pay attention to the remote item, otherwise, when it was irrelevant, it was easy to ignore and without effect. To force observers to pay attention to the remote item in the present experiments, we used a secondary task in which observers indicated whether the target and the remote item were the same or not.

We suggest that the enhancement is due to grouping between the remote item and the target, and specifically a grouping process that depends on the physical similarity of the two. This implies that the task in this condition involves the detection of a repeated item (Butcher & Cavanagh, 2008, 2012) where the repetition overcomes the effects of the flankers on the crowded item. Before describing this hypothesis in more detail, we describe a number of alternatives: response substitution from the remote item, cueing where the remote item initiates a search for targets that match it, and similarity matching where target features are compared with the remote item.

One explanation of the enhancement effect of the remote item is that observers tended to substitute a response that was the remote item category for the target category, i.e., they indicated that the target was a number (or letter) when the remote item was a number (or letter; correspondingly, upper case or lower case letter in Experiment 3). In particular, when observers were uncertain about the identity of the target, their response may have been influenced by the category of the remote item, a clearly discernible item. Indeed, the results of Experiments 1 and 2 demonstrate that performance was worse when the remote item and target had different categories than when they were of the same category, indicating that observers tended to respond in line with the remote item category. However, such a response substitution cannot underlie our main finding in Experiments 1 and 2 because in our critical analysis, the target and remote items were always from the same category and we found an effect of the identity match. Additionally, in Experiment 3 we found that observers were not influenced by the case of the remote item in general, but only when the names of the remote item and the target were also the same so that when the case and name matched, the remote item and target were physically identical.

A second possible explanation is that observers were looking for a target that matched the remote item, as required by the secondary task. With such a strategy, the remote item could have served as a cue for the target that increased attention to target features. Our results in Experiment 2 do not support the expected pattern for cueing with effects predominantly well before (150 to 300 ms) the target appearance (e.g., Posner & Keele, 1967; Posner, Boies, Eichelman, & Taylor, 1969; Cooper & Shepard, 1973; Carr, McCauley, Sperber, & Parmelee, 1982; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). While there was a non-significant trend for a larger advantage when the matching remote item was presented before the target compared to after the target, the large advantage with simultaneous presentation argues against cueing as the only source of the observed uncrowding effect.

A related explanation is that observers extracted features of the crowded target and compared them with the remote item to reach an estimate of similarity (or partial match). If these features were sufficiently similar to those of the remote item, observers would respond with the remote item's category. This strategy should again favor the conditions in which the remote item appears before the crowded target as the crowded target's features will decay rapidly but the remote item's encoded identity will resist decay. Hence, we would expect a performance advantage for all conditions with the remote item presented before the crowded target in Experiment 2. However, the advantage when the remote item was presented 400 or 600 ms before the target did not reach significance, whereas performance did improve significantly when the remote item and crowded target were presented at -200 ms or 0 ms. The apparently weak preview advantage at -600 ms and -400 ms could reflect strategies such as cueing or similarity matching that require some time to analyze the remote item in order to set up the evaluation of the target. Although these strategies cannot be ruled out, we stress that the significant benefits seen at -200 ms and 0 ms favor processes that depend on simultaneity between the remote item and the target.

In particular, we propose that the advantage was due to long-range grouping between remote item and target. When remote item and target had the same shape, grouping by similarity between the two items made the target stand out from the flankers. This is in line with observers' reports about their impressions when queried after the experiment (readers may experience a similar effect when fixating on the remote items in Figure 3A). The advantage only occurred when the remote item was physically the same as the target and not when it was only semantically matched (Experiment 3), as expected under the grouping assumption. In contrast to the cueing and similarity matching explanations, the grouping explanation is of a perceptual rather than a cognitive nature. The grouping explanation predicts a maximum effect at simultaneous presentation of the remote item and the crowded target. As we found a strong advantage at simultaneous presentation (as well as a somewhat weaker advantage at -200 ms) and only a trend at longer SOAs, we propose that the results are best accounted for by the grouping explanation. Similar long-range grouping effects have been reported for the detection of repeated elements (Butcher & Cavanagh, 2008, 2012), and the assimilation of crowded targets by grouped flankers (Sayim & Cavanagh, 2013).

Besides similarity, grouping depends on a number of other factors, in particular, proximity. However, our strongest effect was for the remote item at the fovea rather than the position closest to the target. It may be that there are additional attentional benefits at the fovea (Wolfe, O'Neill, & Bennett, 1998) compared to the periphery, possibly increasing grouping.

Generally, grouping between target and flankers in crowding reduces performance (e.g., Sayim, Westheimer, & Herzog, 2010; Manassi, Sayim, & Herzog, 2012; but see, Greenwood, Sayim, & Cavanagh, 2014). However in our experiments, the grouping is taking place between the target and a flanker well outside the crowding zone and with a flanker that is identical to the target. These factors explain why the effect should be an enhancement in target identification (reduced crowding) rather than a reduction in performance. We conclude that target signals in crowding are not irretrievably lost. On the contrary, these signals can be made visible by long-range, shape-specific grouping that diminishes the deleterious effect of proximate flankers.

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