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Attentional Control Within 3-D Space

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Four experiments investigated whether directing attention to a particular plane in depth enables observers to filter out information from another depth plane. Observers viewed stereoscopic displays and searched for a red line segment among green line segments. The results showed that directing attention to a particular depth plane cannot prevent attentional capture from another depth plane when the colors of the target and distractor are identical. However, it can prevent attentional capture by a singleton from another depth plane when the colors of the target and distractor are different. These results indicate that only when both color and depth information are selective in guiding attention to the target singleton can attentional capture by irrelevant singletons be prevented. The results also suggest that retinal disparity does not have the same special status as location information in two dimensions and should be considered as just another feature along which selection may occur.

The visual system is not capable of simultaneously processing all of the information it receives. Many studies have focused on how a portion of the visual input is selected. It is generally concluded that selection occurs on the basis of location (Broadbent, 1982; Treisman, 1988). In visual search, particular features such as color (e.g., Egeth, Virzi, & Garbart, 1984; Kaptein, Theeuwes, & Van der Heijden, 1995) and shape (Wolfe, 1994; Wolfe & Bennett, 1997) may guide attention selectively to those locations that contain task-relevant features (Kim & Cave, 1995). It is assumed that information gathered through parallel and preattentive processes is used to restrict the deployment of "limited-capacity" attention to particular locations in space.

Rather than guiding spatial attention to particular locations in space, in visual search, grouping mechanisms may segregate spatially contiguous sets of elements, allowing spatial attention to be directed to one subgroup while ignoring another subgroup (Theeuwes, 1996a; Treisman, 1982). Treisman and Gormican (1988) suggested the "group scanning hypothesis," in which attention may be pooled within a small subarea of space in order to exclude surrounding areas. In this view, particular groups of items falling within the attentional window are processed in parallel. Theeuwes (1996a) showed that a conjunction of color and orientation in a large field of distractors can be detected in parallel when grouping on the basis of color and spatial proximity is possible. He suggested that there may be two sequentially operating parallel processes: a first process allowing the segregation of spatially contiguous subsets of elements, followed by a second local parallel process that enables the target to pop out among the remaining elements. Because attention could be restricted to a particular subarea in two-dimensional (2-D) space, a target defined by a conjunction of features became—within the attended subarea—a target defined by a single feature. Again, the underlying notion is that attention can be restricted to a small subarea of space, thereby excluding the surrounding regions of the visual field. In other words, selection can be thought of as a spatial window that can be narrowly or widely focused (Treisman & Gormican, 1988).

Tasks in which spatial precuing (e.g., Posner, 1980) is used also have consistently shown that focusing attention to a location in space provides performance benefits for events that occur at that location and performance costs for events that appear at uncued locations. It has been suggested that attention operates like a spotlight (Posner, 1980) or a zoom lens on a camera (C.W. Eriksen & St. James, 1986; Jonides, 1981). Information that falls within the spotlight (or the field of the zoom lens) is actively processed, whereas information outside the spotlight (or the field of the zoom lens) either passively decays or is actively inhibited.

The great majority of studies show that attention to a location or region in space has a special status allowing the exclusion of information from outside the attended region. In tasks in which participants are instructed to attend to a limited spatial region indicated by a highly valid cue, there is a remarkable ability to process only elements appearing at that location without the interference of elements appearing at "nonattended" locations (e.g., Kahneman & Treisman, 1984; Lavie, 1995; Yantis & Johnston, 1990). Attention is thought to operate like a spatial filter that assumes that inside the focus of attention everything is processed and that outside the focus everything is ignored or actively inhibited (Yantis & Johnston, 1990).

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For example, Yantis and Jonides (1990) and Theeuwes (1991a) showed that spatial attention can be used to filter out irrelevant singletons. When search was eliminated by advanced cuing with absolute certainty for the location of the impending target, onset and offset singletons elsewhere in the visual field did not affect performance. It was concluded that abrupt onsets and offsets ceased to capture attention because the focusing of attention on a particular location blocked out information from elsewhere in the visual field. Also, in visual search, it was demonstrated that once attention is focused on a target item, abrupt onsets elsewhere in the visual field cease to capture attention (Theeuwes, 1995a).

Most of the studies in which the characteristics of spatial attention have been examined have done so within 2-D space. Nakayama and Silverman (1986) suggested that attention can be selectively focused on a specific plane or surface in depth (see also Downing & Pinker, 1985; Gawryszewki, Riggio, Rizzolatti, & Ulmilta, 1987). Given the notion that directing attention to a location in x–y space enables the filtering out of information from another part of the visual field, the question arises as to whether directing attention to a particular depth plane in three dimensions also enables the filtering out of information from other depth planes.

Recent studies have shown that it is possible to focus attention on a particular depth plane defined by binocular disparity (Andersen & Kramer, 1993; He & Nakayama, 1995; Nakayama & Silverman, 1986). For example, Nakayama and Silverman found parallel search for a conjunction of color and depth. Because participants could direct attention to a particular plane in depth, a target defined by a conjunction of features became—within the attended depth plane—a target defined by a single feature (i.e., a singleton). Nakayama and Silverman hypothesized that the visual system can selectively focus attention on a particular depth plane to the exclusion of information at different depths. Along similar lines, as has been claimed for 2-D space, Nakayama and Silverman argued that retinal disparity as well as retinal locus has priority when compared with other visual dimensions such as color and motion.

