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Additive effects of inhibiting attention to objects and locations in three-dimensional displays

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One of the processes thought to underlie visual selection works by biasing attention away from either recently examined locations or objects. The extent of this ''inhibition'' is greatest when the inhibited object and the inhibited location coincide. In Experiment 1, rectangles are presented stereoscopically at different depths but at similar positions horizontally and vertically. Here, any inhibition should be based solely on a spatial code, as the objects, the rectangles are clearly separate objects. In Experiment 2, the corners of the rectangles are joined to produce a single cuboid that extends in depth space. Now inhibition based on both spatial and object codes should be seen because even when on different depth planes the cue and target are associated with the same object. Consistent with our understanding of the additive effects of inhibition of space and object codes, the extent of inhibition in the second study is almost double that of the first. The results further suggest that space-based inhibition operates within a two-dimensional representation while object-based inhibition utilizes a three-dimensional representation.

Selection amongst visual input appears to occur though a combination of the facilitation of some stimuli and the inhibition of others. It has been demonstrated that when a target is presented at a location that has just been cued by an abrupt onset it is initially detected rapidly relative to a noncued location (Posner & Cohen, 1984). If, however, the presentation of the target is delayed, detection is slowed at that location. This slower detection is called ''Inhibition of Return'' (IOR). It has been argued that this inhibition functions to bias attention away from recently examined locations (e.g., Klein & MacInnes, 1999). While originally conceived of as a spatial affect, IOR has been shown to operate both on spatial locations and on objects (e.g., Tipper, Weaver, Jerreat, & Burak, 1994). Furthermore, this effect has been shown to be additive when location and object coincide.

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That two sources of IOR existed and could be separated was shown using moving stimuli. Weaver, Lupiáñez, and Watson (1998) presented four boxes on a screen, one in the centre and the other three equally spaced around it in a triangular arrangement. One square was cued and in the interval before a target was presented the three boxes moved through 120°. This resulted in each box being in a location previously occupied by one of the other boxes. Two results were seen. Firstly, when the target was presented at the same location as the cue there were slowed responses. Secondly, when the target was presented at the box that had been at the cued location, but had since moved, there were also slowed responses. In both the first ''space-based'' and the second ''object-based'' case of IOR, there was a similar slowing of 15 and 23 ms respectively (see also, Tipper, Jordan, & Weaver, 1999). It was noted that these are substantially smaller in size than the typical 40 ms slowing seen when using static displays. It was argued that static displays reflect the combination of object and space-based effects occurring together.

More direct evidence exists showing that IOR from these two sources combine to delay responses. Jordan and Tipper (1998) presented stimuli that in certain orientations produced the Kanizsa illusion of a square. IOR to this object was contrasted with IOR to the same location without the illusory object. Significantly greater inhibition was found when an object and location were cued compared to when cueing the location alone. In a subsequent study, Jordan and Tipper (1999) showed the complementary effect of greater inhibition when an object and location were cued relative to when an object alone was cued. Two objects were presented—rectangles on either side of a fixation cross. The location to be cued was selected so that it was equally distant from targeted locations within the same rectangle and within the opposite rectangle. Slower responses were found to targets that appeared not only at the cued location but also at the new spatial location that was within the same object. Again the inhibition was significantly greater when the object and location were cued compared to when just the object was cued. The larger effect seems to be the result of two quite separated processes operating on the same stimuli.

IOR as well as facilitation, has been largely studied in the two-dimensional horizontal and vertical planes, but facilitation has also been clearly shown to occur in depth (e.g., Atchley & Kramer, 2001; Couyoumdjian, Di Nocera, & Ferlazzo, 2003; Downing & Pinker, 1985). How IOR behaves in depth space is less clear. It has been reported that IOR can stay with locations within a perspective drawing of a brick that rotates partially in depth,(Gibson & Egeth, 1994). But it has also been reported that IOR is insensitive to the depth plane (Theeuwes & Pratt, 2003). They used a stereographic display to investigate whether IOR occurred in three-dimensional space. Four rectangular figure-of-eight placeholders were used as stimuli (similar to the top of Figure 1). Two were presented to the right of a fixation cross and two to the left. Each pair was at virtually the same XY coordinates but separated in depth *by the use of*

