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When Is Search for a Static Target Among Dynamic Distractors Efficient?

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Intuitively, dynamic visual stimuli, such as moving objects or flashing lights, attract attention. Visual search tasks have revealed that dynamic targets among static distractors can indeed efficiently guide attention. The present study shows that the reverse case, a static target among dynamic distractors, allows for relatively efficient selection in certain but not all cases. A static target was relatively efficiently found among distractors that featured apparent motion, corroborating earlier findings. The important new finding was that static targets were equally easily found among distractors that blinked on and off continuously, even when each individual item blinked at a random rate. However, search for a static target was less efficient when distractors abruptly varied in luminance but did not completely disappear. The authors suggest that the division into the parvocellular pathway dealing with static visual information, on the one hand, and the magnocellular pathway common to motion and new object onset detection, on the other hand, allows for efficient filtering of dynamic and static information.

Keywords: attention, visual search, dynamic displays, motion, abrupt onset

From everyday experience, it is clear that dynamic properties of the visual world can guide people in directing their attention. Dynamic stimuli are characterized by transient changes in the visual pattern, such as those induced by motion and abrupt onsets. For example, when searching for a friend in a crowd, one is aided if that friend is waving a hand. Another example is provided by the flashing lights of ambulances, which are explicitly designed to attract attention and notify people of potential danger. It is exactly this detection of potential danger that has been thought to be the underlying reason why the visual system is so sensitive to dynamic information, because movement or abrupt appearances may signal the presence of a competitor or predator. Alternatively, for the predator, dynamic information may reveal something about the prey (see, e.g., Abrams & Christ, 2003; Hillstrom & Yantis, 1994; Tipper & Weaver, 1998, for arguments along these lines). In the present article, we focus on the complementary question, namely, whether, in a dynamic environment, attention can also be efficiently directed toward static objects.

Previous research has indeed confirmed that participants can efficiently detect a dynamic target among static distractors. Using a visual search task in which observers had to detect a moving target among static distractors, Hillstrom and Yantis (1994) and Yantis and Egeth (1999) found no effect of the number of distractors on search reaction times (RTs; i.e., search slopes were flat), indicating that the moving target could be found efficiently and in parallel across the displays used. Similarly, McLeod, Driver, and Crisp (1988) showed that when there is more than one moving item in the display, search is confined to the moving set, and the static set is effectively ignored. With standard moving stimuli, the transients are accompanied by a position change of the object. However, dynamic targets that do not change position also guide attention. For instance, looming targets among static distractors are efficiently found (Hillstrom & Yantis, 1994). This effect is probably related to motion, because the looming is perceived as a 3D movement toward the observer. It is interesting to note that Hillstrom and Yantis also reported efficient search for targets that remained at their locations but that were defined by a "scintillating" noise pattern, a characteristic that might not be so clearly associated with movement.

Another important dynamic property other than motion is the abrupt onset or appearance of an object. Watson and Humphreys (1995) found very efficient search when the target was always defined by an abrupt onset relative to a set of static distractors. Similarly, Watson and Humphreys (1997) later found that search can be restricted to a whole set of new onsets among a set of (at least by then) old static distractors. Both studies provided evidence that, when relevant, onset differences between stimuli can be used to effectively guide attention.

In sum, so far studies have shown that a dynamic stimulus is efficiently selected among static items. However, it is not clear whether the reverse case—a static target among dynamic distractors—allows for efficient detection too. McLeod et al. (1988) showed that a nonmoving item among moving items can be found independent of the number of moving distractors, although search was still somewhat less efficient than for a moving target among stationary distractors. This finding appears to suggest that a static item may indeed be efficiently found among dynamic items. However, it remains a question as to whether motion represents a special case in this scenario or whether static items in general can be efficiently discriminated from dynamic items. In a recent study, Theeuwes (2004) sought to explore this issue by presenting participants with a search task in which the target was always a static

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item (either a vertical or horizontal bar; the participant's task was to detect its orientation), whereas the distractors were all abruptly changing bars of various orientations. That is, in one condition, all distractor bars changed, in a single frame, from horizontal or vertical to either left or right oblique (by 45°; hence, after the change, the target was the only horizontal or vertical bar). In another condition, in addition to changing orientation, the distractors also disappeared from their old locations and abruptly reappeared randomly at new locations (hence, the target was also the only bar that kept its position and was not characterized by an abrupt new onset). The key finding was that search was much more efficient (as indicated by small or even absent set size effects) than in a control condition in which all items (including the distractors) were static. Theeuwes (2004) argued that the visual system calculates in parallel across the whole visual field whether an item is dynamic or static. Attention, then, does not prefer a dynamic item per se but the item that differs the most from its surroundings—in this case, the static item.

However, Theeuwes's (2004) explanation did not go by undisputed. Davis and Leow (2005) recently argued that it is actually not the distinction between dynamic and static that allows for efficient search but that motion is the crucial factor. They argued that Theeuwes's (2004) displays allowed for apparent motion to operate as the items changed from one orientation or position to the other. In line with McLeod et al.'s (1988) earlier results, then, a static among moving items may indeed have been efficiently found. In contrast, a static item among items with other dynamic features, like luminance changes or onsets, may not be found efficiently. In support of this suggestion, Davis and Leow (2005) found that search was highly inefficient for a static target among distractors that abruptly changed both color and luminance (without disappearing). Davis and Leow concluded that filtering on the basis of motion may have a special status, whereas filtering a single static item from a set of items carrying dynamic properties other than motion (such as abrupt luminance changes) may be very difficult.

