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The Bilateral Field Advantage Effect in Memory Precision

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Abstract

Previous research has demonstrated that visual working memory performance is better when visual items are allocated in both left and right visual fields compared to within only one hemifield. This phenomenon is called the bilateral field advantage (BFA). The BFA is thought to be driven by an enhanced probability of storage, rather than by greater precision. In the present experiments, we sought to test whether the BFA can also extend to precision when the parameters of the task are modified. Using a moderate number of to-be-remembered items and 400 ms presentation time, we found better precision in the bilateral condition compared to the unilateral condition. The classic BFA was still found in the form of an enhanced probability of storage, when presentation time was 200 ms. Thus, the BFA appears to convey both enhanced precision and greater probability of storage. The BFA is most likely due to the allocation of more attentional resources, when items are presented in both left and right visual fields.

***Key words*:** Visual working memory; Bilateral field advantage; Memory precision

Visual working memory (VWM) is usually defined as an online workspace where information can be effectively accessed and updated when a visual stimulus disappears (Luck, 2008). Although its capacity appears limited, individual differences in VWM are significantly correlated to performance on complex cognitive tasks (Hollingworth & Luck, 2009; Jonides, Lewis, Nee, Lustig, Berman & Moore, 2008; Luck & Vogel, 2013). VWM has been found to explain 43% of the variance in fluid intelligence across individuals (Fukuda, Vogel, Mayr & Awh, 2010), as well as 46% of the variance across individuals in performance on general cognitive tasks (Johnson, McMahon, Robinson, Harvey, Hahn, Leonard et al., 2013). In addition, a variety of mental disorders are often accompanied by reduced working memory capacity and longer memory consolidation times (Fuller, Luck, Braun, Robinson, McMahon, & Gold, 2009; Gold, Hahn, Zhang, Robinson, Kappenman, Beck & Luck, 2010; Karatekin& Asarnow, 1998; Lee, Cowan, Vogel, Rolan, Valle-Inclan & Hackley, 2010). Thus, it is important to understand the role of VWM in both normal and abnormal cognition.

Delvenne (2005) used a standard change-detection paradigm to examine the capacity of VWM, in which squares were presented either in a single hemifield (unilateral condition) or across both visual hemifields (bilateral condition). The squares reappeared after a blank screen of 1000 ms. Participants were asked to detect a change in the spatial location of one item. Performance was better in the bilateral condition than in the unilateral condition. This phenomenon was named the Bilateral Field Advantage (BFA). A BFA has also been found in other cognitive tasks that involve visual encoding processes, such as visual search (Alvarez & Cavanagh, 2006), visual enumeration (Delvenne, Castronovo, Demeyere & Humphreys, 2011), face recognition (Keyes & Brady, 2010) etc. Notably, Alvarez and Cavanagh (2005) found that the number of objects which could be tracked in a bilateral condition was double that in the unilateral condition, demonstrating that attentional tracking capacity in left and right hemisfields is relatively independent.

Since the change detection paradigm includes different stages of visual processing, the BFA for VWM found by Delvenne et al. (2005) might arise from the initial encoding of visual information rather than at the memory maintenance stage (Umemoto, Drew, Ester, and Awh 2010). To examine whether the BFA occurs in the maintenance stage, Umemoto et al.(2010) conducted a further study. In Experiment 1, they used an orientation recall task in which two teardrop-shaped stimuli or simple lines, sequentially presented in different orientations, were displayed unilaterally or bilaterally. Following a retention period, a randomly oriented stimulus was presented. Participants' task was to adjust the gratings using a computer mouse to match the orientation of the previously presented stimulus held in memory. Relative to the unilateral condition, there were smaller recall errors in the bilateral condition, even for sequential presentation. In order to test whether this BFA derives from an increased number of items stored or from the precision which items were stored, they used a recall paradigm and measured both the number and the precision of the stored items in Experiment 2. They increased set size to four and found that the bilateral distribution of information affected the number of items that could be held in VWM, but not their precision.