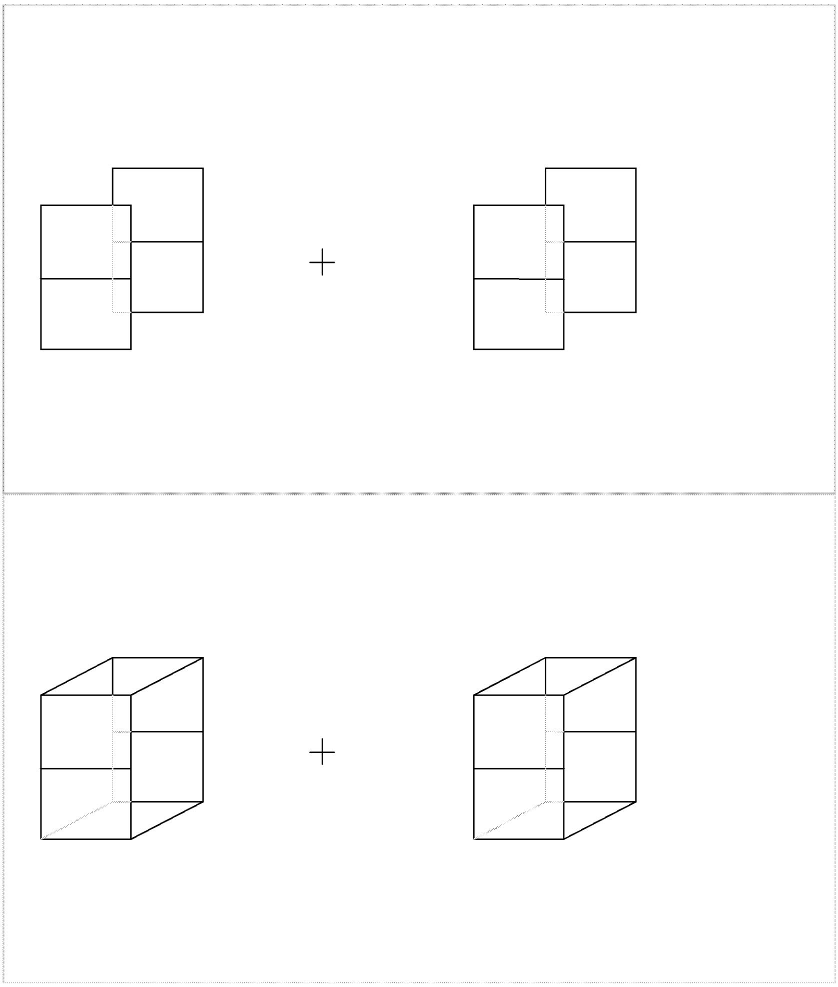

Figure 1. Illustration of the initial stimulus display in Experiment 1 (top) and Experiment 2 (bottom). Stimuli were always presented stereoscopically so that two rectangles appeared at a depth distant to the observer and two at a depth nearer to the observer. The fixation cross was presented at a middle distance from the observer. For the full sequence in a trial see Figure 2.

stereoscopic disparity. The results showed that responses are equally slowed to targets at the two different depth locations so long as they shared the same cued location in horizontal and vertical space. The conclusion reached was that either IOR spreads through depth space or that IOR is operating on a two-dimensional representation, in either case both locations become equally inhibited.

In the context of IOR having ‘‘space-based’’ and ‘‘object-based’’ components these latter results are curious. In a classic two-dimensional display with one rectangle to the right and one to the left of fixation, the cueing of, for example the left, will produce delayed reaction times for two reasons—IOR attached to that spatial location and IOR attached to that object—the rectangle. In the current case with depth created by stereoscopic disparity, there are now two separate objects at each location, one near and one far. We therefore expect no object-based IOR, for example at the back left rectangle when the front left rectangle is cued. Therefore we would not expect the delay in reaction time to be as great as that seen when both object and location are cued, i.e., cueing and targeting the identical rectangle. From the existing literature, we either expect a reduced IOR that could be as much as half that of the combined effect if a space-based IOR that is blind to depth is operating, or no IOR at all if it is not.