There may be a good reason for why a static target allows for more efficient search among moving distractors than among abrupt onset distractors. Although there is substantial evidence that the automatic capture is contingent on stimulus-specific or display-wide attentional settings (e.g., Folk, Remington, & Johnston, 1992; Gibson & Kelsey, 1998), there is also evidence that abrupt onsets automatically capture attention even when they are not relevant to the observer (e.g., Jonides, 1981; Remington, Johnston, & Yantis, 1992; Theeuwes, 1991; Todd & Van Gelder, 1979; Yantis & Jonides, 1984). In a classic example, Yantis and Jonides (1984) presented participants with a varying number of items. After 1,000 ms, parts of the items were switched off, revealing the to-be-searched letters. Simultaneously with these offsets, one new item appeared through an abrupt onset. The abrupt onset was not predictive of the target, yet Yantis and Jonides (1984) found search to be very efficient when the target was the new onset (as indicated by flat search slopes) compared with when it was one of the previewed items. Yantis and Jonides (1984) therefore concluded that onsets capture attention and do so automatically. Important for the present discussion is the finding that when the very same paradigm is applied to motion (i.e., one of the items is moving—occasionally the target), search slopes are not flat when the target is the only moving item in the display, indicating that motion per se does not capture attention automatically (Hillstrom & Yantis, 1994; Yantis & Egeth, 1999; note that Franconeri & Simons, 2003, reported some capture for moving stimuli, but Abrams & Christ, 2003, have argued that it is actually the motion onset that captures attention, not motion per se). The difference in the ability or strength with which motion and abrupt onset stimuli can capture attention may explain why one allows for more efficient search of a static target than the other: Moving distractors may be effectively ignored, whereas abruptly onsetting distractors may automatically capture attention, making search for the static target more difficult.

In the present article, we present six experiments following up on Theeuwes's (2004) results. We investigated whether his finding that a single nonchanging item can be easily found is indeed best explained by a motion filter, as Davis and Leow (2005) suggested, or whether there is also support for the idea that static items can be efficiently detected in dynamic displays in general. To this end, we introduced dynamic displays in which the distractors would abruptly blink on and off in a continuous cycle without changing orientation or position. We argued that this should minimize the apparent motion in the displays and therefore allow for a more stringent test of the hypothesis that static targets can guide attention among dynamic items. This blinking condition was then compared with an apparent motion condition in which the distractors did change orientation (comparable with Theeuwes's, 2004, original displays) and with a control condition in which all items were static. If only motion allows for efficient segmentation of target and distractors, then we should find an improvement relative to the control condition only for the apparent motion condition. However, if we find an equal improvement in the blinking condition, then this lends support to the idea that, more generally, static items can be efficiently detected among dynamic items.

A similar manipulation was recently reported by Pashler (2001). In his visual search task, two sets of items were presented, one red, the other green. Participants were instructed to search one set (e.g., the red one), which would remain static throughout the trial. It is important to note that when search started, the other set (e.g., green) could also remain static, or it could start blinking, as it continuously disappeared and reappeared throughout the trial. Pashler (2001) expected that search in the latter condition might be more difficult, because the continuous blinking was likely to capture attention away from the relevant set. To his surprise, he found that overall RTs in the blinking condition were somewhat faster, indicating that observers could make use of the differences in dynamics to detect the static target. However, there may be a number of caveats in Pashler's (2001) study. First, in the blinking condition of his first two experiments, all dynamic distractors blinked on and off in synchrony. This may have allowed for strong temporal grouping between blinking elements, allowing for them to be efficiently rejected as a single set (Alais, Blake, & Lee, 1998; Blake & Yang, 1997; Lee & Blake, 1999; Leonards, Singer, & Fahle, 1996; Usher & Donnelly, 1998). This grouping may have been further strengthened by the fact that Pashler (2001) used different colors for the static and dynamic sets. In a third experiment, Pashler (2001) abandoned the synchrony and made the dynamic items appear and disappear at random (within constraints). Unfortunately, the results were unclear. There was some RT benefit in the dynamic condition, but it was relatively small, limited to target absent trials, and moreover accompanied by increased errors on target present trials. Note also that Pashler

(2001) did not vary set size, thus performance could only be measured in terms of overall RTs and not in terms of search slopes (reflecting search efficiency). This leaves open the possibility that search efficiency may actually have benefited substantially from the differences in dynamics but that observers needed some time to perform the initial segmentation (leading to increased overall RTs; i.e., a slope effect vs. an intercept effect, respectively). In the present experiments, we controlled for these and several other factors. We consistently find that a static target is efficiently detected among continuously blinking distractors. Contrary to Davis and Leow (2005), we concluded that efficient search for a static among dynamic items is not limited to motion displays. In a final experiment, we investigated how our results and Davis and Leow's results can be reconciled.

