A bilateral advantage in controlling access to visual short-term memory

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Abstract

Recent research on visual short-term memory (VSTM) has revealed the existence of a *bilateral field advantage* (BFA - i.e., better memory when the items are distributed in the two visual fields than if they are presented in the same hemifield) for spatial location and bar orientation, but not for colour (Delvenne, 2005; Umemoto, Drew, Ester, & Awh, 2010). Here, we investigated whether a BFA in VSTM is constrained by attentional selective processes. It has indeed been previously suggested that the BFA may be a general feature of selective attention (Alvarez & Cavanagh, 2005; Delvenne, 2005). Therefore, the present study examined whether VSTM for colour benefits from bilateral presentation if attentional selective processes are particularly engaged. Participants completed a colour change detection task whereby target stimuli were presented either across both hemifields or within one single hemifield. In order to engage attentional selective processes, some trials contained irrelevant stimuli that needed to be ignored. Targets were selected based on spatial locations (Experiment 1) or on a salient feature (Experiment 2). In both cases, the results revealed a BFA only when irrelevant stimuli were presented amongst the targets. Overall, the findings strongly suggest that attentional selective processes at encoding can constrain whether a BFA is observed in VSTM.

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Introduction

It is well recognised that the visual system is contralaterally organised, meaning that information presented to the left visual hemifield is initially processed in the right hemisphere, whereas information presented to the right visual hemifield is initially processed in the left hemisphere (see Gazzaniga, 2000). This information can be integrated across the hemispheres via the corpus callosum, a band of neuro fibers which connects the cerebral hemispheres together and provides a means via which the hemispheres can share information. Studies in healthy individuals have revealed that performance in some visual tasks can sometimes be enhanced when information is divided between the two hemifields, an effect known as the *bilateral field advantage* (BFA) (see the review by Delvenne, 2012). For example, Dimond and Beaumont (1971) provided some of the first demonstrations of the BFA. They showed that the ability to report two digits was significantly improved when each digit was presented in a separate hemifield relative to when both digits were presented within the same hemifield. Since then, the BFA has been observed across a range of visual tasks requiring, for example, visual matching (e.g. Banich & Belger, 1990), multiple object tracking (Alvarez & Cavanagh, 2005), orientation discrimination and detection (e.g. Chakravarthi & Cavanagh 2009; Reardon, Kelly, & Matthews, 2009), rapid item identification (e.g. Awh & Pashler, 2000; Scalf, Banich, Kramer, Narechania, & Simon, 2007) and visual enumeration (Delvenne, Castronovo, Demeyere, & Humphreys, 2011).

Using the change detection paradigm to directly assess the capacity of visual short-term memory (VSTM) within and between hemifields, studies have shown that the BFA occurs also in VSTM. Specifically, memory performance has been shown to improve when the to-be-remembered items are distributed between the two hemifields relative to when they are all presented within a single hemifield. However, this effect has not been observed consistently across stimulus domains. Whilst a BFA has been shown in VSTM for spatial locations (Delvenne, 2005) and orientations (Umemoto, Drew, Ester & Awh, 2010) studies have failed to show a BFA for colour (Delvenne, 2005; Delvenne, Kaddour, & Castronovo, 2011; Mance, Becker & Lui, 2012).

The explanation for such an inconsistency is currently unknown but the dominant view is that the BFA reflects the existence of independent attentional resources in each hemifield. Specifically, the occurrence of a BFA may depend on how attention is deployed over spatial information (Alvarez & Cavanagh, 2005; Delvenne, 2005). Indeed, the tasks in which spatial information was central, such as tracking (Alvarez & Cavanagh, 2005), visual enumeration (Delvenne et al., 2011), short-term memory for locations (Delvenne, 2005) and orientations (Umemoto et al., 2010), for example, consistently show a BFA. When non-spatial features, such as the identity of the objects, are critical, the observation of a BFA appears to depend on the attentional requirement. Typically, recent studies have demonstrated that non-spatial tasks that require identification of target stimuli reveal a BFA only when targets have to be selected from distracter stimuli (Alvarez, Gill & Cavanagh, 2012; Awh & Pashler, 2000; Chakravarthi & Cavanagh 2009; Reardon et al., 2009). This strongly supports the notion that the BFA observed in visual information processing might be a signature of attentional selection.