Similarly, Andersen (1990) and Andersen and Kramer (1993), using an Eriksen flanker task, showed that the effect of incompatible flankers diminished as they were moved away from the target in depth, which is comparable to the effect of increasing retinal distance in two dimensions (cf. B. A. Eriksen & Eriksen, 1974). In contrast to the results of Nakayama and Silverman (1986), who showed that elements in the unattended depth plane were completely filtered out, Andersen's (1990; Andersen & Kramer, 1993) results suggested a gradient-like distribution in depth. Note, however, that unlike Nakayama and Silverman, who used a visual search task, Andersen used a focused attention task in which nearby response-compatible or response-incompatible distractors had to be ignored. The fact that the to-be-ignored distractors were response related (compatible or incompatible) may have been the reason that information from the unattended depth planes could not be completely filtered out. Similar to research on attention in two dimensions, these focused-attention studies suggest a gradient-like distribution in depth, with maximal processing at the focus of attention and declining efficiency at more peripheral locations.

Thus, in general, the results suggest that, similar to focusing attention in two dimensions, it is possible to focus attention to a specific depth plane. The question that we addressed in this research was whether focusing attention to a specific depth plane would also provide the opportunity to filter out elements from another depth plane. More specifically, in the current experiments we tested whether it is possible to search for a color singleton (i.e., an item that is locally unique in some basic visual dimension; cf. Egeth & Yantis, 1997) within the attended (i.e., cued) depth plane without any interference from a singleton in the other, nonattended depth plane. In other words, is it possible for an element to pop out in one depth plane without any interference from salient elements in other depth planes? Because singletons are detected by parallel search across 2-D space, the absence of interference from singletons on other depth planes would suggest that parallel search can be selectively tuned to a specific depth plane. Previous research has shown that when searching in parallel for a target singleton, observers find it impossible to ignore distractor singletons within the same x–y plane when these singletons are as salient as the target singleton being looked for (Theeuwes, 1991b, 1992, 1994, 1996b). Note, however, that in these studies, observers had to search for a target singleton that could appear anywhere in the visual field. This implies that directing spatial attention to a location in 2-D space (as in typical 2-D cuing experiments) could not be used to filter out irrelevant singletons (as in Theeuwes, 1991a). In the current experiments, because the third (depth) dimension was precued, it was possible to direct attention to a particular depth plane while performing a singleton search task.

If it is possible to selectively and exclusively direct attention to a particular depth plane, then irrelevant singletons from another depth plane should not interfere with search even when these to-be-ignored singletons are as salient as the target. On the other hand, if parallel processing cannot be restricted to a particular plane in depth, then elements from another plane should be expected to interfere with search for the singleton within the attended depth plane.

Experiment 1

Experiment 1 was conducted to determine whether participants would be able to attend to a particular depth plane on the basis of a cue that was presented for a short time. He and Nakayama (1995) reported that directing attention to a depth plane defined by binocular disparity is possible when a cue is presented 1–2 s before the stimulus display. Because such a long cue duration makes it possible to make vergence eye movements to the cued depth plane, this procedure cannot establish whether vergence or attention (or both) to the depth plane is responsible for the differences in response times (RTs) between valid- and invalid-cue conditions. To determine whether it is in fact possible to direct attention to a depth plane without making vergence eye movements, we presented the cue and search display in this study within 200 ms, a time frame that is considered to be too short for participants to initiate vergence eye movements (Rashbass & Westheimer, 1961). To examine the extent to which directing attention to a depth plane can serve to filter out information from other depth planes, as tested in the subsequent experiments, we conducted Experiment 1 to ensure that participants could rapidly direct attention to a specific depth plane.

Method

Participants. Eight young adults (aged 19–28 years) participated as paid volunteers. All participants had normal or corrected-to-normal vision and reported having no color vision defects. Before the experiment, participants had to pass a screening test to determine whether they were able to perceive depth in the current displays. The screening displays were identical to those used in the actual experiment and consisted of 12 green line elements in the frontal plane and 12 green line elements in the back plane. One randomly chosen element turned into a red element for 100 ms. During pretesting, participants had to indicate whether the red element was in the front or back plane. The experimenter checked the answer. Participants were required to give 10 correct answers in a row to pass the screening test.

Apparatus. The stereographics displays were presented on a Magnavox 21-in. (53-cm) monitor. Binocular fusion of separate left- and right-eye images was achieved with crystal shutter glasses (Stereographics Corp., Mountain View, CA) that were synchronized with alternating frames (60 Hz per eye). The displays were presented with a Pentium-based computer system (running at 200 MHz) using a Matrox Millenium graphics card. Each participant was tested in a sound-attenuated, dimly lit room, with his or her head resting on a chin rest. The display was located at eye level, 75 cm from the chin rest. The left and right mouse buttons were used for responses.