Here, in Experiment 1, a partial replication of Theeuwes and Pratt (2003) is conducted controlling for potential perceptual confusion caused by overlapping stimuli. As discussed above, we now predict that IOR will be influenced by whether cue and target are presented to the same object. In Experiment 2, the same stimuli are used but the corners are joined to create the impression of one object at each side, i.e., three-dimensional cuboids extending in depth space (Figure 1, bottom). Here, all space-based IOR present in Experiment 1 should be seen but now it should be always combined with an IOR attached to the new object, the cuboid, producing a significantly larger slowing of reaction times.

EXPERIMENT 1

The method largely followed that of previous work (Theeuwes & Pratt, 2003*)* where stimuli are presented at different horizontal locations and at two different apparent depths by the use of stereoscopic disparity. In Experiment 1, the key difference is the increased horizontal separation of the stimuli that had virtually overlapped in the original study. With modest horizontal and vertical separation strong spatial IOR is still expected (Bennett & Pratt, 2001).

Method

Participants. Twenty-eight volunteers took part. All but four were undergraduate university students, aged between 18 and 24 years, who participated for ‘‘participant pool’’ credit, a voluntary system that allows subsequent use of the pool. All participants reported normal or corrected-to-normal vision.

Procedure. Subjects view the display from about 750 mm. The fixation display consisted of a central cross with four grey figure-of-eight premasks ($1.3^\circ \times 2.5^\circ$) drawn with three pixel-wide lines and presented at 4.4° to the left and right side. The figures-of-eight in the back plane were displaced by 1.74° horizontally and by 0.3° vertically. Small (less than 0.1°) grey dots were randomly added in the front and back plane to strengthen the perception of two planes at different depths. The dots appeared everywhere except at the locations of the premasks. The binocular disparity between the depth planes was +/– 15 min of arc relative to the fusion display at which the fixation cross was presented. Binocular fusion of separate left and right eye was achieved by crystal shutter glasses, which were synchronized with alternating frames (30 Hz per eye).

A trial (Figure 2) started with this display presented for 600 ms, after which the fixation cross was switched off. A further 600 ms later, one of the figure-of-eight premasks brightened for 33 ms; 250 ms after this cue the fixation cross was represented and remained on until the end of the trial. Following a further 650 ms, the target was presented by removing segments of a figure-of-eight to reveal either an ''H'' or an ''S''. The target was presented for 116 ms and then the display went blank until the next trial

There was no relationship between the location of the cue and the location of the target, i.e., cue validity was 25%. Participants were asked to fixate on the central fixation cross and not make eye movements during a trial. The subject's task was to identify and respond to the targets as quickly and as accurately as possible and their reaction time was recorded. Their response was recorded using a two-button response box marked ''S'' and ''H''. Participants received 80 practice trials followed by 160 experimental trials; there was no intermission between the two sets of trials. A Hagner Universal Photometer placed against the screen was used to measure the luminosity of blocks of colour corresponding to the background (1.37 cd/m^2), fixation cross (13 cd/m^2), lines in which the premasks were drawn (12 cd/m^2), and the cue (57 cd/m^2).

There were four conditions described by their relationship of the target to the previous cue, ''noncued''—cue and target at same depth but different sides of the display, ''cued same depth''—cue and target appeared at the same depth and same side of the display, ''cued different depth''—cue in one depth plane while the target appeared in the other depth plane but at the same side of the display, and ''noncued different depth''—cue on one side of the display and the target on the other side of the visual display and in a different depth plane.

In order to take part in the study, participants had to complete a screening test to determine whether they were able to perceive depth using binocular disparity. The stimuli consisted of four squares, one presented in each corner of the screen. Two of the squares were presented in the front plane and two presented in the back plane. The depth location of these squares randomly changed every 10 trials. A cross would appear within any of the four boxes and the subject's task was to respond by indicating whether the cross had appeared in a box in the front plane or in the back plane. Any participants who committed more than 25% errors during the screening test were excluded.