Experiment 1: Efficient Search for a Static Target Among Blinking Distractors

In Experiment 1, participants searched for a static horizontal or vertical line segment among tilted distractors (see Figure 1). In the control condition, all distractors were static. We presented participants with two dynamic conditions. In the apparent motion condition, they searched for a static item among items that abruptly flipped back and forth between two orientations, in a continuous cycle. In the blinking condition, they searched for a static item among items that continuously blinked on and off (at the same frequencies as the flipping in the apparent motion condition). We used four different frequencies and two different phases within each frequency, so that the distractors would not all flip or blink at the same time. If the hypothesis that static items in general can guide attention is correct, then we expected efficient search slopes for both the blinking as well as the apparent motion condition. If, on the other hand, motion represents a special case in allowing for efficient guidance of attention by static items, we would only see efficient search in the apparent motion condition.

Method

Participants. Six participants, ranging in age from 21 to 31 years ($M =$ 24.5 years), took part as paid (7€ per hour) volunteers. All participants completed all of the conditions. All had normal or corrected-to-normal vision.

Apparatus and stimuli. The experiment was conducted on a computer with a Pentium IV processor, a 17-in. monitor, and a standard QWERTY keyboard. The software package E-Prime (Psychology Software Tools,

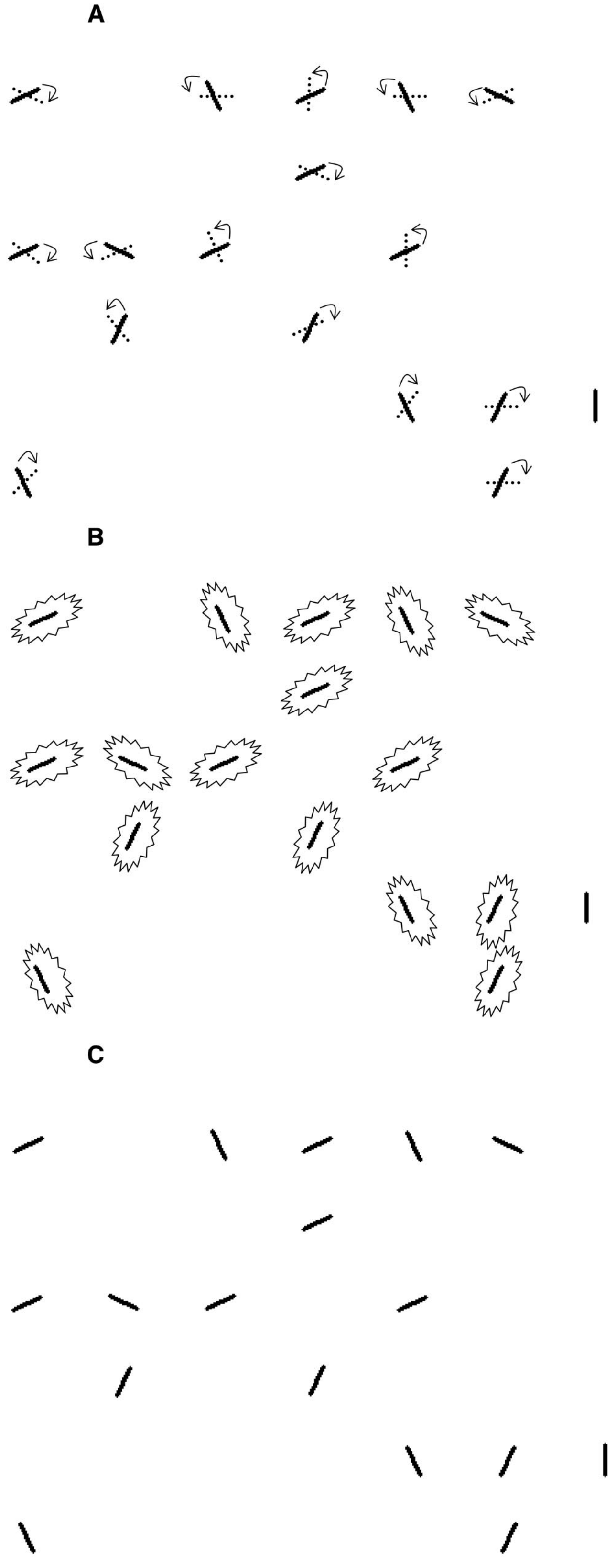

Figure 1. Typical examples of the search displays used in the present study. Participants searched for a static vertical or horizontal line segment among slightly tilted line segments. In the actual experiments, the line segments were white, and the background was black (A). In the apparent motion condition, the tilted lines flipped back and forth between its original orientation and a 45° arc deviation from this position (in either direction, as indicated by the arrows). The tilted lines flipped at a rate evenly distributed over four frequency groups: Each cycle lasted 150, 200, 250, or 300 ms. In each frequency group, half of the lines flipped in phase, and the other half flipped in counterphase (B). In the blinking condition, the tilted lines switched off and on at the same frequencies and phases as in the apparent motion condition, but they did not change orientation (C). In the control condition, all line segments remained static.

