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Bilateral field advantage in visual crowding

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ABSTRACT

Thirty randomly oriented T's were presented in a circle around fixation at an eccentricity of 11° such that each T was crowded by its neighbors. Two locations within the same hemifield (unilateral condition) or one location in each hemifield (bilateral condition) were precued for subsequent probing. Observers were then asked to report the orientation of a target T at one of these locations. A bilateral field advantage was found: target identification was better when the two precued targets were in different hemifields than when they were within the same hemifield. This bilateral advantage was absent when only targets were presented, without any distracters. Further controls showed that this advantage could not be attributed to differences between horizontal and vertical target alignments or to visual field anisotropies. A similar bilateral advantage has been reported for multiple object tracking (Alvarez, G. A., & Cavanagh, P. (2005). Independent resources for attentional tracking in the left and right visual fields. *Psychological Science 16*(8), 637–643) and other attentional tasks. Our results suggest that crowding also demonstrates separate attentional resources in the left and right hemifields. There was a cost to attending to two targets presented unilaterally over attending to a single target. However, this cost was reduced when the two crowded targets were in separate hemifields.

1. Introduction

Visual crowding is a phenomenon wherein identification of a target is severely impaired in the presence of nearby flankers (Andriessen & Bouma, 1976; Bouma, 1970; Westheimer, Shimamura, & McKee, 1976). This effect is pronounced in the periphery (Bouma, 1970; Toet & Levi, 1992) and is distinct from low-level feature interaction based processes such as lateral masking (Chakravarthi & Cavanagh, 2007; Levi, Hariharan, & Klein, 2002; Pelli, Palomares, & Majaj, 2004).

Although several hypotheses have been put forward to explain crowding, a definitive account has not yet been realized (see Levi, 2008 for a recent comprehensive review). Two prominent contenders are the bottom-up 'pooling of signals' hypothesis and the top-down attentional account of crowding. Crowding might reflect 'compulsory pooling of signals' (Levi et al., 2002; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Pelli et al., 2004). This hypothesis posits that object identification follows a two-stage process. In the first – 'feature detection' – stage, features of the object are independently collected; in the second – 'feature integration' – stage, this information is pooled to identify the target. This pooling occurs, independent of other such pooling regions, over some area and when that area includes flankers, the target features are combined with those of the flankers leading to a jumbled percept. Alternatively, crowding might reflect the poor resolution of attention (He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001). The attention resolution theory specifies that attention has a minimum available size of selection region at a given eccentricity. This minimum size is quite a bit larger than the smallest resolvable detail at that eccentricity. Hence, with several objects within such a region, the identity of the target would no longer be independently resolved.

There is accumulating evidence for the attentional account of crowding. For example, Chakravarthi and Cavanagh (2007) showed that the polarity advantage in crowding – a target with a different polarity than its distracters is less amenable to crowding than a target with the same polarity – disappears around 6–8 Hz, which is the same as the temporal resolution of attention as measured in several studies (Battelli, Cavanagh, Martini, & Barton, 2003; Battelli et al., 2001; Rogers-Ramachandran & Ramachandran, 1998; Verstraten, Cavanagh & Labianca, 2000). Crowding might also exhibit other characteristics of selective attention. In this study we test if crowding shows evidence of bilateral field advantage observed in other attentional tasks.

There is a well-established literature that argues for the existence of multiple attentional foci (Castiello & Umilta, 1992; Cave & Bichot, 1999; Kramer & Hahn, 1995; Muller & Findlay, 1987; Scharlau, 2004). For example, identifying spatially separated targets

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presented at precued locations is easier than identifying targets that are presented in between the cued locations (Awh & Pashler, 2000; Bichot, Cave, & Pashler, 1999) suggesting that the attentional focus is not a unitary region. This lack of sensitivity to spatial locations that fall in between cued locations has also been confirmed electrophysiologically (Muller, Malinowski, Gruber, & Hillyard, 2003). Although attention may have multiple foci, the effectiveness of these foci depends on their distribution in the visual field. Importantly, a bilateral advantage has been observed in several tasks – tracking objects attentively (Alvarez & Cavanagh, 2005), searching for a target where a subset of the displayed objects have to be ignored (Alvarez & Cavanagh, 2006), attentional priming (Scharlau, 2004), remembering locations (Delvenne, 2005), comparing identities (Kraft et al., 2004; Muller et al., 2003; Sereno & Kosslyn, 1991), responding to targets placed in different sized objects (Castiello & Umilta, 1992), and even in elementary tasks such as gabor detection and discrimination in the presence of distracters (Reardon, Kelly, & Matthews, 2009), among others. These tasks are easier when the targets are distributed in the two hemifields than if they are located in the same hemifield. A bilateral advantage seems to be a general feature of selective attention and can serve as its signature. Given this and our contention that limitations in the resolution of selective attention underlie crowding, we may expect that crowding too should exhibit a bilateral advantage.

While an attentional explanation of crowding predicts a bilateral superiority in identifying a crowded target, a purely bottom-up crowding mechanism does not make any such specific predictions. According to the bottom-up pooling hypothesis, the visual field is full of independent pooling regions, and the output of one such region should not be affected by the activity of another non-overlapping region regardless of its (hemifield) location. Attention, of course, plays a role in any discrimination task and we add control experiments to show that the results are not a general effect of attentional deployment.