Recently we have been able to show for the very first time in humans a BFA for colour VSTM when directing attention to internal representations using retro-cues. Specifically, we showed that orienting attention to two memorized colours resulted in better memory for those colours, but only when they were displayed in separate hemifields (Delvenne & Holt, 2012). In the present study, we further investigated the link between spatial selective attention and the BFA by examining whether past failures to demonstrate a BFA in VSTM (Delvenne, 2005; Delvenne, Kaddour, & Castronovo, 2011; Mance, Becker & Lui, 2012) can be explained due to the absence of specific task demands on attentional selection at encoding. Participants completed a colour VSTM change detection task which manipulated the spatial distribution of stimuli within or across hemifields. In some of the trials, task specific demands on target selection were manipulated by requiring participants to remember only a subset of the stimuli indicated by the presentation of spatial pre-cues before the memory array (Experiment 1) or on the basis of a salient feature difference (Experiment 2). If the BFA is constrained by attentional selective processes it will only emerge in conditions which place demands on target selection. However, if the BFA is constrained by the stimulus domain, we may expect no evidence of a BFA, since the task specifically required memory for colours.

Experiment 1

Method

Participants

22 subjects completed the experiment (18 females; mean age = 23.50 years; range 19-39 years). Participants were neurologically normal with self-reported correct colour vision and corrected-to-normal visual acuity.

Stimuli and procedure

A computer-based change detection task, generated using E-Prime computer software (Psychology Software Tools, Inc., www.pstnet.com) was presented on a 17inch screen of a 3.20GHz PC. All stimuli were presented on a grey screen background (127 of red, blue and green phosphors) which was divided into 4 invisible quadrants. At a viewing distance of approximately 60cm, each quadrant subtended approximately 4.60° x 4.60° and was positioned so that the centre of each quadrant was 3.74° from the horizontal and vertical meridian. Each trial commenced upon pressing the space bar and was followed by the presentation of a white fixation dot at the centre of the screen (subtending 0.26° x 0.26°). Participants were instructed to fixate this point throughout the trials. In the distracter conditions, two spatial cues were presented within two vertical quadrants or two horizontal quadrants (one cue in one quadrant) for 50ms. After a cue-to-target delay of 50ms (50% of distracter trials) or 500ms, a memory array was presented for 150ms. The memory array consisted of four or six coloured squares presented equally across the two horizontal quadrants (bilateral display) or across the two vertical quadrants (unilateral display) that were cued. The coloured squares subtended .77° x .77° separated with a minimum distance (centre to centre) of 1.60°. The colour of each stimulus was randomly selected from one of six highly discriminative colours (blue, green, pink, red, turquoise, and yellow) which were generated using permutations of red, blue and green phosphors (either 0 or 225 on the scale 0-255). A single colour was not repeated within a quadrant, however repetition of colours across quadrants was possible. In the distracter trials, participants were instructed to remember the colours of the two squares that were cued. In the no distracter trials, no spatial cues were presented (see figure 1).

Following the memory array and after a retention interval of 1000ms, a test array was presented. Participants were instructed to indicate as accurately as possible whether there was a change in the colour of the squares relative to their appearance in the memory array. In 50% of the trials, the colours did not change, whereas in the remaining trials, one square changed colour. The colour of the changed square was selected from a remaining colour not used within the same quadrant. However repetition of colour across quadrants was possible. Participants responded by pressing the appropriate key on the computer keyboard (1= no change; 2 = change). The next trial began once a response had been made. Throughout each trial, participants were instructed to rehearse a series of 3 digits out loud in order to evoke articulatory suppression.

As outlined above, the experiment consisted of 4 possible conditions. There were two distracter conditions, requiring participants to select two targets amongst two distracters (2+2 condition) or four distracters (2+4 condition), and two no distracter conditions, requiring memory for four (4+0 condition) or six coloured squares (6+0). Each condition was tested in a separate block (counterbalanced across participants). There were 96 trials in each distracter condition (48 trials with a 50ms cue-to-target delay and 48 trials with a 500ms cue-to-target delay blocked separately), and 96 trials in each no distracter condition. Within all conditions, 50% of the trials were presented bilaterally and the remaining trials were presented unilaterally. In total, participants completed 384 experimental trials. Prior to each block of trials, participants completed 10 practice trials.