However, it is difficult to explain how the bilateral condition would convey advantages only in terms of the number rather than the precision of stored items. According to the two main theories of visual working memory, there should be a trade-off between the number of items retained and the precision of those items in VWM. Slot-based models propose that visual working memory has a limited number of available “slots” in which a limited set of discrete, fixed-precision representations are stored (Cowan, 2001; Luck & Vogel, 1997). When all slots are filled, no information about additional items can be stored, and the memory precision does not vary with number of items. If the number of to-be-represented items is below the maximum number of slots, then an item can be represented by multiple slots (Zhang & Luck, 2008). Thus, the precision of memory items could be increased only when the number of items is within the capacity. Alternatively, Resource-based models propose that memory resources can be divided up between items flexibly, without a limit to the number of items that can be stored. Thus, the precision, with which an item can be retrieved, is contingent upon the quantity of resources allocated (Bays & Husain, 2008; Bays et al., 2009; Bays et al.2011). One thing the two theories have in common is that they predict an item/precision trade-off when the number of memoranda is relatively low (e.g. less than 4 items). Consistent with the theory, there is robust evidence that memory precision decreases as the number of items to be remembered increases (Barton, Ester, &Awh, 2009; Bays & Husain, 2008; Gorgoraptis, Catalao, Bays, & Husain, 2011).

Given a trade-off between the number and precision of stored items, if bilateral distribution of information affects the number of items held in VWM, it should also affect memory precision, especially when the number of items is low. The reason Umemoto et al. (2010) did not observe a difference of memory precision between bilateral and unilateral conditions could be that they asked participants to remember too many items. The limited memory resources available for a large number of stored items might lead to such poor precision for all items that a statistically significant difference of memory precision between bilateral and unilateral conditions might not be observable.

In the present study, we used a recall procedure similar to the one employed by Umemoto et al. (2010), but optimized to explore whether a bilateral field advantage also arises in memory precision. To accomplish this, we used a moderate number of memory items and sufficient presentation time. Specifically, we asked participants to remember only two items per trial to ensure that set size is lower than the point at which working memory precision reaches asymptote (Anderson & Awh, 2012; Zhang & Luck, 2008). In terms of presentation time, we choose 400 ms for presenting two items, which would allow more time for encoding each item compared to the 500 ms presentation time for remembering four items which was used in Umemoto et al. (2010)'s study. Our working hypothesis is that, with the number of memory targets set to two, each item might be assigned more available resources in both the bilateral and unilateral conditions. Thus every item should obtain enough resources, so the probed item should not vary in terms of the probability of storage, but only in memory precision.

EXPERIMENT 1

Participants

Nineteen right-handed college students, with normal color vision and normal or corrected-to-normal visual acuity (13 female) from Liaoning Normal University, took part in the study. Each participant in Experiment 1 were paid ¥10 for participation and gave written informed consent. The methods for this study were approved by the Research Ethics Committee of Liaoning Normal University.

Stimuli

Visual stimuli were produced by MGL (http://gru.brain.riken.jp/doku.php?id=mgl:overview), a set of custom OpenGL libraries running in MATLAB. The orientation stimuli were sinusoidal gratings with 0.7contrast, spatial frequency and 3cycles/degree in a circular aperture (size, 0.9°) appeared on a background of gray (48.4 cd/m2). The edges of the stimuli were smoothed and no sharp change in luminance was present between the grating and the background. The gratings were presented at four corners of an invisible square (eccentricity, 3º). A fixed point (0.2º) was presented in the center of the screen throughout our experiment. Each stimulus appeared on a CRT monitor (800 × 600 pixels, 144Hz refresh rate, with linearized luminance levels), and subjects viewed the screen at a distance of 60cm in a dim room. Participants were told to keep their eyes focused on the fixed center point throughout the experiment.

Procedure

Each trial began with a 200 ms arrow cue, followed by a 100 ms blank screen, a 400 ms memory array, a 1000 ms blank screen, a probe array presented until a response was recorded, and finally 1500 ms of feedback (see Figure.1). There were eight possible directions for the arrows in the cue ("left", "lower left", "upper-left", "right", "lower right", "upper-right", "up", "down"), indicating which region of the array to remember. Participants only needed to remember one or two targets. For example, if the cue was "up", "right", "down" or "left" then participants needed to remember two targets, and if the cue was "lower left", "upper-left", "lower right" or "upper-right" then participants only needed to remember one target (see Figure.1). In all conditions, a square outline appeared after the 1000 ms blank period in the location of one stimulus. Participants rotated the orientation of the probe grating, which was always presented at the screen center, to reproduce that of the cued grating. Three mouse buttons were applied to adjust the vertical probe grating: one rough adjustment key, for rotating the probe by a free angle and two meticulous adjustment keys ±1° per key press. A subsequent trial wouldn't start until participants were satisfied with the adjustments they had made and pressed the space key to receive feedback.