2. Experiment 1A: bilateral advantage in crowding

In this experiment, we directly test the prediction that crowding should demonstrate a bilateral advantage if attentional selection underlies crowding. In a severely crowded display, we asked subjects to monitor two targets presented in the same hemifield or in opposite hemifields. According to the attentional hypothesis, identifying a target in the latter should be easier.

2.1. Methods

2.1.1. Subjects

Ten experienced subjects, aged 26–35 years, with normal acuity provided informed consent and participated in this experiment.

2.1.2. Materials and stimuli

Vision Shell stimulus production software was used to produce and display stimuli on an Apple Power Macintosh and 18" Sony monitor.

Targets and distracters (Fig. 2) were dark gray T's in four possible orientations (upright, inverted, rotated left, or rotated right) presented on a uniform gray background of luminance 34.2 cd/m^2 (CIE coordinates: $x = 0.307$, $y = 0.313$). At a viewing distance of 57 cm, the two bars that made up each T were 1° in length. The contrast for the T's was fixed at 0.25. Thirty T's were presented at equidistant points on an imaginary circle of radius 11° from fixation. The center–center distance between adjacent T's was ~2.2° (this places the T's well within Bouma's bound (Bouma, 1970; Toet & Levi, 1992) of 1/4× eccentricity for effective crowding in the circumferential direction). With this arrangement we would expect significant crowding of any given T by its neighboring T's (see Fig. 1).

2.1.3. Procedure

There were three conditions in this experiment: *Attend 1*, *Attend 2-Bilateral*, and *Attend 2-Unilateral*. In each condition, the trial sequence was the same. Black placeholder circles were present on the screen throughout the testing session. Each trial started with a precue in the form of a change in the color of a ring from black to bright green. In the *Attend 1* condition, one of the 30 circles would be precued to indicate that subjects should attend that location. The *Attend 1* condition served as a baseline for the performance in the other two main conditions. In the *Attend 2-Bilateral* and *Unilateral* conditions, two ring locations were precued. These highlighted rings were separated by one of 6 possible, randomly chosen, separations: 11, 13.2, 15.4, 17.6, 19.8, and 22° apart (in other words – with 5–10 circles separating the two target locations). This was done to prevent preferentially attending to any specific set of locations. It would also rule out any explanations that were based on the specific locations of targets in the visual field (for example, known effects such as the horizontal–vertical asymmetry, Carrasco, Talgar, & Cameron, 2001). Also, the targets themselves were beyond crowding distance of each other. In the *Attend 2-Bilateral* condition, one location in each hemifield (left and right) was precued. These locations would be either in the upper field or in the lower visual field. In the *Attend 2-Unilateral* condition, the two locations were both in the same hemifield – either the left or the right. Thus, subjects had to attend to two locations – either in opposite hemifields or in the same hemifield, respectively – in these conditions. The two targets were never presented in the same quadrant. Locations on or near the vertical and horizontal midlines were never tested.

The precue lasted for 150 ms. Three hundred milliseconds later T's were flashed in all the circular placeholders for 200 ms. The subjects were instructed to try and attend to only the T's in the

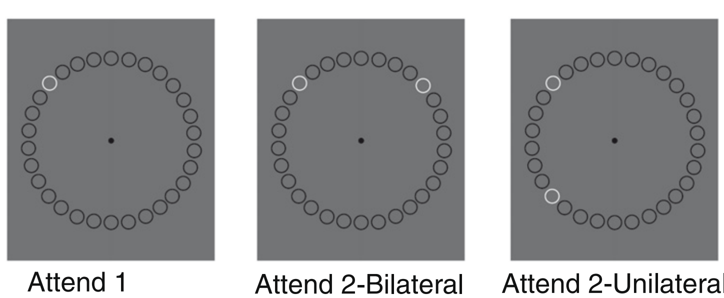

Fig. 1. The three conditions in experiment 1. Each panel represents one condition. Black placeholders were present throughout a session. T's always appeared within these placeholders. Locations to be attended in each condition are highlighted in white. Left: *Attend 1* condition: one location was precued; subjects had to attend to that location and report the orientation of the T presented there. Middle: *Attend 2-Bilateral* condition: two locations, one in each hemifield, were precued. Right: *Attend 2-Unilateral* conditions: two locations within a hemifield were precued. In the latter two conditions subjects were finally required to report the orientation of the T in one the two precued locations.

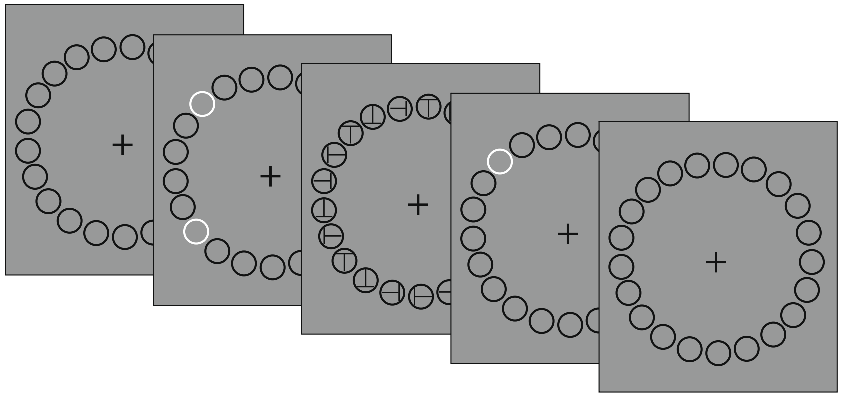

Fig. 2. Trial sequence in experiment 1A. Placeholders were present throughout the experiment. For illustrative purposes, the number of placeholders shown here is fewer than in the actual experiment. Two locations in the *Attend 2* conditions or one location in the *Attend 1* condition were precued for 150 ms (indicated in white here). 300 ms later, target and distracter T's in various orientations were presented briefly for 200 ms. A post-cue followed this display after 300 ms indicating the target T to be reported.