Results and discussion

Mean response accuracy (%) was analysed to assess performance across each condition. However to provide a second representation of the results, A’ from signal detection theory (Aaronson & Watts, 1987; Grier, 1971; Pollack & Norman, 1964) was also computed. Figure 2 displays the accuracy and A´ values for each condition. As the A´ analysis mirrored the accuracy analysis, only the statistical results on accuracy are reported here.

In order to investigate whether the BFA may be influenced by the cue-to-target delay, the analysis was conducted separately on each cue-to-target delay condition (50ms, 500ms). A three-way 2 (distracter: no distracters, distracters) x 2 (total set size: 4, 6) x 2 (display: bilateral, unilateral) repeated measures ANOVA including trials with a 500ms cue-to-target delay, revealed a main effect of distracter [$F(1, 21) = 9.74$, $p < .01$], a main effect of size [$F(1, 21) = 69$, $p < .001$] and a main effect of display [$F(1, 21) = 14.59$, $p < .005$]. Post-hoc analyses revealed that accuracy was greater in conditions with a total set size of four stimuli relative to six stimuli, and in bilateral displays relative to unilateral displays. In addition, accuracy was significantly greater in conditions which required targets to be filtered from distracters (2+2, 2+4) relative to conditions with no distracters (4+0, 6+0) suggesting that participants successfully selected targets amongst distracters**.** Importantly, the results showed a significant interaction between distracter and display [$F(1, 21) = 6.88$, $p < .05$] revealing overall, a significant BFA in conditions with distracters (2+2, 2+4) [$t(21) = 3.81$, $p < .005$] and no difference between bilateral and unilateral displays in conditions with no distracters (4+0, 6+0) (see figure 2)[1]. Note that when the change and non-change trials are analysed separately, this interaction appears to be significant for the accurate detection only [change trials: $F(1, 21) = 11.26$, $p < .005$; non-change trials: $p = .92$]. However, the same analysis including distracter trials with a 50ms cue-to-

[1]Due to the fact that the stimuli within bilateral displays were aligned horizontally and the stimuli within unilateral displays were aligned vertically, there is a possibility that the BFA in the distracter condition reflects a horizontal advantage in VSTM processing. In order to account for a possible effect of stimulus alignment, a different sample of participants (N=20) completed a control experiment which replicated the distracter 2+2 condition (with a 500ms cue-to-target delay) with the exception that stimuli were crosses and presented within one single hemifield. The centre of the four invisible quadrants was moved 7.44° to the left or to the right of fixation, resulting in 4 invisible quadrants within each hemifield. Mean response accuracy for horizontal and vertical stimuli orientations within the left and right hemifields was compared using a two-way 2 (hemifield: left, right) x 2 (orientation: horizontal, vertical) repeated measures ANOVA. The analysis revealed no main effects or interactions suggesting that the BFA cannot be accounted for by stimulus alignment.

target delay failed to replicate such findings. Despite revealing a significant main effect of size [$F(1, 21) = 80.93$, $p < .001$], with accuracy greater in conditions with 4 stimuli (2+2, 4+0) relative to 6 stimuli (2+4, 6+0), the results showed no effects of distracter or display and no significant interaction between them.

The results of Experiment 1 support the notion that selecting targets from distracters can promote a BFA in a memory task. However, in order to support this claim two outstanding possibilities need to be addressed. Firstly, since the distracter conditions required memory for two targets whereas the no distracter conditions required memory for four or six targets, it can be suggested that the BFA can be explained due to the processing of two target stimuli rather than attentional selection. Secondly, since the BFA was observed when the targets were cued, it is possible that the BFA is the result of the attentional orienting effects of pre-cues rather than the selection of targets from distracters. Experiment 2 addresses these possibilities using a filtering task without spatial pre-cues, requiring the selection of targets from distracters on the basis of a salient feature difference (shape). In addition, a condition with two target stimuli in the absence of distracters was included. If the BFA is due to the aforementioned possibilities then no evidence of a BFA should be observed when participants select targets from distracters on the basis of shape, however a BFA may be observed when processing two target stimuli in the absence of distracters.