Stimuli. The stimulus display consisted of 24 tilted (20° randomly to the right or left) green line segments (size = 0.76° × 0.15°; luminance = 3.1 cd/m^2 measured through the shutter glasses). There were always 12 elements in the front plane and 12 elements in the back plane presented on an imaginary 4 × 3 matrix (6.8° × 6.0° within a single depth plane). On each trial, the color of one randomly chosen green line element turned red (luminance = 1.0 cd/m^2) and constituted the target line element.

Initially, the two depth planes, each having 12 line elements, were presented for 1.5 s to enable participants to perceive the depth separation between the two planes. A green outline rectangle (7.8° × 7.0°) was then presented at one of the depth planes for 100 ms; this served as a cue to indicate the depth plane that was most likely to contain the red target line. After an interstimulus interval of 50 ms, the color of one of the green line segments was changed to red; this constituted the target line segment. After 50 ms, the complete stimulus field was erased (see Figure 1). The cue indicated the depth plane on which the red target line would appear with a probability of 80%. The red target line appeared on the uncued depth plane 20% of the time.

The green outline rectangle was presented with an abrupt onset at one of the depth planes. Research in 2-D space has shown that transient or sudden-onset events capture attention automatically (Nakayama & Mackeben, 1989; Theeuwes, 1991a; Yantis & Jonides, 1984; but see Folk, Remington, & Johnston, 1992). Therefore, we expected the rectangle to be an effective way to cue attention to one of the two depth planes, assuming that 100 ms is sufficient time to direct attention in 3-D space.

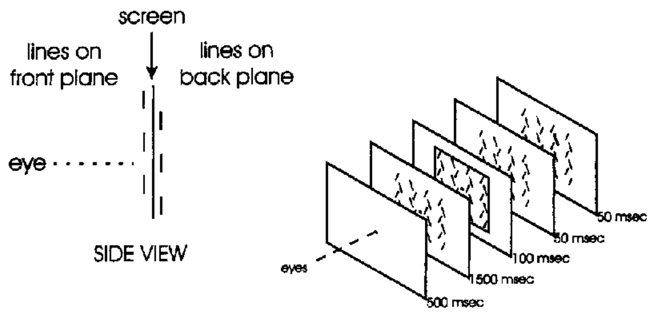

Figure 1. The right side of the figure shows a schematic diagram of the time course of the displays. The first, third, and fifth panels of lines appeared at the near depth. The second, fourth, and sixth panels appeared at the far depth relative to fixation. The outline rectangle (third frame) indicated the depth plane at which the target would appear with an 80% probability. On the left is an illustration of how the planes extend in depth.

The back plane was shifted 0.91° vertically to ensure that elements were not overlapping in x–y space (i.e., when looking at the display without seeing depth, it looks like a 4 × 6 matrix of 24 line elements). The binocular disparity between the depth planes was ±25′ of arc relative to the fusion display at which the fixation cross was presented. These values are near the maximum disparity separation possible without loss of fusion.[1]

Procedure. Participants were instructed to search for the red line element and indicate whether it was tilted to the right or the left by pressing the right or left mouse button. A tone sounded when an error was committed. Participants were told that the outline rectangle indicated with an 80% probability the depth plane at which the target line would appear. They were instructed to make use of that information to speed their responses. Both speed and accuracy were emphasized. After a block of 240 practice trials, participants performed one block of 240 experimental trials. In 192 trials the outline rectangle indicated the depth plane at which the red line would be presented (the cue-valid condition); in 48 trials the rectangle indicated the wrong depth plane (the cue-invalid condition). In half of the trials the red target line appeared in the frontal depth plane; in the other half of the trials it appeared in the back depth plane.

Results

Figure 2 shows the mean RT and error rates for the valid- and invalid-cue conditions for when the target appeared in the front (i.e., at crossed disparities) and back (i.e., at uncrossed disparities) depth planes. An analysis of variance (ANOVA) on RT with cue validity and depth plane (front or back) as factors showed a main effect of validity, $F(1, 7) = 11.9$, $p < .05$. As can be seen in Figure 2, participants responded faster when the target appeared at the cued depth plane than when it appeared at the uncued plane.

[1] A pilot experiment showed that with a binocular disparity of ±25′ of arc, trained observers (the authors) had no trouble fusing the two images. Observers reported having a clear perception of two separate planes extending in depth.

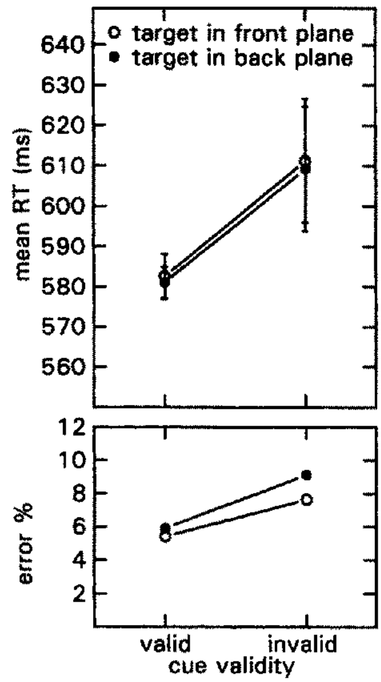

Figure 2. Experiment 1: Mean reaction times (RTs) and error percentages as a function of cue validity for the red line target in the front and back planes.