INSERT FIGURE1 ABOUT HERE

The grating's orientation was random, with the constraint that two gratings presented in the array had at least a 10° gap. Before the gratings appeared, eight different arrow cues appeared randomly. Every condition had 120 trials, for a total of 360 trials across nine blocks of 40 trials each. Before the experiment started, participants practiced for at least 20 trials. The whole experiment lasted about one hour.

Data analysis

For each trial, we calculated the difference between the recalled orientation and the cued grating orientation. Fitting the offset data using the mixture model first proposed by Zhang and Luck (2008), we separately measured the storage probability (guessing rate, g) and precision (SD) of the responses. Data analysis was performed using the Mem Toolbox (Suchow, Brady, Fougnie, & Alvarez, 2013). We fit each individual's data separately using the mixture model, and then averaged all participants' guessing rate and SD separately across different conditions, ran one-way repeated measures ANOVA with three levels (bilateral, unilateral, single) for each result parameter.(Figures 2a–c). The p values of the main effects and interactions were corrected using the Greenhouse-Geisser adjustment.

INSERT FIGURE2 ABOUT HERE

Results

Consistent with our predictions, we found evidence for the BFA in precision. For the precision parameter (SD) (Figure 2d), a significant main effect of display [$F(2,36) = 34.03$, $p<0.001$, $\eta2= 0.654$] was revealed by repeated measures ANOVA. The SD for the bilateral condition was significantly lower than for the unilateral condition [$t(18)=2.64$, $p<0.02$, Cohen's $d=0.42$]. The single condition was significantly lower than the bilateral condition [$t(18)=5.30$, $p<0.001$, Cohen's $d=1.11$].

Also consistent with predictions, we did not observe a BFA for guess rate. For guess rate (g) (Figure 2e), a significant main effect of display [$F(2,36) = 9.86$, $p<0.01$, $\eta2=0.354$] was revealed by repeated measures ANOVA. Yet, there was no significant difference between the bilateral and unilateral conditions [$t(18)=1.22$, $p=0.239$, Cohen's $d=0.15$]. The single condition was significantly lower than the bilateral condition [$t(18)=3.34$, $p<0.005$, Cohen's $d=0.96$].

Discussion

The results of Experiment 1, in line with our expectations, suggest that memory precision improved when the number of memoranda was low, since the SDs in the single condition were significantly lower than the other two conditions. More importantly, the SD for the bilateral condition was lower than for unilateral displays, indicating that the BFA also conveyed enhanced precision.

To examine the parameters of the BFA precision effect more carefully, we conducted Experiment 2 to explore whether there was still a precision BFA for remembering two items when memory resources are challenged. Recent studies (Liu &Becker, 2013; Becker et al., 2013) have indicated that orientation information is consolidated in a serial process. In that case, reduced exposure time might lead to fewer resources being allocated to each item, particularly with regard to orientation. Thus, in the Experiment 2, we manipulated the exposure times (200 ms and 400 ms) within-subjects to modulate the resources allocation. This manipulation allowed us to assess whether challenged resource could eliminate or reduce the BFA of precision.

Experiment 2

Participants

Sixteen new volunteers (11 female), with normal color vision and normal or corrected-to-normal visual acuity from Liaoning Normal University, were recruited for Experiment 2. Subjects were paid ¥10 for their participation and signed written informed consent.

Procedure

The same stimuli and procedures used in Experiment 1 were used for Experiment 2 with the following exceptions. We removed the single condition since it was not central to testing the robustness of the BFA precision effect. We also added a within-subjects manipulation of the presentation time. This resulted in a 2 (200 ms versus 400 ms) ×2 (bilateral versus unilateral) experimental design. The experiment included eight blocks of 40 trials each. Subjects completed at least 20 practice trials and a total of 320 test trials (see Fig.3). The *p* values of the main effects and interactions were corrected using the Greenhouse-Geisser adjustment.