Experiment 2

Method

Participants

Thirty-four paid volunteers took part in the study (19 females; mean age = 24.1, range 18 – 38 years). All had normal (self-reported) or corrected-to-normal visual acuity and normal colour vision.

Stimuli and procedure

As in Experiment 1, participants completed a change detection task however the following changes were made. After the presentation of the fixation cross (500ms) a memory array was presented for 100ms consisting of either two crosses (size 2 condition) or two crosses and two circles (distracter condition) (see figure 3). At a viewing distance of approximately 60cm the crosses and circles subtended .77° x .77° separated with a minimum distance (centre to centre) of 1.92° between stimuli. Participants were instructed to remember only the colours of the crosses and to ignore the colours of any circles that were presented.

As outlined above, the experiment required memory for two targets amongst two distracters (2+2 condition) or two targets with no distracters (2+0). Each condition consisted of 96 trials (48 change trials and 48 no-change trials) resulting in a total of 192 experimental trials which were randomly distributed into 2 blocks of 96 trials. Within each condition, 50% of the trials were presented bilaterally and the remaining trials were presented unilaterally. Participants completed 20 practice trials to familiarize themselves to the task.

Results & discussion

Mean accuracy scores were compared using a two-way 2 (condition: distracter, no distracter) x 2 (display: bilateral, unilateral) repeated measures ANOVA. This revealed a significant main effect of distracter [$F(1, 33) = 44.04$, $p < .001$], with accuracy being significantly greater in the no distracter condition compared to the performance in the distracter condition, and no main effect of display. However, the interaction between distracter and display was marginally significant [$F(1, 33) = 3.62$, $p = .066$], and paired sample t-tests revealed a significant BFA in the distracter condition [$t(33) = 2.19$, $p < .05$] but no significant difference in mean accuracy scores between bilateral and unilateral displays in the no distracter condition. In addition, when the change and non-change trials are analysed separately, this interaction appears to be (marginally) significant for the accurate detection only [change trials: $F(1, 33) = 3.21$, $p = .082$; non-change trial: $p = .62$]. The A′ analysis mirrored the overall results (see Figure 4). Therefore, the findings suggest that the BFA in Experiment 1 cannot be simply accounted for by the processing of two target stimuli or by the presentation of pre-cues before the memory array. Instead, the findings strongly support that the BFA is a signature of attentional selection.

General discussion

The aim of the present study was to investigate whether the BFA in colour VSTM is constrained by attentional selective processing. In two experiments, participants completed a change detection task which required the selection and storage of simultaneously displayed targets amongst distracter stimuli in arrays displayed within and across hemifields. In Experiment 1, targets were selected based on spatial locations indicated by spatial pre-cues before the memory array. The results revealed that selecting targets from distracters promoted a BFA whereas memory for targets in the absence of distracters showed no hemifield effects. The findings of Experiment 2 show that the BFA in Experiment 1 cannot be accounted for by the number of targets presented (two) or exclusively by the spatial pre-cueing of targets. Specifically, Experiment 2 revealed a BFA when targets were selected from distracters on the basis of a salient feature (shape) in the absence of spatial pre-cues and showed that the BFA failed to emerge in conditions which required memory for two targets in the absence of distracters. Previous studies in VSTM, revealing a BFA for spatial information but not colour (Delvenne, 2005; Delvenne et al., 2011; Mance, et al., 2012), suggest that the BFA might be constrained by the nature of the memory representation (Alvarez & Cavanagh, 2005; Delvenne, 2005). However the present findings strongly suggest that attentional selective processes also constrain whether a BFA can be observed.