An ANOVA on error rates showed a main effect of validity, $F(1, 7) = 10.2$, $p < .05$. Consistent with RT, error rates were lower for the valid- than the invalid-cue trials.

Discussion

The results of this experiment are clear: Participants were faster and made fewer errors when the target line appeared at the cued depth plane then when it appeared at the uncued depth plane. These results provide strong evidence that participants can and did focus attention on the cued depth plane with our stimuli and experimental protocol. Although previous 3-D visual search results (e.g., He & Nakayama, 1995; Nakayama & Silverman, 1986) could be explained in terms of vergence eye shifts, the current setup with the short exposure duration ensured that the observed validity effects were caused by shifting of attention to a depth plane and not by vergence eye movements.

The absence of an interaction of cue validity with whether the target was in the front or back plane suggests that when attention is focused on a depth plane, it takes the same amount of time to shift from the back to the front plane as it takes to shift attention from the front to the back plane. This indicates that attention in three dimensions does not have a viewer-centered spatial distribution, at least with multielement visual search displays. Viewer-centered representations of attention have been reported by other researchers in focused-attention tasks with few objects (Andersen & Kramer, 1993) and in cuing tasks in which few objects appear in the display (Downing & Pinker, 1985; Gawryzewski et al., 1987). In these situations, either task-irrelevant distractors have been found to interfere more with target processing when they appear between the observer and the target than when they appear beyond the target, or participants are faster to respond when a target appears at an uncued location closer to rather than more distant from the cued location. However, other researchers have failed to find evidence for viewer-centered representations of attention in 3-D space (Andersen, 1990; Atchley, Kramer, Andersen, & Theeuwes, 1997; Hoffman & Mueller, 1994). The present results are consistent with the findings of this latter group of researchers.

Experiment 2

The results of Experiment 1 established that the current paradigm enables participants to effectively direct attention to a particular depth plane. As in Experiment 1, in Experiment 2 participants had to search for a color singleton (a red target element among green nontargets). Previous research has shown that search for a color singleton is efficient and can be conducted in parallel (Treisman & Gelade, 1980; Wolfe, 1994). In Experiment 2 we tested whether searching for a singleton within an attended (cued) depth plane would prevent attentional capture from an irrelevant singleton in another depth plane. Experiment 2 provided the most stringent test of this hypothesis because the to-be-ignored singleton from the other depth plane had the same color as the target presented at the cued depth plane. Unlike in Experiment 1, the line segments were now randomly tilted or vertical line segments. In Experiment 2, participants had to search for the tilted red line segment and ignore the vertical red line segment. In terms of bottom-up saliency and top-down activation toward the relevant color, the target singleton and the to-be-ignored singleton were equivalent. They differed only in terms of their orientation (i.e., the tilted red element was the target; the vertical red element was the distractor) and the depth plane on which they appeared.

Because all the line segments were randomly either vertical or tilted, participants should not have been able to use orientation information to effectively guide spatial attention. Previous research has shown that the discrimination of the orientation of a line segment in similar kinds of displays required serial search involving focal attention (e.g., Theeuwes, 1991b; Treisman & Gormican, 1988). Because this shape information is not available at an early preattentive level, orientation information cannot guide attention to the target. In fact, because the target and the distractor singleton had the same color and because orientation information should not have been effective in guiding attention, only depth information should have been available to guide attention to the target line segment. If participants can completely ignore the irrelevant singleton in the to-be-ignored (i.e., uncued) depth plane, then one would expect RT to the target to be the same as in the control condition in which there was no distracting singleton. In Experiment 1, we found that a depth cue with an 80% validity was sufficient for observers to focus attention on a specific depth plane. In the present study, we used a 100% valid depth cue to ensure that attention would be focused on a specific depth plane.

Method

Participants. Eight young adults (aged 18–31 years) participated in the experiment. Participants were screened for adequate stereo vision in the same manner as in Experiment 1.

Stimuli. The stimulus field was similar to that in Experiment 1 except that half the lines were randomly tilted and half were vertical. At stimulus onset, one of the green tilted lines turned red, constituting the target line, while one of the vertical green lines turned red, constituting the to-be-ignored distractor. Compared with Experiment 1, the tilted line segments were slightly more tilted (40°) to make the decision to respond "left" or "right" easier. The cue was 100% valid in that it indicated with absolute certainty the depth plane at which the target would appear.

Procedure. Participants were told that the cue was 100% valid and that they should use the cue to minimize RT. Again, participants indicated whether the red tilted line was tilted to the left or the right. There were three conditions: no distractor, distractor in the different depth plane, and distractor in the same depth plane. All conditions were run in separate blocks of 144 trials, with the order randomized among participants. During practice (144 trials), these conditions were randomized within one block of trials.