Table 1

Average Error Percentages for the Different Conditions and the Different Set Sizes of Experiments 1–6

Experiment and condition	Set size 9	17	33
1			
Control	5.58	7.30	10.26
Apparent motion	3.20	4.10	4.44
Blink	3.55	3.90	5.33
2			
Control	0.56	0.43	0.74
Apparent motion	2.33	1.75	1.44
Blink	1.90	2.22	1.73
3			
Control	3.05	3.39	6.92
Random blink	4.10	3.01	4.25
Standard blink	4.26	2.15	3.12
4			
Control	3.73	4.71	3.38
Blink	2.68	0.68	3.76
Apparent motion	3.00	3.33	2.69
5			
Control	1.22	1.79	3.06
All blink	2.22	1.98	6.25
Standard blink	4.04	2.09	3.23
6			
Control	3.99	4.32	7.33
Twinkle	4.54	5.47	4.66
Bright blink	4.52	3.82	4.30
Dark blink	5.19	4.92	3.75

Pittsburgh, PA) was used for the layout and timing of the experimental trials. The stimulus field consisted of a 7 × 6 imaginary matrix (12.68° × 8.26° visual angle). In its cells, white line segments (Commission Internationale de l'Eclairage [CIE] x, y coordinates: .283, .301, respectively) of size 0.76° were randomly placed. The distractors could appear anywhere on the 7 × 6 matrix, and the target could appear anywhere except in the middle (row 4 or columns 3 or 4). The luminance of the line segments was 65.62 cd/m^2, and the background was 0 cd/m^2, as measured with a Tektronix photometer. In each display, there was a vertical or horizontal white line target among white lines that were tilted 22.5° to either side of the horizontal or vertical.

Procedure. Participants sat at approximately 90 cm from the monitor, with their fingers resting on the *z* and *m* keys, which were used as the response buttons. The experiment consisted of 15 blocks, each containing 90 trials. The order of the blocks was repeated every three blocks and was counterbalanced across the participants. Each sequence of three blocks corresponded to three main conditions: In the apparent motion condition, participants looked for a static horizontal or vertical white line among tilted white lines that flipped back and forth between its original orientation and a 45° arc deviation from this position (in either direction). The tilted lines flipped at a rate evenly distributed over four frequency groups: each cycle lasted 150, 200, 250, or 300 ms. In each frequency group, half of the lines flipped in phase and the other half flipped in counterphase. In the blinking condition, participants looked for a static horizontal or vertical white line among blinking tilted white lines. This means that the tilted lines switched off and on at the same frequencies and phases as in the apparent motion condition, but they did not change orientation. In the control condition, participants looked for a static horizontal or vertical white line among static tilted white lines. In all conditions, set sizes varied randomly within a block, among 9, 17, and 33 (i.e., 8, 16, or 32 distractors plus one target). The task was to determine the orientation of the target element. Participants pressed *z* for vertical lines and *m* for horizontal lines. The task was assumed to require focal attention to be directed to the target element. Before every block, text appeared on the screen instructing the participants which condition followed, either *apparent motion*, *blinking*, or *control*. Participants were instructed that both speed and accuracy were important. The first three blocks were disregarded as practice. The other 12 blocks were included in the analyses. The experiment took approximately 120 min, with breaks between the blocks.

Results

Error percentages were overall low (see Table 1), and an analysis of variance (ANOVA) revealed no significant effects. We therefore concentrated on the mean RTs of the correct trials.

Trials on which RTs were two and a half standard deviations away from the mean were excluded from analysis, resulting in a loss of approximately 4% of the trials. See Figure 2 for a graphical depiction of the findings. A two-way ANOVA on mean RT for each participant, with condition (control, apparent motion, or blinking) and set size (9, 17, or 33) as factors, revealed a main effect for condition, as RTs were elevated in the control condition compared with the apparent motion and blinking conditions, $F(2, 10) = 22.02$, $MSE = 101{,}194.86$, $p < .001$, and a main effect for set size, as RTs increased with set size, $F(2, 10) = 19.03$, $MSE = 58{,}566.74$, $p < .001$. There was also a significant interaction reflecting the steeper search slope in the control condition compared with the apparent motion and blinking conditions, $F(4, 20) = 15.74$, $MSE = 12{,}014.35$, $p < .001$. Equivalent overall effects were present throughout all subsequent experiments and will not be reported on further. Instead, we concentrated on the separate comparisons between conditions. These revealed that RTs were faster and search slopes were shallower in both the apparent motion condition and the blinking condition than in the control condition: effects of condition, $F(1, 5) = 26.02$, $MSE = 128{,}794.84$, $p < .005$; $F(1, 5) = 19.55$, $MSE = 170{,}617.65$, $p < .01$; and Condition × Set Size, $F(2, 10) = 17.72$, $MSE = 14{,}935.69$, $p = .001$; $F(2, 10) = 15.34$, $MSE = 19{,}629.03$, $p = .001$, respectively. It is important to note that there was no difference in RTs, or in search slopes, between the blinking condition and the apparent motion condition (all ps $> .40$).

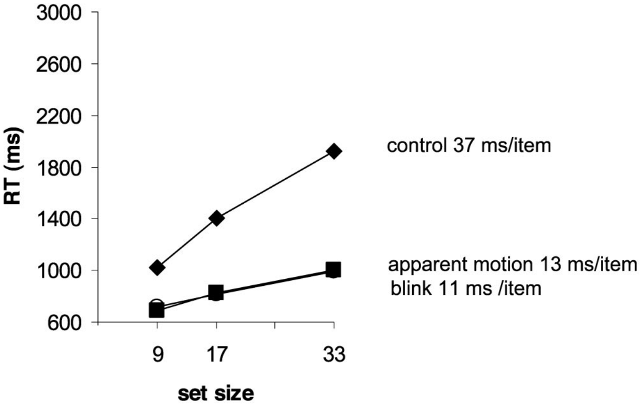

Figure 2. Mean reaction times (RT) for each condition of Experiment 1 (control, apparent motion, and blink) as a function of set size. For each condition, the mean search slopes are provided.