precued locations. 300 ms following the disappearance of the T's, one of the two precued locations (or the same location as was precued in the *Attend 1* condition) was post-cued (for 150 ms) to indicate that the orientation of the T in that location should be reported.

2.2. Results

A repeated measures one-way ANOVA was conducted on the performance in the three conditions, which revealed that they were different from each other [$F(2, 18) = 12.6$; $p < 0.0005$]. We then conducted pair-wise t-tests among the three conditions. The p values reported for all t-tests in this article are Bonferroni corrected for multiple comparisons, unless otherwise noted.

As seen in Fig. 3, subjects found it easier to do the task when they had to attend to two crowded targets presented in different hemifields (*Attend 2-Bilateral* mean = 59%) than when they had to attend to targets in the same hemifield (*Attend 2-Unilateral* mean = 52.5%). This bilateral advantage was reliable [$t(9) = 3.02$; $p<0.05$]. Also, performance in the *Attend 1* condition was far lower than ceiling (mean = 70%) confirming that the target was crowded in the display we used. [Pilot testing had shown that unflanked targets at the tested contrast and locations, both with and without placeholders were identified at close to 100% accuracy.] However, there was a further cost in having to attend an additional target, whether in the opposite hemifield [$t(9) = 3.03$; $p<0.05$] or in the same hemifield [$t(9) = 3.97$; $p = 0.01$]. The finding that a cost is incurred when two targets are attended relative to when a single target is attended is consistent with earlier findings (Baylis & Driver, 1993; Duncan, 1984; Eriksen & James, 1986; Lamy & Egeth, 2002; McMains & Somers, 2004, 2005; Niesser, 1967). When subjects had to attend to two targets, a decrement was evident in both behavioral and imaging (BOLD signals) measures relative to when they had to attend to only one location (McMains & Somers, 2005). The results of this experiment do not demonstrate complete independence of resources for the two hemifields. If the resources for the two hemifields were completely independent, we would expect that performance in the *Attend 2-Bilateral* condition would not be different from the *Attend 1* condition (as the two hemispheres should be able to independently process the two targets).

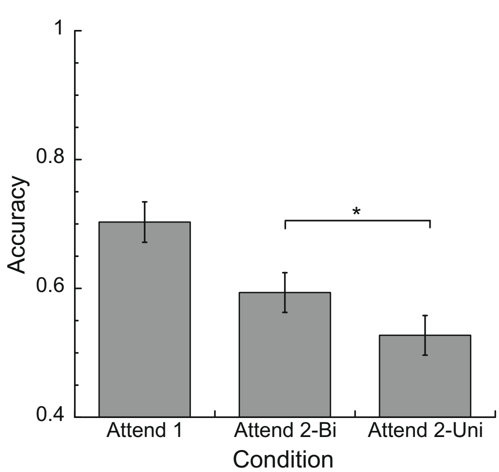

Fig. 3. Experiment 1A results: the graph plots mean accuracy ($n = 10$) in the three experimental conditions. Error bars represent one SEM.

3. Experiment 1B: is the bilateral advantage due to a horizontal vs. vertical advantage?

In experiment 1A, we tried to ensure that the targets were not exactly aligned horizontally in the bilateral condition and vertically in the unilateral condition so as to avoid any possible effects of known visual field anisotropies such as the vertical–horizontal asymmetry (Carrasco et al., 2001). We did this by randomly varying the location of each target on every trial, but with certain restrictions (see experiment 1A methods above). However, by necessity, the targets in the unilateral condition were more vertically aligned with respect to each other than in the bilateral condition. This might potentially explain the observed bilateral advantage. Perhaps it is easier to deploy attention horizontally than vertically or identification is easier when targets are arranged horizontally rather than vertically.

To control for this confounding factor, in experiment 1B, we presented four equidistant targets on the horizontal meridian, two in each hemifield. With this arrangement we can now determine, by cueing two targets in the same or in opposite hemifields, whether we continue to see a bilateral advantage. If the advantage observed in experiment 1A is an artifact of the horizontal alignment of the targets in the bilateral condition, then no such advantage should be observed here, as all targets are on the same horizontal line.

3.1. Methods

3.1.1. Subjects

Five experienced subjects, aged 22–33 years, with normal or corrected to normal vision participated with informed consent in this experiment.