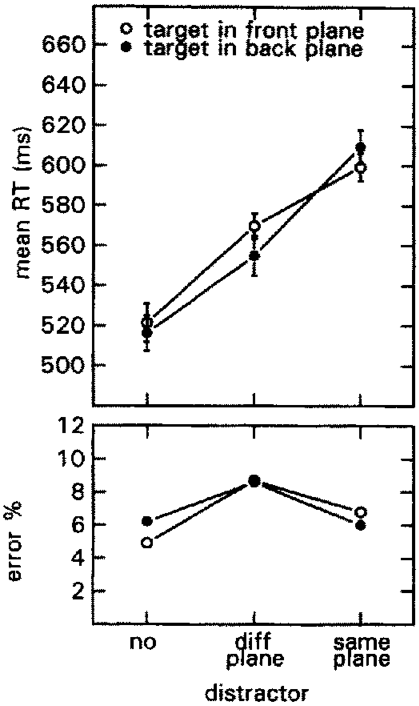

Figure 3. Experiment 2: Mean reaction times (RTs) and error percentages as a function of distractor condition (no distractor, distractor in a different depth plane, and distractor in the same depth plane) for the target in the front and back planes.

Results

An ANOVA on RT showed only a main effect for distractor condition (no distractor; distractor in a different depth plane; and distractor in the same depth plane), $F(2, 14) = 40.7$, $p < .001$. As can be seen in Figure 3, relative to the condition in which there was no distractor, a singleton distractor within a different depth plane significantly slowed search, $F(1, 7) = 16.49$, $p < .001$. However, a singleton distractor in a different plane caused significantly less interference than a singleton in the same depth plane, $F(1, 7) = 73.8$, $p < .001$. These results suggest that while participants are searching within an attended depth plane, singletons from another depth plane do interfere, but not as much as do singletons from the same depth plane. An ANOVA on error rates showed no statistically reliable effects, indicating that differences in response latencies were not attributable to speed–accuracy trade-offs.

Discussion

The results show that directing attention to a particular depth plane does not prevent attentional capture from a singleton presented at a nonattended depth plane. Furthermore, even when the depth plane was cued with 100% validity, as in the current experiment, and when the two depth planes were maximally separated within the limits of binocular fusion, the irrelevant singleton at the nonattended depth plane interfered with search. Because the target and the distractor singleton had the same color, only depth information could be used to guide attention selectively to the target line segment. Obviously, this cue was not sufficient to enable observers to completely filter out task-irrelevant information from the other depth plane. Note, however, that interference was not as great as when the irrelevant singleton was presented at the same depth plane as the target.

Again, there was no evidence that singleton distractors in front of the attended plane closer to the observer (i.e., attend to the back plane with the singleton distractor in the front plane) caused more interference than singletons in the depth plane behind the attended plane away from the observer. Like in Experiment 1, these findings argue against a viewer-centered distribution of attention in 3-D space in multielement displays.

Experiment 3

The results of Experiment 2 showed that directing attention to a particular depth plane cannot prevent attentional capture from a singleton presented in another depth plane. However, before we could conclude with certainty that observers cannot filter out information from the other depth plane, we had to ensure that observers were indeed focusing attention on the cued depth plane. Even though Experiment 1 clearly showed that observers did focus attention on the cued depth plane, it is possible that, depending on the distractor condition (which was blocked over trials in Experiment 2), observers changed the extent they were focusing on the cued depth plane. For example, the task in the control condition, in which only a target singleton was presented on the cued depth plane, could have been performed without the need for any depth information (e.g., observers could have closed one eye). If this was the case, then this condition would represent an inadequate control, invalidating the crucial comparison with the condition in which the distractor was presented in the different depth plane. To ensure that participants did focus their attention on the cued depth plane equally across control and distractor conditions, in Experiment 3 we presented the control and distractor conditions mixed within blocks of trials.

Finally, it was important to ensure that the naive observers used in these experiments were indeed fusing the displays. If participants are unable to fuse the displays and are unable to perceive two clearly separated depth planes, then it would not be surprising if there was interference from the singletons from the other depth plane. Before the start of the experiment, participants were asked whether they could clearly perceive two planes extending in depth.

There was another concern that may have invalidated our results. Because observers were set to detect the cue that was presented as an abrupt onset, observers were set to detect a "temporal discontinuity" (Folk et al., 1992). Consistent with the contingent capture hypothesis (Folk et al., 1992), which argues that attentional capture is contingent on the top-down control settings (i.e., in this case temporal discontinuity), the distractor may have captured attention because it represented a temporal discontinuity. Because target and distractor singletons were revealed by changing the green color of two of the premask elements into red, a dynamic luminance discontinuity did in fact occur because red had a luminance that was less than that of the green premask elements.

To ensure that there were no temporal luminance discontinuities when the target and distractor singletons were revealed, we presented red and green colors at equiluminant values. Previous research has shown that equiluminant color changes do not capture attention even when observers are set to look for it (Theeuwes, 1995b). If, however, observers could adopt an attentional set for a dynamic color change (i.e., a change of color without a change in luminance), then the distractor would still capture attention because it matched an attentional color setting to detect change. Although this is highly unlikely given that equiluminant color changes cannot be detected (Theeuwes, 1995b), we made sure that this could not occur anyway by changing the color of all elements except the target and distractor elements. In other words, the target and the distractor singletons were the only elements that did not change colors in the display.