INSERT FIGURE3 ABOUT HERE

Results

We again fit each individual's data separately with the mixture model proposed by Zhang and Luck (2008), and then averaged all participants' guessing rate and SD separately across different conditions. For the precision parameter (SD) (Figure 4a), a 2 (200 ms versus 400 ms) ×2 (bilateral versus unilateral) repeated measures ANOVA revealed a significant main effect of display [$F(1,15) = 12.69$, $p<0.05$, $\eta 2=0.458$]. No significant main effects of time [$F(1,15)=1.55$, $p=0.231$, $\eta 2=0.094$]. A significant two-way interaction was obtained for time×display [$F(1,15)=4.726$, $p<0.05$, $\eta 2=0.240$]. When the memory array presentation time was 200 ms, there was no significant difference between the bilateral and unilateral conditions [$t(15)= 0.387$, $p=0.704$, Cohen's d=0.04]. When the memory array presentation time was 400 ms, the SD for the bilateral condition was significantly lower than for the unilateral condition [$t(15)= 2.998$, $p<0.01$, Cohen's d=0.69]. Further, when memory items were presented bilaterally, the SD for 400 ms was significantly lower than for 200 ms [$t(15)= 2.194$, $p<0.05$, Cohen's d=0.54]. When memory items were presented unilaterally, there was no significant difference between 200 ms and 400 ms [$t(15)= -0.851$, $p=0.408$, Cohen's d=0.14].

For guess rate (g) (Figure 4b), there were no significant main effects of time[$F(1,15)=1.781$, $p=0.202$, $\eta 2=0.106$], display[$F(1,15)=0.012$, $p=0.915$, $\eta 2=0.001$], nor a time ×display interaction[$F(1,15)=1.578$, $p=0.228$, $\eta 2=0.095$]. We used paired t-tests and found that there was a significant difference between the bilateral and unilateral conditions when the memory array presentation time was 200 ms [$t(15)= 2.202$, $p<0.05$, Cohen's d=0.47]. The results of Experiment 2 were generally consistent with those from Experiment 1.

INSERT FIGURE4 ABOUT HERE

Discussion

The results of Experiment 2 at 400 ms are generally consistent with those from Experiment 1. The SD in the bilateral condition was still significantly lower than in the unilateral condition and no guess rate difference between the bilateral and unilateral conditions. However, inconsistent with the resource model prediction, the observed pattern of BFA in the 200 ms condition was different from that in the 400 ms condition. The SD differences disappeared at 200 ms and the BFA mainly appeared in the reduction of the guess rate. The result of the 200 ms condition seems in line with the findings for four items in the study of Umemoto et al. (2010).

Alternatively, it seems to be possible that with short exposure durations, participants could be more likely to mistake which orientation was at which location during encoding. As a result, they may be more likely to report the un-cued item at test. We analyzed this possibility by testing the Experiment 2 data with a swap model (Bays et al, 2009), however the incidence of mislocalization was indistinguishable between the unilateral and bilateral conditions. This indicates that mislocalization was not the influencing factor for a BFA to emerge[1].

Though participants were told to keep their eyes focused on the fixed point throughout experiments 1 and 2, it is still possible that they could move their eyes in the 400 ms condition (see, for example, Roberson, Hanley &Pak, 2009). There is a possibility that the BFA in the 400 ms condition reflects a horizontal saccade advantage in VWM. The bilateral advantage observed at 400 ms exposure time might simply reflect the fact that participants have been able to move their eyes more efficiently between two bilaterally (i.e., horizontally-aligned) presented items as

[1] The mislocalization error (b value) were quite low in every condition (mean b <.024). No significant difference in b value between uni- and bi-lateral condition in both 200 ms (p=.865) and 400 ms (p=.137). This indicates that mislocalization was not the influencing factor for a BFA to emerge.

compared to two unilaterally (i.e., vertically-aligned) presented items. In order to test this possibility, we conducted Experiment 3.

Experiment 3

Participants

Twelve new volunteers (6 female) with normal color vision and normal or corrected-to-normal visual acuity from Liaoning Normal University were recruited for Experiment 3. Subjects were paid ¥10 for their participation and signed written informed consent.