Discussion

Experiment 1 shows that participants are equally efficient in detecting a static target among moving items as in detecting a static target among blinking items. This is not in accordance with Davis and Leow's (2005) explanation that a static target can only be rapidly found among moving items. Instead, it provides evidence for Theeuwes's (2004) original account that in general a static target can be found efficiently among dynamic items. It also corroborates and extends Pashler's (2001) earlier findings of faster overall RTs when half the distractors are blinking synchronously. Relatively efficient search in the blinking condition is more surprising, given the evidence reviewed in the introduction that abrupt onsets capture attention automatically. In the blinking condition, the static target was present among up to 32 distractors continuously blinking on and off at various rates. This constant multitude of abrupt onsets should have prevented observers from quickly finding the target. We will return to this issue in the General Discussion. Before that, we need to exclude several alternative explanations of our findings. A first alternative explanation may be based on the average luminance level across display frames within a trial and was tested in Experiment 2.

Experiment 2: Controlling for Average Luminance Level

In Experiment 2, we investigated the possibility that it was the average luminance of the target that causes efficient search in the blinking condition in Experiment 1. Note that across the changing frames of the blinking condition, the static target (which is always on) has a higher average luminance than the surrounding dynamic distractors, because the latter are switched off on half the number of frames. Furthermore, there is evidence that luminance is perceived differently shortly after stimulus onsets and offsets (Eagleman, Jacobson, & Sejnowski, 2004). This may have enabled participants to efficiently search for an overall luminance difference instead of for a static item among dynamic items. To control for this, in Experiment 2, we varied the luminance of all elements randomly. The luminance of the target varied between 25% and 62.5% of the maximum; the luminance of the distractors, when on screen, varied between 25% and 100% of the maximum. Therefore, the average luminance of the distractors across frames varied between 11.25% and 50% of the maximum, assuring that neither the average luminance of the target, which on most trials was lower than 50% of the maximum, nor the momentary luminance of the target within each frame, which was exactly in between that of the distractors present, could provide a reliable clue for search. If average luminance is the cause of the relatively efficient search for a static among blinking items, then the more efficient search in the blinking condition compared with the control condition should no longer be possible in Experiment 2. In contrast, relatively efficient search in the apparent motion condition should still be possible. If it does not play any role in causing the relatively efficient search of a static among on- and offsets, then the search slopes in the apparent motion and blinking conditions should remain similar, as was the case in Experiment 1.

Method

Six new participants, ranging in age from 21 to 25 years (M = 24.3 years), took part as paid (7€ per hour) volunteers. Everything was identical to Experiment 1, except that now the luminance of the target element varied randomly between 16.32 cd/m^2 (CIE x, y coordinates = .290, .300, respectively) and 41.04 cd/m^2 (CIE x, y coordinates = .282, .300, respectively); the luminance of the distractor elements randomly varied between 16.32 cd/m^2 (CIE x, y coordinates = .290, .300, respectively) and 65.62 cd/m^2 (CIE x, y coordinates = .283, .301, respectively). Thus, the target had a luminance between 25% and 62.5%, and the distractors had a luminance between 25% and 100% of the maximum luminance. This was to assure that neither average luminance across frames nor momentary luminance within each frame was a reliable clue for target search.

Results

Error percentages were overall low, as can be seen in Table 1. However a two-way ANOVA, with condition (control, apparent motion, or blinking) and set size (9, 17, or 33) as factors, revealed a main effect for condition, $F(2, 10) = 6.73$, $MSE = 1.53$, $p < .05$, but no effect for set size nor for the interaction (ps > .7). Overall, fewer errors were made in the control condition than in the dynamic conditions. However, there was no effect on error slopes, and most important there was no difference between the apparent motion and blinking conditions (all ps > .7). We therefore concentrated on RTs.

Trials on which RTs were two and a half standard deviations away from the mean were excluded from analysis, resulting in a loss of approximately 3% of the trials. Figure 3 shows a graphical depiction of the results, which were analyzed in the same way as in Experiment 1. Separate comparisons between the conditions revealed that RTs were faster and search slopes were shallower in both the apparent motion condition and the blinking condition than in the control condition: condition, $F(1, 5) = 18.91$, $MSE = 312{,}377.36$, $p < .01$; $F(1, 5) = 19.16$, $MSE = 351{,}068.71$, $p < .01$; and Condition × Set Size, $F(2, 10) = 21.61$, $MSE = 25{,}522.36$, $p < .001$; $F(2, 10) = 16.75$, $MSE = 42{,}762.39$, $p = .001$, respectively. It is important to note that there were no differences in RTs or slopes between the blinking condition and the apparent motion condition (all ps > .10). If anything, there was a trend for participants to be faster in the blinking condition than in the apparent motion condition.

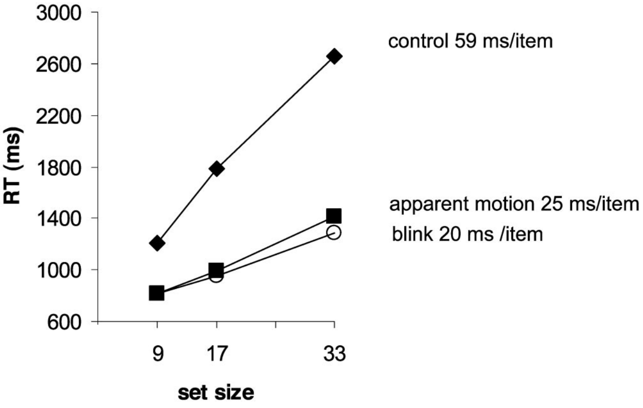

Figure 3. Mean reaction times (RT) for each condition of Experiment 2 (control, apparent motion, and blink) as a function of set size. For each condition, the mean search slopes are provided.