The findings are in line with previous studies which have revealed a BFA in tasks requiring attentional selection (Alvarez et al., 2012; Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009). In those studies, participants were required to detect and discriminate the orientations of targets (Chakravarthi & Cavanagh 2009; Reardon et al., 2009), identify targets during rapid presentation (Awh & Pashler, 2000) or search for targets in a visual array (Alvarez et al., 2012) in the presence of distracter stimuli. Each study revealed that a BFA only emerged when participants were required to process target stimuli whilst simultaneously ignoring distracter stimuli. Similarly, each of these studies used spatial pre-cues to indicate the locations of targets. However, Chakravarthi & Cavanagh (2009) also demonstrated that the BFA cannot be explained by attentional cueing across hemifields. They showed that the BFA failed to emerge when objects were cued in the absence of distracters, suggesting that the BFA is specifically a feature of selecting targets from distracters.

Likewise to those previous experiments, the present study required two relevant stimuli to be selected and processed. Acknowledging that attention and VSTM share a limit of 3-4 items (Alvarez & Cavanagh, 2005; Luck & Vogel, 1997) the ability to select and retain those relevant stimuli can be recognised as within the bounds of efficient processing. In addition, since the no distracter conditions across both experiments assessed memory for two, four and six item arrays, we can conclude that the failure to show a BFA cannot be explained due to under- or over- capacity processing, supporting further that the requirement to select is crucial to the emergence of the BFA.

The results extend our previous findings of a BFA in colour VSTM when attentional selection was directed within VSTM representations (Delvenne & Holt, 2012) revealing that selection at encoding can also promote a BFA in VSTM. However, in the present study the BFA was dependent on the time to deploy attention at encoding. Whereas a BFA emerged in conditions with cue-to-target delays of 500ms, no hemifield effects were shown in conditions with cue-to-target delays of 50ms. Supporting the idea of a strong relationship between the BFA and selective attentional processes, an effect of distracter was only revealed in conditions with a 500ms cue-to-target delay, indicating inefficient selection of targets from distracters in conditions with a 50ms cue-to-target delay.

The present study revealed a BFA when targets were selected on the basis of spatial and featural cueing. Despite also revealing a BFA for location–based selection, Alvarez and colleagues (2012) failed to show a BFA for feature-based selection when relevant targets were selected on the basis of luminance cues. At first glance, it might be suggested that the role of selection in the BFA is domain specific. However, we propose that the post selective processes associated with maintaining the selected locations in our memory task might also account for the emergence of the BFA. In the change detection task employed here, once the targets were selected from distracters at the initial encoding stage, participants were required to maintain a representation of each target's location throughout a blank retention interval. In contrast, the visual search task employed by Alvarez and colleagues did not require this additional step. The subset of stimuli to be searched which was cued on the basis of luminance (black versus white) remained cued throughout the duration of the search task, thus the maintenance of stimuli locations was not required. This was not the case when Alvarez and colleagues cued the relevant subset of stimuli with spatial cues. The cues preceded the search array and required a representation of the relevant locations to be maintained across a retention interval of 1 second and throughout the duration of the search task. Therefore, we suggest that the BFA in selection is dependent not only on the early selection of targets from distracters but is also a result of post-selective processes required to maintain selection.

Demonstrations of a BFA in spatial working memory for locations (Delvenne, 2005) and orientations (Umemoto et al., 2010) but not colour (Delvenne, 2005; Delvenne et al., 2011; Mance et al., 2012) strengthen the argument that the maintenance of selected spatial locations in the present study is a significant aspect of the BFA. We suggest that the emergence of the BFA in these cases can be accounted for by existence of independent attentional resources within each hemifield (Alvarez & Cavanagh, 2005). Previous studies have shown that the rehearsal of spatial memory representations relies on the deployment of sustained spatial attention to the to-be-remembered locations during the maintenance stage (see Awh & Jonides, 2001). Therefore, we suggest more efficient rehearsal across hemifields relative to within may account for the emergence of the BFA.

However, we cannot deny the existence of a role of early selection stages on the BFA. Since the colour constraints in the present experiments resulted in the repetition of colour across quadrants, the requirement to bind the colour and location of each stimulus was expected across both distracter and no distracter conditions. Despite this, the BFA was not observed in the no distracter conditions suggesting that the emergence of the BFA is, at least to some extent, related to the early selection of targets from distracters. Chakravarthi & Cavanagh (2009) discuss that a within hemifield deficit in a selection paradigm might be explained due to the activation of attentional suppressive surrounds around targets, which despite reducing distracter interference, also subsequently render the processing of multiple targets as problematic. Since the suppressive regions are less effective across the vertical meridian (e.g. Mounts & Gavett, 2004), the processing of targets across hemifields is more efficient.