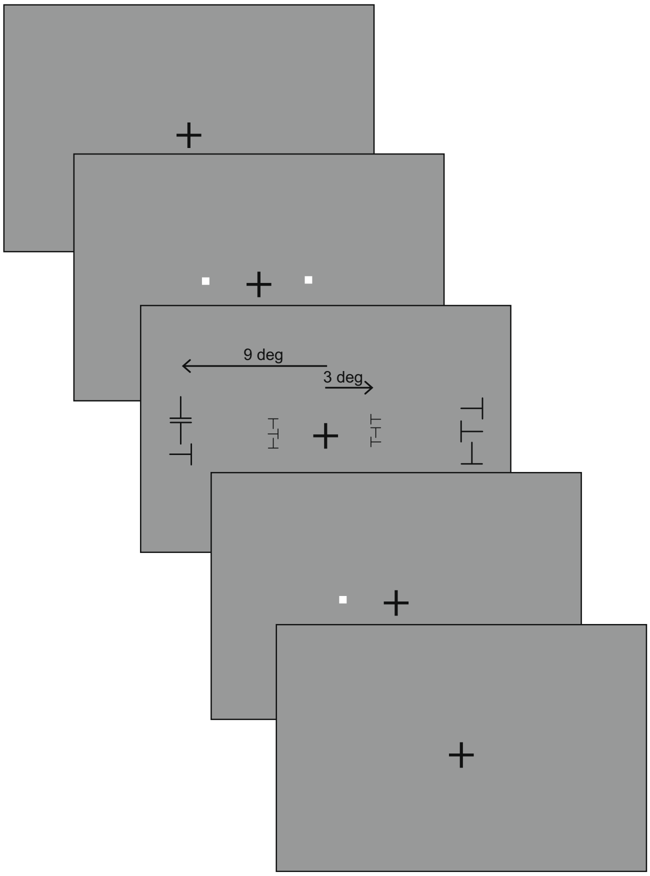

Fig. 4. Trial sequence in experiment 1B. Four targets were presented at 9, 3, 3 and 9° (left to right) from fixation, respectively, on the horizontal meridian. Each target was flanked by two distracters (one above and one below). The T's at 9° were scaled versions of the one's at 3°. Two locations in the *Attend 2* conditions or one location in the *Attend 1* condition were precued for 100 ms (indicated in white here). 100 ms later, target and distracter T's in various orientations were presented briefly for 100 ms. A post-cue followed this display after 100 ms indicating the target T to be reported.

3.1.2. Stimuli

The stimuli used were high contrast black T's (4.2 cd/m^2). One T each was presented at 3 and 9° to the left and right of fixation on the horizontal meridian (Fig. 4). Thus there were a total of four potential targets and the distance between adjacent T's was 6°. The distances were chosen such that the targets themselves did not crowd each other. Each target T was flanked by two distracter T's above and below it (in the vertical direction). The T's at 3° were 0.4° in size and were spaced 0.5° apart. The size and spacing of T's at 9° were scaled (1.2° size and 1.5° spacing) to ensure equal visibility and crowding as that of the nearer T's. No placeholder circles were used. Cueing was done by presenting green squares of size 0.3° at the locations of the target.

3.1.3. Procedure

The same three conditions were present in this experiment: *Attend 1*, *Attend 2-Bilateral*, and *Attend 2-Unilateral*. In the *Attend 1* condition, one of the targets was precued. In the *Attend 2-Bilateral* condition, two targets, one in each hemifield, were precued. These could be either the two near T's (at 3° eccentricity) or the two far T's (at 9° eccentricity). In the *Attend 2-Unilateral* condition, the two T's in one hemifield (right or left) were precued. The three conditions were interleaved in a session, with 80 trials per condition.

The timing of cue and target presentation was modified from that in experiment 1A such that the chance for any eye movements was minimized. Green precues were presented for 100 ms at locations determined by the condition being tested. 100 ms after the cues were removed, all four targets and their distracters were presented for 100 ms. 100 ms after the T's were removed, a post-cue was presented for 100 ms in one of the precued locations. Observers were asked to report the orientation of the target T at that location. Since the stimuli were presented for such a short time, any eye movements would only work against better performance in the bilateral condition (since in half the trials the targets were 18° apart).

3.2. Results

As in experiment 1A, a clear and consistent bilateral advantage was seen (Fig. 5). It was easier to identify targets in different hemifields (*Attend 2-Bilateral* mean = 80%) than in the same hemifield (*Attend 2-Unilateral* mean = 69%) [$t(4) = 10.11$; $p < 0.0025$]. A repeated measures one-way ANOVA showed that the performance in the three conditions were different [$F(2, 8) = 15.87$; $p < 0.0025$]. There was a cost in identifying two targets in the same hemifield (mean = 69%) compared to identifying just one (*Attend 1* mean = 89%), as in experiment 1A [$t(4) = 4.4$; $p < 0.05$]. However, unlike in experiment 1A, performance in the *Attend 1* and *Attend 2-Bilateral* conditions were not different [$t(4) = 2.24$; $p > 0.1$] indicating a larger degree of independence in attentional resources for the two hemifields than was found in experiment 1A.