Discussion

The results were essentially the same as in Experiment 1 and unaffected by the luminance differences. We therefore dismiss the notion of average or temporary luminance uniqueness as a cause of the relatively efficient search of a static target among blinking distractors. Note, however, that overall, search slopes were a bit increased compared with Experiment 1, but this affected all conditions in the same way. Thus, the variable luminance of target and distractor elements made search a little more difficult in general, without affecting the ability to efficiently segment static from dynamic items.

Experiment 3: Controlling for Long-Range Apparent Motion and Temporal Grouping

In Experiment 3, we assessed the possibility that apparent motion might still provide an explanation for the relatively efficient search of the static target surrounded by on- and offsets. In both Experiments 1 and 2, the distractors of the blinking condition were evenly distributed over four frequency groups, and within each frequency group, half the lines were in phase and the other half were in counterphase. This may have permitted for long-range apparent motion to occur (Burt & Sperling, 1981): If two lines were in the same frequency group but in counterphase, it could appear that one line was jumping back and forth between two positions. Although this should have been much weaker than in the actual apparent motion condition, it may just have been sufficient for the relatively efficient search found in the blinking condition. To determine whether this long-range apparent motion is the explanation of the relatively efficient search in the blinking condition, in Experiment 3, we added a random blinking condition. Instead of at a fixed frequency, in the random blinking condition, all blinking elements switched on and off randomly. All blinking lines had an equal chance of switching (turning from on to off or vice versa) after 150 ms, 200 ms, 250 ms, or 300 ms. How much time it took before the previous switch occurred did not affect chances for when the current switch would occur. Consequently, in the random blinking condition, the odds are much smaller that at any given moment two elements are in counterphase at the same frequency, and long-range apparent motion therefore is unlikely to occur. If long-range apparent motion is part of the explanation of why a static target is relatively efficiently found among blinking distractors, then it is expected that in this experiment, search in the random blinking condition will not be as efficient as search in the standard blinking condition.

In addition to acting as a control for long-range apparent motion, the random blinking condition also allowed us to investigate whether temporal grouping contributes to the relatively efficient search of the static target among blinking distractors. In Experiments 1 and 2, the blinking distractors changed at either one of four frequencies. It may have been the case that items that shared a frequency were grouped together. Because there were four frequencies, observers may have always distinguished four distractor groups, regardless of whether the distractor set consisted of 8, 16, or 32 items (resulting in four temporal groups of 2, 4, or 8 items, respectively). Relatively efficient rejection of these temporal groups as a whole would then result in relatively efficient search. Evidence that observers are able to use temporal differences to group certain stimuli and segment them from others comes from a study by Lee and Blake (1999; see also Alais, Blake, & Lee, 1998; Blake & Yang, 1997; Leonards, Singer, & Fahle, 1996; Usher & Donnelly, 1998). In their displays, all items moved in random directions, and most items changed direction at random moments in time. However, one spatially contiguous patch of items always changed direction at the same moment. Even though the direction in which they changed was still random, the fact that these items changed together was sufficient for them to be perceived as segmented from the background elements. Lee and Blake (1999) concluded that synchrony per se is a strong segmentation cue. Note that in our displays, the synchronously blinking items were usually not spatially contiguous—a factor that has been shown to weaken grouping by synchrony (Fahle & Koch, 1995; Forte, Hogben, & Ross, 1999; Kiper, Gegenfurter, & Movshon, 1996). Nevertheless, it seemed prudent to control for this factor. In the random blinking condition of the present experiment, there were no frequency groups, and temporal grouping of the distractors could no longer contribute to efficient search. Consequently, if temporal grouping of the distractors caused relatively efficient search of the static target in the dynamic displays used in Experiments 1 and 2, relatively efficient search is no longer expected in the random blinking condition in Experiment 3.

Method

Twelve participants, ranging in age from 20 to 30 years ($M = 23.7$ years), took part as paid (7€ per hour) volunteers. This experiment was identical to Experiment 1, except now there was a random blinking condition instead of the apparent motion condition. In the random blinking condition, the tilted elements all stayed on the screen for a random period between 150 and 300 ms. Every tilted element had a chance of 25% to switch on or off after 150 ms, 200 ms, 250 ms, and 300 ms. Previous switching time did not affect following switching times. The experiment consisted of 9 blocks of 90 trials. The order of the blocks was repeated every three blocks and was counterbalanced across participants. The first three blocks were regarded as practice.

Results

Error percentages were overall low (see Table 1), and an ANOVA, with condition and set size as factors, only revealed a significant effect for set size, $F(2, 22) = 3.64$, $MSE = 9.04$, $p < .05$. We concentrated on the mean RTs of the correct trials.