Those effects might be facilitated by the observed differences in the ability to split attention within and across hemifields, with demonstrations of more efficient division across hemifields (Kraft et al., 2005; Malinowski, Fuchs, & Muller, 2007; Muller, Malinowski, Gruber & Hillyard, 2003). On the other hand, Reardon and colleagues (2009) suggest that the observance of a BFA might be accounted for by unilateral superiority for perceptual grouping and spatial integration (e.g. Butcher & Cavanagh, 2008, Pillow & Rubin, 2002) which produces a negative effect on performance when task demands require the perceptual segregation of targets and distracters within hemifields. Whilst the present study supports a selection deficit within relative to across hemifields, further research should address these possibilities in order to uncover the mechanisms of the BFA.

In conclusion, the present study provides a fuller understanding of the BFA in VSTM, affording a plausible explanation for the previous failures to observe a BFA in colour VSTM (Delvenne, 2005; Delvenne et al., 2011; Mance et al., 2012). Complementing our previous findings of a BFA in VSTM when attention is directed within VSTM representations (Delvenne & Holt, 2012), the present study reveals for the very first time that attentional selection at VSTM encoding can also promote a BFA.

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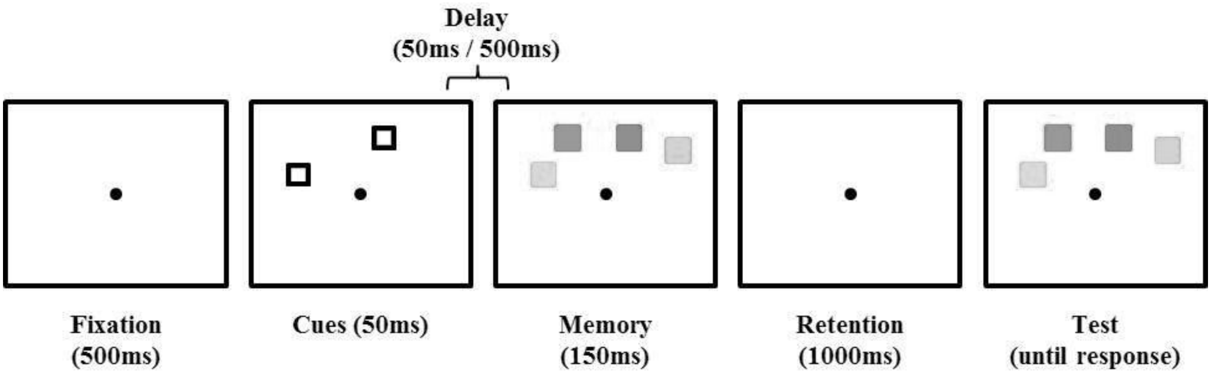

Fig.1. The trial procedure for distracter trials in Experiment 1. The different gray levels represent different colours. (For illustration purposes the objects are not drawn to scale).