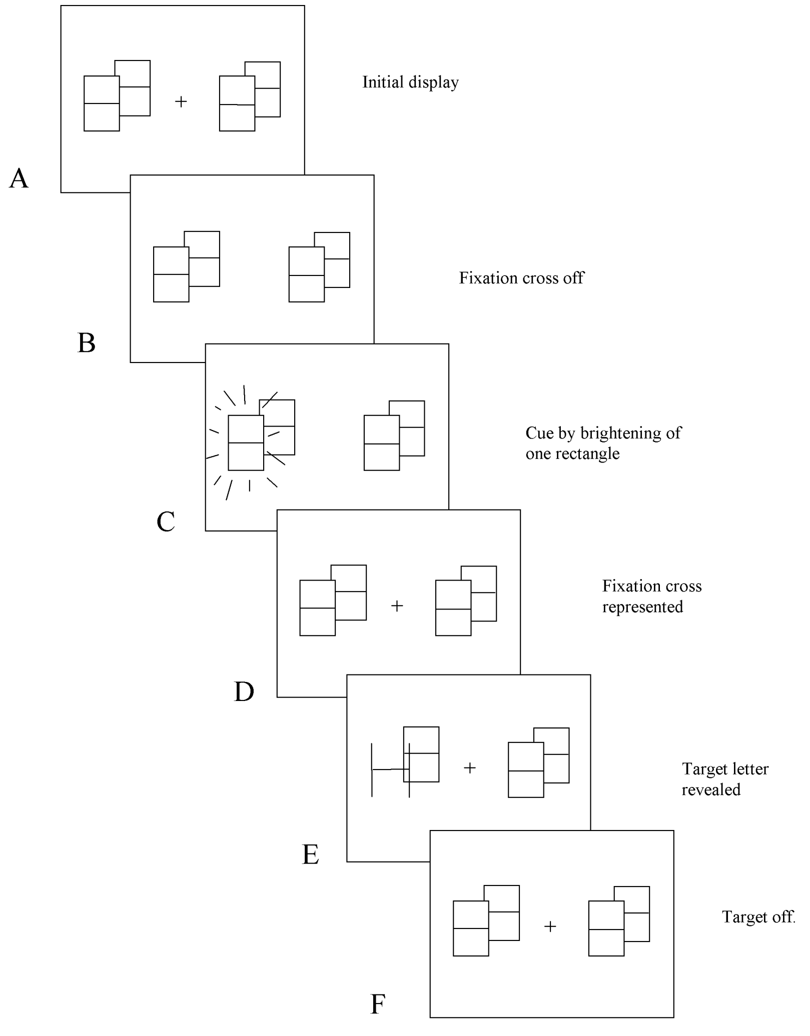

Figure 2. Illustration of the trial sequence in Experiment 1. See text for details.

Results

Two volunteers failed the screening test and their data was discarded. Results are shown in Table 1. Separate ANOVAs were performed on errors and reaction time. In each, there were four levels corresponding to the relationship of the target to the previous cue, as described above. The levels were, ''noncued'', ''cued same depth'', ''cued different depth'', and ''noncued different depth''.

TABLE 1
Mean reaction times (ms) and percentage errors for the four conditions within each experiment

	Noncued	*Cued same depth*	*Cued different depth*	*Noncued different depth*
Experiment 1	585 (4.0)	608 (4.6)	595 (4.0)	582 (4.7)
Experiment 2	584 (4.6)	609 (3.0)	608 (4.1)	583 (4.7)

There was no effect of condition on errors made, $F(3, 81) = 2.10$, $MSE = 2.09$, $p = .11$. Any responses greater than 1000 ms and less than 100 ms were discarded. This accounted for 1.74% of the data. In terms of reaction time there was a main effect of cueing, $F(3, 81) = 7.60$, $MSE = 496.67$, $p < .0001$. Planned comparisons showed significant differences in the three critical conditions. There was a classic horizontal cueing effect, i.e., slower responses when the target occurred at the same horizontal and vertical position as the cue, $F(1, 80) = 14.92$, $p < .01$. Critically, the extent of this inhibition was less when the target shared only the same horizontal location as the cue compared to when it shared the horizontal and depth location, $F(1, 80) = 4.95$, $p < .05$. This was significantly different from when the target occurred at the noncued location, i.e., shared the same depth plane but was at a different horizontal position to the cued rectangle, $F(1, 80) = 4.76$, $p < .05$.