Trials on which RTs were two and a half standard deviations away from the mean were excluded from analysis, resulting in a loss of less than 3% of the trials. See Figure 4 for a graphical depiction of the findings. The results were analyzed in the same way as in the previous experiments. Separate comparisons between the conditions revealed that RTs were faster and search slopes were shallower in both the random blinking condition and the standard blinking condition than in the control condition: condition, $F(1, 11) = 60.10$, $MSE = 158{,}449.59$, $p < .001$; $F(1, 11) = 75.07$, $MSE = 118{,}051.12$, $p < .001$; and Condition × Set Size, $F(2, 22) = 28.60$, $MSE = 29{,}929.91$, $p < .001$; $F(2, 22) = 29.30$, $MSE = 21{,}412.60$, $p < .001$, respectively. Furthermore, the search slope in the random blinking condition was somewhat shallower than the search slope in the standard blinking condition (11.9 ms per item compared with 16.3 ms per item): Condition × Set Size, $F(2, 22) = 4.26$, $MSE = 4{,}206.86$, $p < .05$.

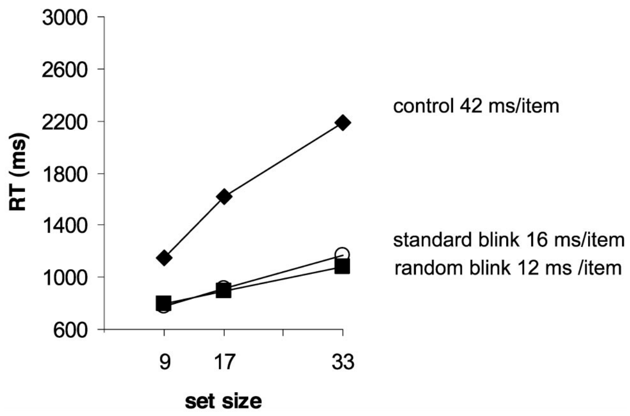

Figure 4. Mean reaction times (RT) for each condition of Experiment 3 (control, standard blink, and random blink) as a function of set size. For each condition, the mean search slopes are provided.

Discussion

We found that participants were neither slower nor less efficient in the random blinking than in the standard blinking condition. There may have been some long-range apparent motion in the standard blinking conditions of Experiments 1 to 3, but if there was, it should have been reduced substantially in the present random blinking condition. If long-range apparent motion was a major contributor to the relatively efficient search of a static among dynamic items, we should therefore have found increased slopes in the random blinking condition. However, if anything, we found slightly (but significantly) decreased slopes. Therefore, the findings from Experiment 3 imply that long-range apparent motion does not contribute to the relatively efficient search for a static element among on- and offsets.

Another account tested in Experiment 3 was temporal grouping. It could be argued that four temporal groups of distractors were created in Experiments 1 and 2 and that this caused the relatively efficient search for the static among dynamic items. In the random blinking condition, temporal synchrony between any of the distractors was eliminated, yet relatively efficient search for the static target was still observed. We concluded that temporal grouping of the distractors cannot be the cause of the relatively efficient search for a static target among dynamic distractors. Instead, we proposed the fact that it is static grants the target a unique status among the dynamic distractors, resulting in relatively efficient search.

Experiment 4: Search for a Static Target Without Preknowledge

Because in all previous experiments conditions were blocked and participants knew beforehand whether the distractors were dynamic or static, it could well be that the top-down expectations of participants influenced the efficiency with which they selected a static target among dynamic items. To assess this possibility, in the present experiment, we randomly mixed all conditions. The target was static, whereas the distractors could undergo apparent motion, blink, or remain static as well. Because conditions appeared in random order, participants did not know beforehand what kind of distractors they would be presented with. If preknowledge is crucial for the relatively efficient search of a static target among dynamic distractors, it is expected that this search is no longer efficient in this experiment.

Method

Ten participants, ranging in age from 18 to 27 years ($M = 20.7$ years), took part as paid (7€ per hour) volunteers. The apparatus, stimuli, and procedure were the same as in Experiment 3, except for the following changes. There were three conditions: the control condition, the blinking condition, and the apparent motion condition. The control condition and the blinking condition were the same as the control condition and the random blinking condition, respectively, in Experiment 3. The apparent motion condition was the same as the apparent motion condition in Experiment 1, except now the items moved at random rather than at a given frequency. The tilted elements stayed in one orientation for a random period between 150 and 300 ms. Every tilted element had a chance of 25% to flip 45° arc deviation from its current orientation (in either direction) after 150 ms, 200 ms, 250 ms, and 300 ms. Previous switching time did not affect following switching times. The experiment consisted of five blocks, and one block consisted of 90 trials. Within one block, all conditions were randomly mixed. The first two blocks were disregarded as practice.

Results

Error percentages were overall low, as can be seen in Table 1. A two-way ANOVA, with condition (control, apparent motion, or blinking) and set size (9, 17, or 33) as factors, revealed no significant effects. Therefore, we concentrated on RTs.