Method

Participants. Eight young adults (aged 18–28 years) participated in the experiment. Participants were screened for adequate stereo vision in the same manner as in Experiment 1. Before the start of the experiment, participants were asked whether they could clearly perceive two planes extending in depth. All participants reported perceiving two separate depth planes, and none reported perceiving any double images, which suggests that observers were fusing the displays appropriately.

Stimuli. The stimulus field was similar to that used in Experiment 2 except that rather than changing the color of the target and the distractor singleton from green to red, we changed the color of all nontarget elements of the premask from red to an equiluminant green (3.1 cd/m^2). In this way, the only elements that did not change color were the target and the distractor singletons.

Procedure. The procedure was identical to that used in Experiment 2, except that the no-distractor condition, the condition with the distractor in a different depth plane, and the condition with the distractor in the same depth plane were presented in a randomized order within one block of 288 trials. There were short breaks after 96 trials. Participants were given 144 practice trials.

Results

An ANOVA on RT showed a main effect of distractor condition (no distractor; distractor in a different depth plane; distractor in the same depth plane), $F(2, 14) = 81.7$, $p < .001$. In addition, the interaction between distractor and target location (front vs. back plane) was also reliable, $F(2, 14) = 4.6$, $p < .05$. Even though the overall RTs were higher (see Figure 4), the RT pattern observed was similar to that found in Experiment 2: Relative to the control condition, a singleton distractor within a different depth plane significantly slowed search, $F(1, 7) = 49.0$, $p < .001$. However, a singleton distractor presented in a different depth plane caused significantly less interference than a singleton in the same depth plane, $F(1, 7) = 36.8$, $p < .001$. Note that the effect size (about 70 ms) was similar to that observed in Experiment 2 (about 80 ms). Even though the interaction reached significance, additional planned comparisons between the near and far depth planes for the control and different depth conditions were not reliable. An ANOVA on

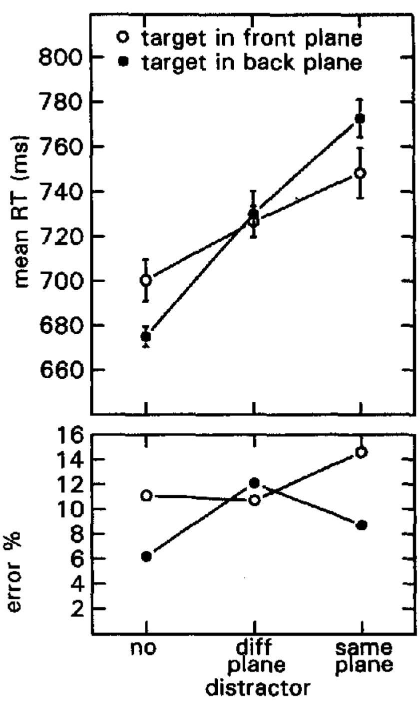

Figure 4. Experiment 3: Mean reaction times (RTs) and error percentages as a function of distractor condition (no distractor, distractor in a different [diff] depth plane, and distractor in the same depth plane) for the target in the front and back planes.

error rates showed no statistically reliable effects, indicating that differences in response latencies were not attributable to speed–accuracy trade-offs.

Discussion

The results of Experiment 3 are similar to those observed in Experiment 2: Directing attention to a particular depth plane could not prevent capture from a singleton from another depth plane. Because the control and distractor conditions were presented in mixed blocks, the possibility of differential attentional allocation strategies across conditions was minimized. In addition, because the distractor singleton was revealed without any abrupt (color or luminance) change, it was ensured that the presently observed capture of attention by the distractor in the nonattended depth plane was not attributable to an attentional set for dynamic discontinuities, as inferred from the contingent capture hypothesis of Folk et al. (1992).

Experiment 4

Experiments 2 and 3 provided stringent tests of whether it was possible to completely filter out information from a nonattended depth plane because the color that participants were looking for in the cued depth plane was the same as the color they had to ignore in the uncued depth plane. In Experiment 4 we tested whether it was possible to ignore a color singleton from the uncued depth plane when it had a color different from that of the target. In other words, in this experiment both color and depth information could guide attention to the target singleton. One group of participants searched among gray elements for a red target element while ignoring a green singleton presented either at a different depth plane or at the same depth plane as the target, and another group of participants searched for a green element and ignored the red element.

Method

Participants. Sixteen young adults (aged 19–27 years) participated in the experiment. All participants were screened with the same stereo vision test as had been used in the previous experiments.

Stimuli. The stimulus field was identical to that used in Experiment 2 except that the nontarget line segments were gray (4.2 cd/m^2). For half of the participants, the target line was red (2.8 cd/m^2) and the irrelevant singleton was green (2.8 cd/m^2), whereas for the other half this assignment was reversed. The group of participants searching for red was tested first, and approximately 4 months later the group searching for green was tested.

Procedure. The procedure was identical to that used in Experiment 2.

Results

An ANOVA performed on RTs with distractor and target location as a within-subject variable and target color as a between-subjects variable showed a main effect for color, $F(1, 14) = 12.8$, $p < .01$, and distractor condition, $F(2, 28) = 10.9$, $p < .05$. Because the interaction between color and distractor condition was not reliable ($F < 1$), we collapsed the data over color conditions. As can be seen in Figure 5, the irrelevant singleton in the uncued depth plane did not affect search for the singleton in the cued depth plane ($F < 1$). However, when this same singleton was presented within the same depth plane as the target singleton, it did slow search significantly, $F(1, 14) = 11.8$, $p < .01$. The main effect of color indicated that detecting a red element between gray lines was faster than detecting a green element between gray elements.