Discussion

The results are consistent with expectations (Table 2). The classic result of two-dimensional cueing is seen. For example, with one rectangle to the right and one to the left of fixation, cueing one of these produces a 23 ms slower reaction time to targets at the cued relative to the noncued location. More critically, when the targeted object is at the same horizontal but in a different depth plane to that cued the extent of IOR is still significant but reduced in extent to 13 ms. This is close to half that seen when the targeted object and location are identical to that cued. This suggests that only one form of IOR was present and within the

TABLE 2
Mean IORs (ms) relative to noncued location

	Experiment 1	*Experiment 2*
IOR in horizontal space	23 ms	25 ms
IOR in depth space	13 ms	25 ms

current framework it is likely to be space-based IOR. This IOR appears to be operating within a two-dimensional representation as stimuli at both depths are being inhibited. Given this interpretation, the greater inhibition that exists when cue and target are at an identical location/object is likely to be due to object-based IOR to that specific rectangle. This appears to be operating within a three-dimensional representation. If it were not, no difference would be seen in the extent of IOR at the far and near rectangles.

To strengthen this interpretation it is necessary to be sure that the reduced IOR at the different depths is not due to the additional small horizontal and vertical separation between the front and back stimuli. It is also necessary to explore further whether the IOR seen in the first experiment was indeed a space-based one. This is done in Experiment 2 by using the same spatial relationships but manipulating the object-based IOR that is assumed to be missing when the target differs only in depth to the cue. In this experiment the two corresponding front and back stimuli are joined at the corners to form two cuboids (Figure 1, bottom). A cued rectangle is now part of a larger object extending in depth. We expect IOR to spread within this three-dimensional object much as found for two-dimensional objects (Jordan & Tipper, 1999; Leek, Reppa, & Tipper, 2003; Reppa & Leek, 2003).

EXPERIMENT 2

Method

The same method was used except that three pixel-wide lines (0.12°) joined the corners of the corresponding rectangles.

Participants. Twenty-four new participants matching the same criteria as Experiment 1 took part.

Results

All participants passed the stereo screening test. As in Experiment 1 an ANOVA with four levels was conducted. The levels were defined by the relationship of the target to the previous cue, (1) ‘‘noncued’’—cue and target at same depth but different sides of the display, (2) ‘‘cued same depth’’—cue and target appeared at the same depth and same side of the display, (3) ‘‘cued different depth’’—cue in one depth plane while the target appeared in the other depth plane but at the same side of the display, and (4) ‘‘noncued different depth’’—cue on one side of the display and the target on the other side of the visual display and in a different depth plane. There was no significant difference in the percentage of errors made, $F(3, 69) = 0.50$, $MSE = 1.63$, n.s. Trials outside 100–1000 ms (1.38%) were removed. Results are shown in Table 1. There was an effect of cueing condition, $F(3, 69) = 9.89$, $MSE = 500.37$, $p = .001$. However, it is now clear that placing the target at the same or at different depths to that cued makes no difference (less than 2 ms) when the cue and target are within a single object. This was confirmed by post hoc analyses with Tukey HSD tests. There was no difference between the ''cued same depth'' and ''cued different depth conditions''. Significant differences ($p < .05$) did exist between (a) the ''noncued'' and ''cued same depth'', (b) the ''noncued'' and ''cued different depth'', (c) the ''cued same depth'' and the ''noncued different depth'', and (d) the ''cued'' and ''noncued different depth''.