Procedure

The same procedure as Experiment 2 400 ms condition was repeated except that the invisible square (eccentricity, 3º) moved 4.24º to the left and right of the fixed point so that the two memory items were within a single hemifield (Figure 5). In the vertical condition, the two items were vertically aligned in the far left, far right, near left or near right side of the fixed point. In the horizontal condition, the two items were horizontally aligned top left, top right, bottom left or bottom right side of the fixation point. Subjects viewed the screen at a distance of 60cm in a dim room and they were told to keep their eyes focused on the fixed point throughout the experiment. To ensure two memory items in both vertical and horizontal condition were in a single hemifield, there were only two possible directions for the arrows in the cue ("left" or "right"), indicating which region of the array to remember. The experiment included six blocks of 40 trials each. Subjects completed at least 30 practice trials before the test trials. The *p* values of the main effects and interactions were corrected using the Greenhouse-Geisser adjustment.

INSERT FIGURE5 ABOUT HERE

Results

Fitting the data with the mixture model proposed by Zhang and Luck (2008), we separately measured the guess rate (g) and precision (SD) of responses as a proxy for the representations which were stored in working memory, as in Experiment 1 and 2. Using paired t-tests, we found that: for the precision parameter (SD) (Figure 6a), when the memory array presentation time was 400 ms, there was no significant difference between the horizontal and vertical conditions [$t(11)= -0.019$, $p=0.985$, Cohen's $d=0.03$]. For guess rate (g) (Figure 6b), the differences remained non-significant [$t(11)= 0.716$, $p=0.489$, Cohen's $d=-0.20$].

INSERT FIGURE6 ABOUT HERE

Discussion

In Experiment 3, neither SD nor guess rate differed significantly between the horizontal and vertical conditions. Thus, the BFA of precision at 400 ms in previous experiments cannot be explained by the horizontal alignment of stimulus pairs, it must have been caused by the presentation of the two memory items in different visual hemifields.

General discussion

A large amount of previous research has demonstrated a bilateral field advantage (BFA) in visual processing (Awh & Pashler, 2000, Alvarez & Cavanagh, 2005, Delvenne & Holt, 2012, Umemoto et al., 2010). In visual working memory, the bilateral distribution of information has previously been found to affect the number of items that could be maintained, but not their precision (Umemoto et al., 2010). The main purpose of the current study was to explore whether the precision of a bilateral memory array could be improved by reducing the number of memoranda. In Experiment 1, the results provided evidence that the BFA could arises in memory precision when there was sufficient time and the number of memoranda was limited to two. The results of Experiment 2 replicated and extended Experiment 1. There was still a precision BFA at 400 ms. However, with a 200 ms presentation time, the BFA disappeared in memory precision but appeared in the guess rate. The result in the 200 ms condition provided a conceptual replication of Umemoto et al. (2010). Experiment 3 indicated that the BFA arises when the to-be-remembered items are presented in different visual hemifields rather than merely in horizontal alignment.

There are three possible explanations for a BFA in a VWM task. The first is that the BFA results from a faster rate of encoding. The second is that the representations of memory items fade away faster in the unilateral condition during the memory maintenance phase (Umemoto et al., 2010). The third is that the BFA reflects increased memory resources when items are distributed across both hemifields. An explanation based on faster encoding is unlikely, since Umemoto et al. (2010) still observed a bilateral advantage using sequentially presented stimuli, suggesting that the BFA could not be explained fully by differences in encoding speed. The second possibility is also hard to sustain, because previous studies found that the representations of memory items did not fade significantly within a retention interval of four seconds (Zhang & Luck, 2009). The memory retention time in Umemoto et al. (2010) and in the present study was only 900 ms, so forgetting is unlikely to be the cause of the BFA. Thus, the most likely explanation for the BFA in the current study is increased memory resources for visual processing in bilateral fields compared to in a single hemifield.

We discuss the result according to the main VWM models. The resource model allows for VWM resources to be flexibly allocated between items in a display, with fewer resources per item and thus reduced precision as the set size increases. Participants in Experiment 2 were asked to remember two orientations without any priority. Thus, the two orientations should have been allocated equal memory resources. According to this theory, the representational precision should differ between the bilateral and unilateral conditions, but the probability of storage should be the same for both conditions. However, the bilateral advantage in guess rate observed in 200 ms, similar to the findings from Umemoto et al., (2010) appears to be inconsistent with this theory.