An ANOVA on the error rates also showed a main effect for color, $F(1, 14) = 8.3$, $p < .05$, indicating that it was easier to detect a red element between gray elements than a green element between gray elements. None of the other factors or any of the interactions was reliable.

Discussion

These findings suggest that directing attention to a particular depth plane can prevent the capture of attention by a singleton located at a different depth. When presented within the same depth plane as the target, the singleton in the other color caused interference. However, when the singleton in the other color was presented at a different depth plane, this interference was no longer observed, which suggests that when the attentional system is selectively tuned to one depth plane, singletons from another depth plane may be filtered out. Obviously, when both color and

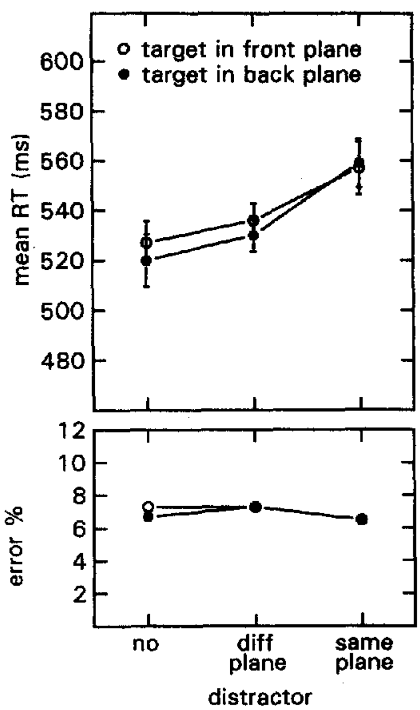

Figure 5. Experiment 4: Mean reaction times (RTs) and error percentages as a function of distractor condition (no distractor, distractor in a different [diff] depth plane, and distractor in the same depth plane) for the target in the front and back planes.

depth information can be used to guide attention, capture from an irrelevant singleton can be prevented.

It is important to note that the main effect of color suggests that detecting a red element between gray elements is easier than detecting a green element between gray elements. These findings suggest that red was more salient than green. However, because the main effect of color did not interact with the distractor location condition, these results suggest that observers are able to filter out information from the other depth plane even when the singleton in the other depth plane is more salient than the singleton in the attended depth plane.

There was no evidence for an asymmetry of attention in depth, consistent with the previous experiments. Thus, there appears to be little evidence for a viewer-centered representation of attention for multielement 3-D displays.

General Discussion

The present study addressed the question of whether directing attention to a particular plane in depth enables observers to filter out information from another depth plane. Experiment 1 established that directing attention to a particular depth plane is possible and that directing attention does provide processing speed benefits even when detecting singletons. Experiments 2 and 3 showed that when the color of the to-be-ignored singleton is the same as the color of the target, directing attention to a particular depth plane reduces but does not eliminate interference from the irrelevant singleton. In other words, pop-out from the color singleton did not occur only within the attended depth plane. Experiment 4 showed that when the color of target and distractor are different and presented at different depth planes, the task-irrelevant singleton in the other depth plane fails to capture attention.

One might have expected that in our studies participants would have adopted an attentional set to respond to a particular color (i.e., the color red) at a particular depth plane (i.e., the cued depth plane). Consistent with the contingent capture hypothesis (e.g., Folk et al., 1992), one would expect only stimuli that matched these top-down control settings to capture attention. This hypothesis predicts that only singletons at the cued depth plane and having the color of the target should capture attention. In other words, if attention can be set to a particular depth plane, one would not expect capture of attention by the singleton in the unattended depth plane, as was observed in Experiments 2 and 3. The contingent capture hypothesis also predicts that a singleton in a different color from the target at the same depth plane should not capture attention. However, as illustrated by the results obtained in Experiment 4, this was not the case. It seems that only when both target properties (i.e., both color and depth plane) are selective in signaling the target can capture by an irrelevant singleton be prevented. This suggests that focusing attention to a particular depth plane does not have the same special status as focusing attention in two dimensions (see Theeuwes, 1991a; Yantis & Jonides, 1990) because focusing attention on a particular depth plane does enable an observer to filter out information from other depth planes. In other words, unless attention is focused on a particular location in two dimensions, capture of attention by salient singletons can be prevented only when all target properties (i.e., color and depth plane) are selective in signaling the target. Similar results were reported recently by Theeuwes and Burger (1998); they showed that during visual search in two dimensions (in which attentional focusing to a location in two dimensions was not possible), attentional capture by salient singletons could be prevented only when participants know both the color they were searching for and the color of the singleton to ignore. Note, however, that Folk and Remington (1998) recently found that in addition to capture of attention, irrelevant singletons may also cause "filtering costs," which suggests that irrelevant color singletons may produce RT costs without causing an actual shift of spatial attention.