Discussion

Joining the two separate rectangles to form a single cuboid at each side of the display increased the IOR so that reaction times at both the near and far surfaces were identical (Table 2). This contrasts with the significantly different size of IOR to stimuli at different depths in Experiment 1. It seems reasonable to assume that in Experiment 1 only spatial IOR was operating when cue and target were on different objects at different distances from the viewer. In contrast, in Experiment 2 space-based and object-based IOR are having a combined effect. This would explain the increase—the close to doubling of the IOR in the cued different depth condition.

Recent work has shown that cueing and targeting different parts of an object produces different extents of IOR. Local surface plane orientation appears to be critical (Leek, 2004). When the cued and targeted surfaces of an object are at different orientations, IOR increases. When they are on planes of the same orientation no difference is seen. The current results could be viewed as consistent with this as here we have cued and targeted the front and back surfaces of a cube which being parallel share the same planar surface orientation, albeit at a different depth. No differences in extent of IOR were seen.

GENERAL DISCUSSION

The results are consistent with our understanding of the additive effects of IOR. In the first experiment, two objects shared virtually the same location in horizontal and vertical space. When one was cued, subsequent reaction time was slowed presumably because IOR was attached to it and to its location. Targeting the other object at that location (same XY but different depth) produced an IOR effect that was only half that of the within-object effect; consistent with the notion that IOR was not attached to the object. Changing the display so that the two objects are perceived as a single object extending in depth significantly increases IOR to the extent that the slowing is found to be identical at both rectangles. While the results are as predicted by much previous work (e.g., Jordan & Tipper, 1999; Reppa & Leek, 2003), they are different to those of

Theeuwes and Pratt (2003). It is possible that with the virtual complete overlap of stimuli that was used in the Theeuwes and Pratt experiment the perceptual system treated the rectangles that were separated in depth as a single object. Those results then would be equivalent to the current Experiment 2.

One might assume that the increase in spatial distance between cue and target at the two-dimensional level in Experiment 1 as compared to Theeuwes and Pratt might have produced the different results, because it is known that IOR declines with increased distance between cue and target in the picture plane (e.g., Maylor & Hockey, 1985). However, Experiment 2 discounts this explanation, as exactly the same difference between cue and target was tested, and here large IOR effects were obtained. The fact that IOR increases in Experiment 2 when a single object is perceived suggests that it was object-based IOR that was missing in Experiment 1 when the cued rectangle was not joined to the targeted rectangle. Given this, the inhibition seen in the first experiment, when the cue and target share the same horizontal and vertical positions but differ in depth, is likely to be space-based IOR. This space-based IOR appears to operate within a two-dimensional representation given that it is uninfluenced by depth separation. The current results are also consistent with the interpretation that object-based IOR operates within a three-dimensional representation and that this is additive with a depth blind spatial IOR.

We may speculate that the two-dimensional spatial and three-dimensional object-based representations mediating IOR evolved to serve particular action systems. The current findings support the previous conclusions that inhibition associated with objects appears to be represented in sophisticated cortical systems (Tipper et al., 1997). Such object-based representations possess three-dimensional structure because, first, real-world objects are three-dimensional entities; second, attention can move in depth between objects; and third, actions such as reaching to grasp objects require coding of hand and object location in three dimensions. It is certainly the case that IOR can be observed in tasks where people reach for targets at various distances from the hand (Howard, Lupiáñez, & Tipper, 1999). In this context, the current evidence further supports the notion that object-based IOR is represented in a three-dimensional form.

In contrast, IOR has also been demonstrated when saccades to targets are required (e.g., Abrams & Dobkin, 1994). The frame of reference necessary to guide saccades is retinotopic, where the eye has to move to shift stimulation from peripheral to foveal areas on the retina. Such a retinotopic representation mediating IOR in the superior colliculus (e.g., Rafal, Posner, Frieman, Inhoff, & Bernstein, 1988) is by its very nature two dimensional. Note that Abrams and Dobkin showed that only space-based IOR could be detected when saccades to targets were required; the saccade system mediating IOR appears to be blind to objects. We may speculate in closing therefore, that if saccades to targets were required in a replication of Experiment 1, then no effects of cueing separate objects in depth will be observed if the coordinate system mediating saccades is blind to depth- and object-based representations.

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