Rather, this pattern of results favors an account of the BFA according to the slots+averaging model, which presumes that working memory resources are divided into discrete slots. When the memory array's set size is greater than the number of slots, more available slots lead to a decrease in the guess rate (g). When the set size of a memory array is less than the number of slots, more available slots leads to an increased precision. In that case, both the bilateral precision advantage and the bilateral guess rate advantage can be attributed to having more slots involved in memory within the bilateral condition. In addition, in Experiment 2 when memory items were presented bilaterally, the SD at the 400 ms presentation time was significantly lower than for 200 ms, indicating that more slots were employed in 400 ms, which suggests that slots are sequentially employed. However, there was no difference between 200 ms and 400 ms when memory items were presented unilaterally. We consider that this may be due to a limitation in participants' working memory capacity. Most of the participants could only remember two orientations in the unilateral condition, suggesting that only two slots were available in the unilateral condition, and 200 ms presentation time is sufficient for employing two slots but challenged for employing three slots. This suggests that no matter how long the memory array was presented in the unilateral condition, each item in the memory array could only take one slot.

However, there is no evidence that memory resources are independent in the left and right hemifields, because there is no evidence that twice as many objects can be stored in both left and right hemifields as in the same hemifield. It is more likely that left and right hemifields share the same memory resources system. Thus, the BFA seems unlikely to arise merely because bilateral fields obtain more memory resource than unilateral fields. A more likely explanation is that the total amount of memory resources would be the same in the two conditions, but the efficiency of those resources in VWM would depend on how many attentional resources can be allocated. If there are more attentional resources available in the bilateral condition, the available memory resources would be used more efficiently. As an illustrative example, imagine that there were four drawers (memory slots), powered by electricity (attentional resources). Ample electrical power might allow all four drawers to open simultaneously, but weak electrical power might allow only two drawers to open. The bilateral and unilateral condition would both have four drawers, but the bilateral condition would have more electrical power to drive the drawers. Support for this view comes from previous studies findings that individuals need attentional resources to maintain the VWM representation and that a strong BFA was observed in visual attention tasks (e.g. Alvarez & Cavanagh, 2005; Delvenne & Holt, 2012). It could also explain why previous BFA studies on working memory only found the effect on location and orientation rather than color. The process of orientation is more likely tied to the involvement of visual attention. So a BFA for orientation would be more likely to arise.

In conclusion, this study shows for the first time that the BFA can be demonstrated using a precision index, and that the BFA appears to have more attentional resources available when items are spread across the two hemifields.

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Figure Captions

Figure.1. Schematic of Experiment 1 trial structures for each condition. Eight different arrows randomly cued subjects' memory. The "right" and "left" cues make up the unilateral condition; the "up" and "down" cues make up the bilateral condition; and the "lower left," "upper-left," "upper-right," and "lower right" cues make up the single condition.

Figure.2. Model-fit results from Experiment 1. Histograms in the top row show probability-density functions for the response offsets in (a) the unilateral condition, (b) the bilateral condition, and (c) the single condition. The mean standard deviation (SD), and guess rate (g) are also shown for each condition. Graphs in the bottom row (d–e) show average values for the two parameters from individual-level data fits in each of the three conditions. Error bars indicate ±1 SEM.

Figure.3. Schematic of Experiment 2 trial structures. Four different arrows randomly cued subjects' memory. The "right" and "left" cues make up the unilateral condition, and the "up" and "down" cues make up the bilateral condition.

Figure.4. Model-fit results from Experiment 2. (a) and (b) show SD and g as a function of condition. Error bars indicate ±1 SEM.* indicates a statistically significant difference between two levels of a factor; ns indicates no statistically significant difference between two levels of a factor.

Figure.5. Schematic of Experiment 3 trial structures. Two different arrows randomly cued subjects' memory. In the vertical condition, the two items were vertically aligned in a single hemifield. In the horizontal condition, the two items were horizontally aligned in a single hemifield.

Figure.6. Model-fit results from Experiment 3. (a) and (b) show SD and g as a function of condition. Error bars indicate ±1 SEM.*