Several objections need to be addressed before these results can be considered meaningful. In the bilateral condition, half of the trials required attending to targets that were farther away (target–target distance 18°) than those in the other half (6°). In the unilateral condition, the targets were always separated by 6°. It is possible that the difference in performance was driven primarily by improved performance when the targets were further apart (Bahcall & Kowler, 1999; Mounts & Gavett, 2004). We did not find any effect of target–target distance in the bilateral condition. Performance was the same in the bilateral condition whether the targets were close to (mean = 80%) or far from (mean = 80%) each other. Another possibility is that there is a difference in identification performance at the two eccentricities, even though size and spacing were scaled. In the unilateral condition, the two cued targets were at different eccentricities (and thus with different size

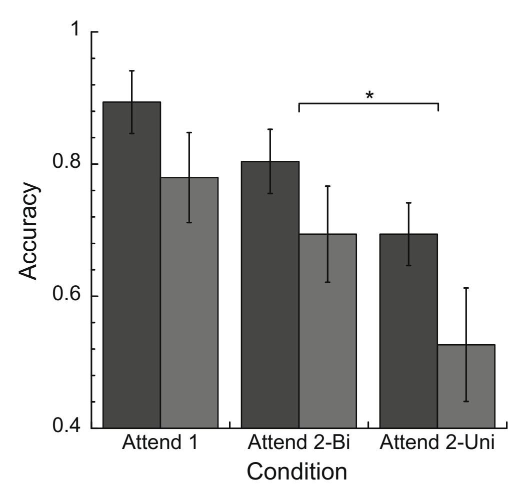

Fig. 5. Experiment 1B results: the graph plots mean accuracy ($n = 5$) in the three experimental conditions. Results from the experiment where the size and spacing of the stimuli were scaled are indicated in dark gray; results from the experiment where all stimuli are the same size are indicated in light gray. The light gray bars represent performance on targets at 9° eccentricity (the farther and harder to see targets). Error bars represent one SEM.

and spacing) whereas in the bilateral condition, the two targets were at the same eccentricity (and hence with the same size and spacing). If identification is easier at one eccentricity than at the other, the bilateral advantage might merely be a reflection of reduced task difficulty in some trials. However, we found that identifying a single target was the same whether the target was at 3° (mean = 90%) or at 9° (mean = 89%) suggesting that eccentricity did not play a role [$t(4) = 0.15$; $p = 0.9$] when the stimuli were scaled appropriately. Furthermore, we compared trials in the two conditions where the target–target distance was the same (6°) and the reported target was presented at the same eccentricity (3°). Here, all factors for the reported target are equated across the two conditions except whether the other cued target was in the same or different hemifield. Here too a significant bilateral advantage was seen [bilateral = 80%, unilateral = 74%; $t(4) = 5.72$; $p = 0.005$, not Bonferroni corrected].

A final alternative explanation of these results is that there is an advantage in identifying objects of the same size. In the bilateral condition, the attended targets were always the same size, but in the unilateral condition the two targets were of different sizes. The observed bilateral advantage might merely be a consequence of a superior ability in identifying targets of the same size. One reason that this might not be the case is that in experiment 1A all targets were the same size and yet we observed a bilateral advantage. However, to test this more rigorously, we reran experiment 1B on five observers (four of whom were the same observers as in the scaled targets version), while keeping the sizes of all T's the same (equal to that of the T's at 3° eccentricity in experiment 1B). This arrangement produced the same result, despite the fact that the far T's were harder to identify (mean *Attend 1* performance at 9° eccentricity = 78%) than the near ones (mean *Attend 1* performance at 3° eccentricity = 96%). For example, the accuracy in identifying the distant T (the harder to see T) was better if a second attended T was in the opposite hemifield than if it was in the same hemifield [see Fig. 5: bilateral = 69%, unilateral = 53%, $t(4) = 9.53$; $p = 0.002$]. Once again, there was no significant difference between attending to a single target and attending to two bilateral targets [*Attend 1* = 78%, *Attend 2-Bilateral* = 69%; $t(4) = 2.63$; $p > 0.25$], indicating a greater degree of independence of resources in the two hemifields.

Experiment 1B shows that even when all the targets are aligned horizontally, a bilateral advantage is seen indicating that the effect observed in experiment 1A was not a result of any anisotropies in the visual field or a difficulty in deploying attention in the vertical direction. Further, the procedure was modified to prevent any possible eye movements, suggesting that eye movements are not responsible for the observed results. Finally, adding a second target in the opposite hemifield did not decrease performance significantly, suggesting independence in attentional resources of the two hemifields.

4. Experiment 2A: bilateral advantage for letter recognition under uncrowded conditions?

The main finding of a bilateral advantage in crowding strengthens the attentional account of crowding. However, we need to examine alternative explanations for these results. One possibility might be that there is a bilateral advantage for recognition of individual letters that is a general property of recognition that can be seen even under uncrowded conditions. If so, the results would not reflect any special link between crowding and attention, as crowding would merely be demonstrating an already existing advantage. Another possibility is that visual short-term memory (VSTM) and not attention exhibits bilateral advantage (see Delvenne, 2005). It might be easier to *retain* objects divided across hemifields than within hemifields. If so, we would expect the same results as above even if there were no bilateral advantage for crowding.

We tested these possibilities directly in this experiment. The setup was similar to that of experiment 1A, except that the targets were uncrowded in this case. If a generalized bilateral advantage exists for identifying letters, we should see evidence for such an advantage here as well. Similarly, if the advantage exists for retaining two object identities in VSTM (and not at the selection stage), then performance should reflect this advantage.