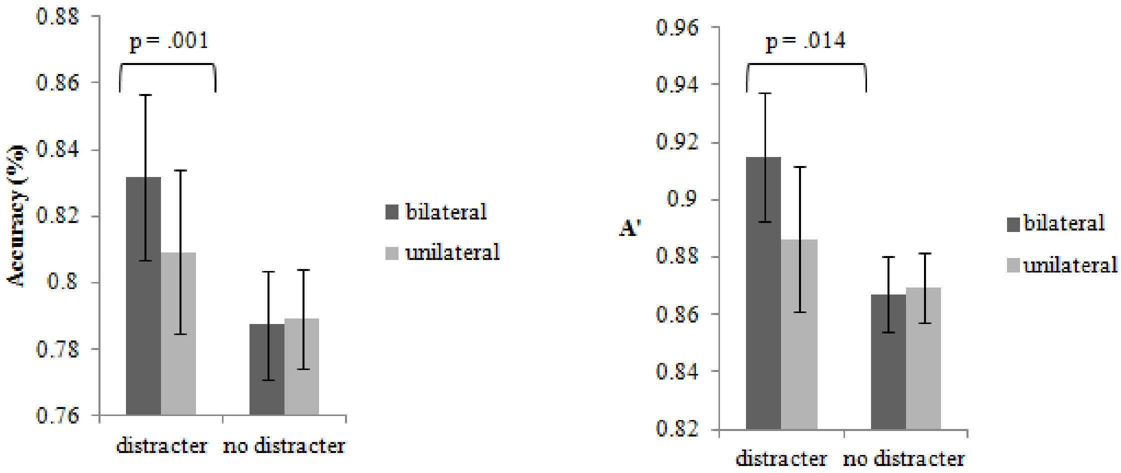

Fig. 2. Mean response accuracy (%) and A′ values as a function of condition (distracter, no distracter) and display (bilateral, unilateral). Distracter conditions include 2+2 and 2+4 (with 500ms cue-to-target delay), whereas the no distracter conditions include 4+0 and 6+0. The error bars represent the standard error of the mean values.

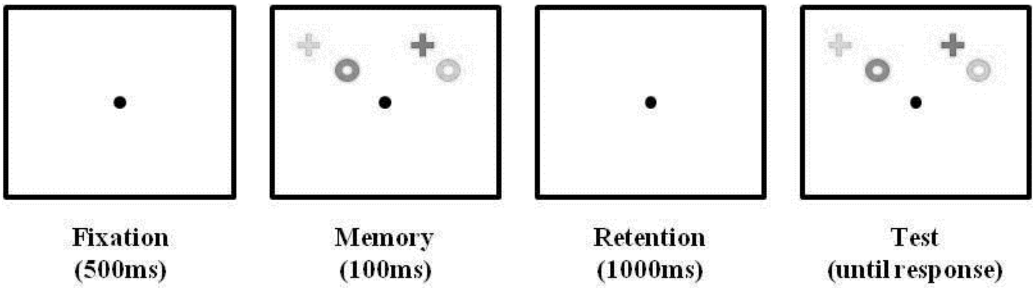

Fig. 3. The trial procedure for distracter trials in Experiment 2. The different gray levels represent different colours. (For illustration purposes the objects are not drawn to scale).

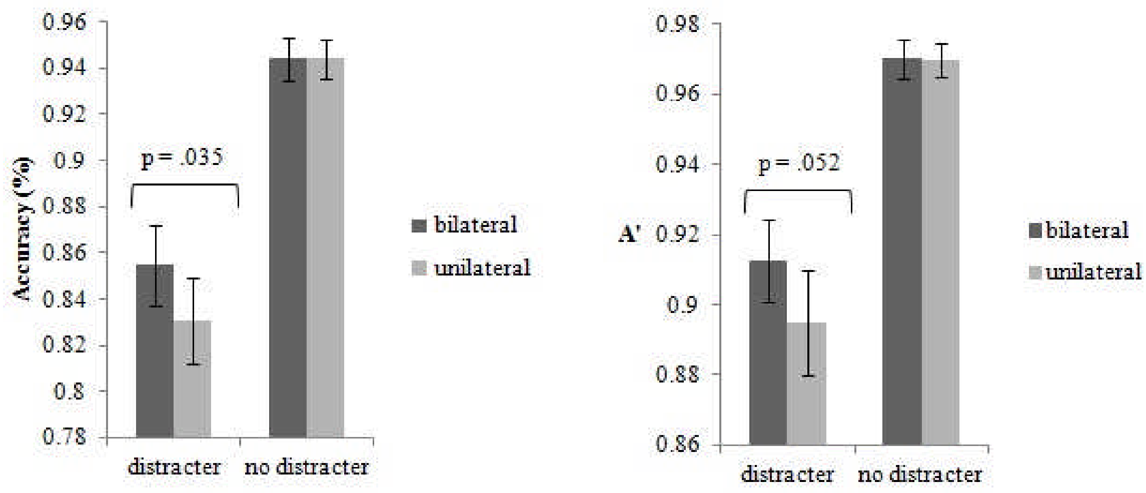

Fig. 4. Mean response accuracy (%) and A´ values as a function of condition (distracter, no distracter) and display (bilateral, unilateral). The error bars represent the standard error of the mean values.