Models of visual search that assume that selection is the result of an interaction between goal-directed and stimulus-driven factors (Treisman & Sato, 1990; Wolfe, 1994) can predict the current results if it is assumed that depth information can be used as just another dimension that helps to segregate a target from distractors. Consistent with these models, it has to be assumed that depth information is available early in processing to allow top-down guidance of attentional selection. Our results suggest that only when both color and depth are selective in defining the target is search effective and not hindered by the presence of distractors. Thus, within the context of these visual search models, all elements within the cued depth plane receive a high activation, as would the elements that are the same color as the target. Obviously, because of "noise" within the selective attention system, a red object from the uncued depth plane might occasionally be erroneously selected. Along similar lines, in Experiment 4, an element in the wrong color but in the same depth plane might occasionally be selected, causing interference of the green element when it is located within the same depth plane as the target. The greater the number of feature dimensions available to help separate the target from the distractors, the less interference is observed.

If it is assumed that early in vision, color is detected preattentively and in parallel in specialized modules (e.g., Treisman & Gormican, 1988) independent of depth information, then it is to be expected that a singleton having the same color as the target in another depth plane would cause interference. However, this account would not predict an effect of cuing a depth plane, as we found in Experiment 1, because the detection of a singleton would proceed early in vision at a level at which depth information is not yet available. Also, if this notion is correct, it should be able to explain why the interference in Experiments 2 and 3 caused by the singleton at a different depth plane was less than the interference when this singleton was presented at the same depth plane. Consistent with this notion, it should also be able to explain why a different color did not cause any interference when presented at another depth plane but did cause interference when presented at the same depth plane (Experiment 4).

One way to conceptualize the results obtained in our experiments is to assume that early in vision, spatial attention is directed toward a particular plane in depth. Within the attended plane, search for the singleton proceeds in parallel. Directing the "attentional window" to a depth plane might gate information from this depth plane, thereby giving this information priority over information present in other depth planes (see also Theeuwes, Kramer, & Atchley, in press). Selective attention to a depth plane might inhibit inputs from all but the attended depth plane, in a way comparable to that described in the classic filter theories (e.g., Broadbent, 1958; Treisman, 1964). When the target is presented at the unattended (uncued) depth plane, as in our Experiment 1, it takes somewhat longer to respond because processing input from the uncued depth plane is attenuated. Also, when the to-be-ignored singleton having the same color as the target is presented at the uncued depth plane, as in our Experiment 2, its processing is also attenuated. Yet, when it is presented within the attended depth plane, little attenuation of the irrelevant singleton occurs because filtering by depth is not possible. Similar to the group scanning hypothesis (Treisman & Gormican, 1988), in order to exclude information from the uncued depth plane, within the master map of locations, attention may be pooled within the cued depth plane. Because information from the uncued depth plane is attenuated rather than eliminated, singletons from the uncued depth plane occasionally may capture attention.

In the current set of experiments, we addressed attentional selectivity between two different common depth planes. Recently, He and Nakayama (1995) pointed out that common surface rather than common depth is preferred in 3-D visual attention. In their experiments, it was shown that selective attention can be directed efficiently to any well-formed, perceptually distinguishable surface extending in depth. For an efficient allocation of attention, it was not necessary that all elements be at the same depth from the observer. It seems important to determine in future studies whether singleton distractors that are located at different depths from the target but on a common surface will interfere with target processing even when they are distinguishable from the target on other features. Such a result would suggest that surfaces that transcend in depth are searched in parallel.

It is important to note that in the current experiments there was no evidence for a viewer-centered representation of attention in depth, whereas researchers using a focused-attention task with only a few items present in the display reported that irrelevant distractors between the observer and the target interfered more than distractors that appeared beyond the target (e.g., Andersen, 1990; Andersen & Kramer, 1993; Gawryzewski et al., 1987). One possible way to reconcile these differences is to assume that focusing attention on a particular location in 3-D space invokes a viewer-centered representation, whereas spreading attention to an entire depth plane may invoke a "viewer-independent" 3-D representation. Focusing attention to a particular location in space may result in a representation in which the observer considers the attended location in space relative to himself or herself, resulting in the viewer-centered representation. In other words, because there is an attentional "anchor" point in space (i.e., a point at coordinates x, y, and z), the environment is represented relative to that point. However, when attention is spread across a particular depth plane, there cannot be a particular anchor point resulting in a 3-D representation of space. Note that these differences may be related to parallel and serial processing in visual space. If observers search serially through visual space, attention is assumed to move in a focused fashion serially through space, each time processing an object at a particular location in space. This type of search may result in a viewer-centered representation. However, when searching in parallel across visual space (as in our singleton detection task), attention is not set at a particular location, which results in a 3-D representation that is not viewer centered. If these speculations hold up, this would also imply that when people search in everyday life for a particular object in visual space by means of directed eye movements, they would have a viewer-centered representation, whereas when they just look at a scene without actually searching they would have a 3-D representation. These and other characteristics of attention in 3-D space should be addressed in future studies.

In summary, our results indicate that only when both color and depth information are selective in guiding attention to the target singleton can attentional capture by irrelevant singletons be prevented. The results suggest that retinal disparity does not have the same special status as location information in two dimensions and should be considered as just another feature along which selection may occur.

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