4.1. Methods

4.1.1. Subjects

Nine experienced subjects, aged 22–35 years, with normal or corrected to normal vision participated with informed consent in this experiment.

4.1.2. Materials and stimuli

The materials and stimuli used were the same as in experiment 1A except for a few changes. In this experiment no distracters were presented. The target T's were set to 0.04 contrast (based on pilot testing on three subjects) so as to obtain an accuracy of around 80% when presented in isolation at the tested eccentricity. We also did not present the placeholder circles as they might mask the weak target signals.

4.1.3. Procedure

The same three conditions were present in this experiment: *Attend 1*, *Attend 2-Bilateral*, and *Attend 2-Unilateral*. However, we presented isolated (and hence uncrowded targets) in all three conditions. The trial sequence was the same as in experiment 1A (see Fig. 6) with subjects having to attend to 1 target location in the *Attend 1* condition and two locations (either in opposite hemifields or in the same hemifield) in the two *Attend 2* conditions.

4.2. Results

There was no difference (Fig. 7) in identifying targets whether presented in the same hemifield (*Attend 2-Unilateral* mean = 66%) or in different hemifields (*Attend 2-Bilateral* mean = 65.5%) [$t(8) = 0.15$; $p = 1$]. This rules out explanations that seek the origin of the bilateral advantage, observed earlier, in processes other than selective attention such as letter recognition or in the VSTM. We might infer from these results that the bilateral advantage noticed earlier is particular to target selection among clutter. This provides further support for the attentional hypothesis of crowding. Awh and Pashler (2000) reported a similar result – no bilateral advantage was observed for number recognition in the absence of distracters.

As in experiment 1A, there was a cost for attending to two targets over that of attending to only one target (*Attend 1* mean = 79.4%) irrespective of whether the second target was in the same hemifield [$t(8) = 3.69$; $p < 0.025$] or in the opposite hemifield [$t(8) = 3.65$; $p < 0.025$]. Thus, adding a second target reduced performance significantly, consistent with earlier findings (e.g., McMains & Somers, 2005).

5. Experiment 2B: bilateral advantage for cueing?

The bilateral advantage in crowding might occur at one of two steps: the step at which cues draw attention to the target location or at the step at which attention selects the targets among distracters. It is possible that bilateral cues are more effective in drawing

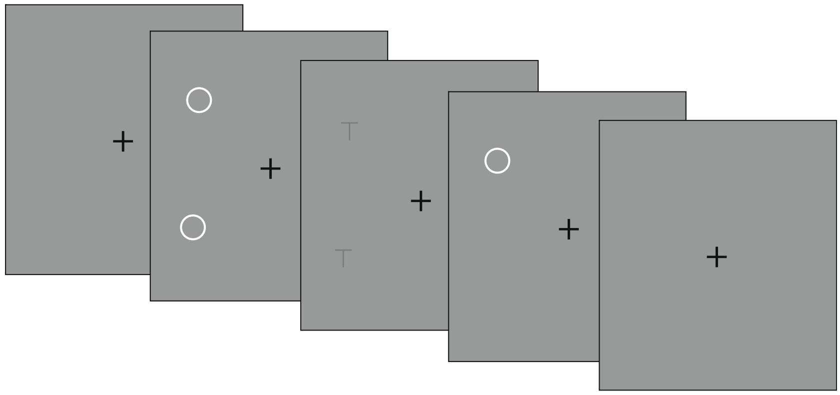

Fig. 6. Trial sequence in experiment 2A. Placeholders were absent in this experiment. With that exception, the sequence was the same as in Experiment 1A. Two locations in the *Attend 2* conditions or one location in the *Attend 1* condition were precued for 150ms (indicated in white here). 300 ms later, target and distracter T's in various orientations were presented briefly for 200 ms. A post-cue followed this display after 300 ms indicating the target T to be reported.

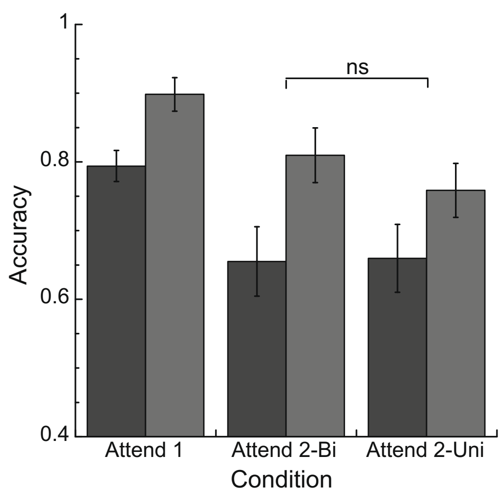

Fig. 7. Experiment 2 results: the graph plots mean accuracy in the three experimental conditions. Results from the experiment 2A (no distracters, no placeholders) are indicated in dark gray; results from the experiment 2B (no distracters but placeholders present) are indicated in light gray. Error bars represent one SEM.

attention to target locations (irrespective of whether there are distracters or not) than unilateral ones. The attentional hypothesis of crowding argues that crowding is a consequence of limitations in the selection step of attention. Hence, finding evidence that the bilateral advantage occurs at this step but not others would strengthen this hypothesis. The procedure for this experiment was the same as in experiment 2A, but with placeholders present as in experiment 1A. If the bilateral advantage occurs at the step where cues draw attention to the target locations to the exclusion of other locations, we should observe a bilateral advantage with this setup.

5.1. Methods

5.1.1. Subjects

Ten experienced subjects, aged 22–35 years, with normal or corrected to normal vision participated with informed consent in this experiment.

5.1.2. Materials and stimuli

The materials and stimuli used were the same as in experiment 2A except for the addition of placeholders as in experiment 1A. The target T's were set to 0.1 contrast (based on pilot testing on two subjects) so as to obtain an accuracy of around 80% when presented in isolation at the tested eccentricity.

5.1.3. Procedure

The same three conditions were present in this experiment: *Attend 1*, *Attend 2-Bilateral*, and *Attend 2-Unilateral*. However, we presented isolated (and hence uncrowded targets) in all three conditions. The trial sequence was the same as in experiment 1A (see Fig. 8) with subjects having to attend to 1 target location in the *Attend 1* condition and two locations (either in opposite hemifields or in the same hemifield) in the two *Attend 2* conditions.

5.2. Results

There was no difference (Fig. 7) in identifying targets whether presented in the same hemifield (*Attend 2-Unilateral* mean = 76%) or in different hemifields (*Attend 2-Bilateral* mean = 81%) [$t(9) = 1.63$; $p > 0.25$]. This suggests that the bilateral advantage observed in experiment 1 was not because attention was being more successfully drawn to bilateral targets relative to unilateral targets. It is not the cueing step that manifests a bilateral advantage. A bilateral advantage is seen when targets need to be *selected* among distracters, as we have been arguing.

As in experiments 1A and 2A, there was a cost for attending to two targets over that of attending to only one target (*Attend 1* mean = 90%) irrespective of whether the second target was in the same hemifield [$t(8) = 5.14$; $p < 0.005$] or in the opposite hemifield [$t(8) = 3.61$; $p < 0.025$]. Thus, adding a second target reduced performance significantly, consistent with earlier findings.

6. General discussion

We sought to determine whether crowding exhibits any characteristics of selective attention as would be expected if it underlies crowding. The results from experiment 1A showed that, indeed, crowding demonstrates a bilateral advantage, a known signature of selective attention (Alvarez & Cavanagh, 2005; Awh & Pashler, 2000; Castiello & Umilta, 1992; Kraft et al., 2004; Muller et al., 2003; Reardon et al., 2009). Experiment 1B replicated the bilateral advantage in crowding even when all stimuli were arranged in a horizontal layout suggesting that the primary result cannot be attributed to any anisotropies in the visual field or differences in the ability to deploy attention in various directions. Experiment 2 ruled out the possibility that the results were an artifact of other processes. It was shown that the bilateral advantage did not result

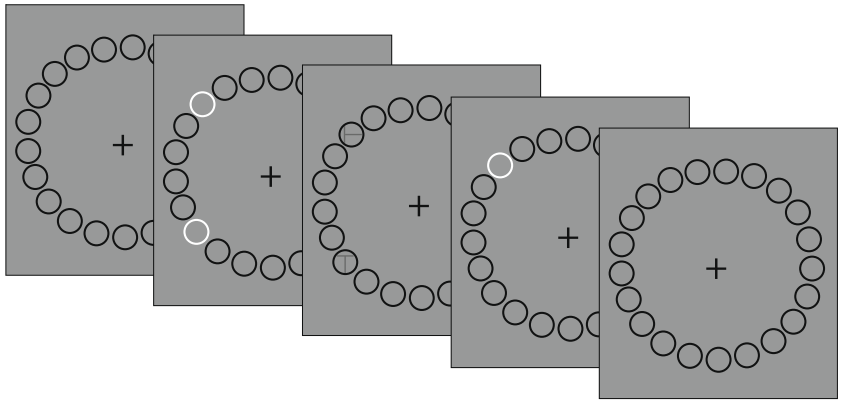

Fig. 8. Trial sequence in experiment 2B. The sequence and stimuli were the same as in Experiment 2A. However placeholders were present in this experiment.

from a generalized advantage for letter identification or from a bilateral advantage for storing letters/objects in VSTM. Thus, our results support the attentional hypothesis of crowding.

6.1. Bilateral advantage or hemifield independence?

Our results provided mixed evidence for a complete hemifield independence of resources: less than complete in experiment 1A and possibly complete in experiment 1B. So our evidence overall favors a bilateral advantage rather than strict independence. This bilateral advantage might be due to an inability to distribute resources within a hemifield, while incurring no or a smaller cost to distribute resources between hemifields. Consistent with this interpretation, there is electrophysiological evidence showing that splitting attention is far easier between hemispheres than within a hemisphere (Malinowski, Fuchs, & Muller, 2007; Muller et al., 2003). Further, there is evidence that although attention can be split *within* a hemifield, this incurs higher costs than splitting across the midline (Kraft et al., 2004; Malinowski et al., 2007), which is what we see here under crowded conditions. A second possible mechanism for the observed bilateral advantage relies on the existence of suppressive surrounds around attentional foci (Alvarez & Cavanagh, 2005; Bahcall & Kowler, 1999; Cutzu & Tsotsos, 2003; Hopf et al., 2006; Mounts, 2000a, 2000b; Tsotsos, Culhane, Wai, Davis, & Nuflo, 1995). It can be argued that these inhibitory influences are extremely effective within a hemifield (Alvarez & Cavanagh, 2005; Sereno & Kosslyn, 1991) but not as much across the midline. It must be noted that the two accounts described above are not necessarily mutually exclusive – the latter might be the implementation of the former.

6.2. Bilateral advantage and the two crowding hypotheses

Our results showed a consistent bilateral advantage in crowding, but no such advantage when distracters were absent. This advantage indicates the existence of long-range inhibitory interactions between targets, in the presence of distracters, that far exceed the spatial extent of crowding (Bouma, 1970; Toet & Levi, 1992). This result alone is not necessarily specific to crowding and could be attributed to a general property of limited attentional resources that would affect any task. However, the pattern of the result – interference within hemifields but not across, and only for a task with distracters, not for an isolated target – does provide a link to the properties of attention that are specific to crowding. In particular, several articles have shown that suppressive regions surround each attended target only when there are distracters (Awh & Pashler, 2000; Muller & Ebling, 2008; Muller, Geyer, Zehetleitner, & Krummenacher, 2009; Reynolds, Chelazzi, & Desimone, 1999; Serences, Yantis, Culberson, & Awh, 2004; Setic & Domijan, 2008). Other articles also show that these suppressive surrounds do not cross the vertical meridian (Kraft et al., 2007; Mounts & Gavett, 2004; Muller et al., 2003). This explains why there would be a bilateral advantage in our crowding task, where distracters are present, but not in the identification of isolated targets. The presence of distracters both interferes with selection, as they fall within the selection region for the target, and triggers suppressive surrounds that interfere with the processing of the other target if it is in the same hemifield. This places crowding in the set of tasks where the presence of distracters triggers a bilateral advantage that can be linked to the suppressive surrounds of attention. On the other hand, the bottom-up compulsory pooling hypothesis is constrained by a single spatial parameter – *critical spacing*: the distance between the target and distracters beyond which crowding is not seen. Several studies have shown that critical spacing is less than or equal to half the target eccentricity (Bouma, 1970; Pelli et al., 2004; Toet & Levi, 1992). Features within critical spacing of the target are pooled together *independent* of all processing outside this region. Hence, this account does not predict any interactions between non-overlapping pooling regions. In all of our experiments, the two cued targets were always farther away than the critical spacing at that eccentricity. The bottom-up pooling hypothesis would not predict interference between these two targets, whether they were in the same hemifield or different hemifields, and whether distracters were present or absent, contrary to what we found. To deal with our data, the preattentive pooling conjecture has to add the entire attentional framework that, on its own, can already explain both crowding and the bilateral advantage. So, although the results do not rule out a compulsory pooling mechanism, they only make it unnecessary.

These experiments provide evidence that selective attention modulates target identification only when the target is crowded and not when it is isolated. That is, they serve as further demonstration that attentional inhibitory surrounds and a consequent bilateral advantage (experiment 1A) or hemifield independence (experiment 1B) occur only in the presence of distracters, in this case, the flankers that are crowding the target.

6.3. Other related studies

In an effort to test interference between attentional foci, Bahcall and Kowler (1999) used a stimulus setup similar to ours and found that identification performance for two letters improved with increasing separation between them. Their results seem to indicate that attentional foci inhibit each other and that this inhibition can extend across the midline (as at large inter-target distances, one of the targets would usually be across the midline). Incidentally, they also reported, in passing, a bilateral advantage for letter identification. However, it is not clear if the letters in their display were crowded. Also, this result is confounded with inter-target distance – as bilateral stimuli usually tended to have larger separations than unilateral stimuli. In our study, the targets were crowded and the average distance between the two targets remained the same. We obtained a significant bilateral advantage.

In a study to investigate whether attention could be split, Awh and Pashler (2000) designed experiments that also tested the occurrence of bilateral advantage. They asked observers to identify two digits presented parafoveally either bilaterally or unilaterally among letters. The targets appeared in two of four possible locations with the distance between them remaining constant, unlike in our experiment. Although the stimuli were not crowded they obtained a consistent bilateral advantage for numeral identification except when no distracters were present. These results are similar to those obtained in this study.

These two studies taken in conjunction with our results suggest that when a target in clutter is to be identified, a bilateral advantage is observed. Whether the targets are crowded (as in our experiments) or not (Awh & Pashler, 2000), there is a distinct bilateral advantage for identification of objects as long as these items are surrounded by distracters. There seems to be a continuum of visual experiences of objects in clutter ranging from uncrowded targets (far distracters) to highly crowded targets (very close distracters). These results imply that a common process of selection underlies this entire continuum. The same attentional process (with an inhibitory surround) selects targets when distracters are present, with target selection in the absence of distracters appearing to be a qualitatively different process (without an inhibitory surround). If so, target identification in clutter would be affected by having to select and process the distracters as well leading to an impairment in the ability to identify the target: crowding.

7. Conclusions

In three experiments we demonstrated that there is a bilateral advantage for identifying a crowded target and that this cannot be attributed to a bilateral advantage for letter identification or VSTM or to visual field anisotropies. We conclude that identifying objects among distracters displays bilateral advantage, a signature of attention, and that this result is consistent with the attentional account of crowding.

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