Trials on which RTs were two and a half standard deviations away from the mean were excluded from analysis, resulting in a loss of less than 4% of the trials. Figure 5 shows a graphical depiction of the results, which were analyzed in the same way as in the previous experiments. Separate comparisons between the conditions revealed that RTs were faster and search slopes were shallower in both the apparent motion condition and the blinking condition than in the control condition: condition, $F(1, 9) = 33.37$, $MSE = 163{,}180.86$, $p < .001$; $F(1, 9) = 38.22$, $MSE = 236{,}706.26$, $p < .001$; and Condition × Set Size, $F(2, 18) = 33.27$, $MSE = 33{,}206.08$, $p < .001$; $F(2, 18) = 30.34$, $MSE = 52{,}100.45$, $p < .001$, respectively. Moreover, participants were faster and had

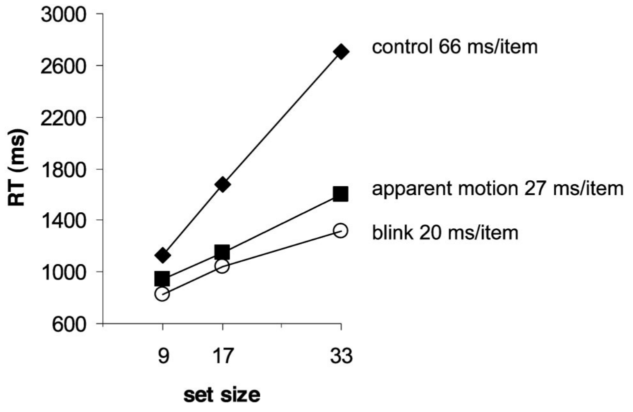

Figure 5. Mean reaction times (RT) for each condition of Experiment 4 (control, apparent motion, and blink) as a function of set size. For each condition, the mean search slopes are provided.

shallower search slopes in the blinking condition compared with the apparent motion condition: condition, $F(1, 9) = 42.31$, $MSE = 10{,}738.61$, $p < .001$, and Condition × Set Size, $F(2, 18) = 5.84$, $MSE = 9{,}188.81$, $p < .05$, respectively.

Discussion

The results of Experiment 4 were highly comparable with Experiments 1 and 2. Again participants were slower in the control condition than in the apparent motion condition and the blinking condition. Because in the current experiment, conditions were mixed, these results show that participants do not need to know before the start of the trial that the distractors are dynamic to use this information as a cue to search for the static target. Note that although the general pattern of results was the same, overall search slopes were increased compared with Experiment 1. Thus, the lack of preknowledge regarding the nature of the target made search a little more difficult in general, without affecting the ability to segment static from dynamic items.

In accordance with the trend observed in Experiment 2, we found participants to be slightly faster in the blinking condition than in the apparent motion condition. This tendency might be due to the fact that on- and offsets provide a stronger dynamic cue than movement. We will elaborate on this in the General Discussion.

Experiment 5: Search for a Dynamic Target Among Dynamic Distractors

There is the possibility that there is nothing special about static items. A static among dynamic items may be unique in the sense that it changes at an infinitely slow frequency, but perhaps observers can efficiently direct their attention at any unique frequency. To test this possibility, we introduced the all blinking condition in which not only the distractors blink on and off but the target does too—at a unique frequency. Furthermore, there were three versions of this condition, presented in separate blocks. In the slow blinking target condition, the target would show the lowest blinking rate of all items in the display. In the medium blinking target condition, the target blinked at a frequency in between the frequencies of the distractors. In the fast blinking target condition, the target blinked at the highest rate of all items. We included these different versions because previous evidence has indicated that the unique target feature may have to be linearly separable from the distractor features for efficient search to occur (Bauer, Jolicoeur, & Cowan, 1996; D'Zmura, 1991; Saumier & Arguin, 2003; Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992). Thus, efficient search for a unique frequency may occur for the low- and high-frequency targets (because they are linearly separable from the distractors) but not for the medium-frequency target. For the purpose of comparison, we also included a standard blinking condition in which only the distractors blinked (at frequencies matched to those in the all blinking conditions) and a control condition in which all items were static. If static targets have a special status, then we should only see efficient search in the standard blinking condition. If any unique frequency allows for the efficient search, then we should also find improved performance in the all blinking conditions compared with the control condition.

Method

Seven participants, ranging in age from 16 to 29 years ($M = 20.1$ years), took part as paid (7€ per hour)volunteers. There were seven conditions. Three all blinking conditions, three standard blinking conditions, and a control condition. In the slow blinking target condition, the target element switched on or off every 350 ms, and the tilted elements switched on or off every 150, 200, 250, or 300 ms. As in Experiments 1 and 2, the tilted elements were evenly distributed over frequency groups, and within one frequency group, half switched in phase and half switched in counterphase. The medium blinking target condition was the same as the slow blinking target condition, except that now the target switched on or off every 250 ms, and the distractors switched on or off every 150, 200, 300, or 350 ms. In the fast blinking target condition, the target switched on or off every 150 ms, and the distractors switched on or off every 200, 250, 300, or 350 ms. For comparison, there were also three standard conditions. In these conditions, the target was always static, but the distractors behaved in the same way as in the slow, medium, and fast blinking target conditions. Finally, the control condition was the same as the control condition in Experiments 1, 2 and 3, in which all items were static. Before every block, there appeared a text on the screen instructing the participants which of the seven conditions followed. The experiment consisted of five clusters of seven blocks, and each block consisted of 36 trials. The order of the blocks was the same within each cluster. The order was determined by a 7 × 7 Latin square design.

Results

Error percentages were overall low (see Table 1), and an ANOVA, with condition and set size as factors, revealed no significant effects. We therefore concentrated on the RTs.

Trials on which RTs were two and a half standard deviations away from the mean were excluded from analysis, resulting in a loss of less than 4% of the trials. See Figure 6 for a graphical depiction of the findings. First, we looked at whether there were any differences among the different versions of the all blinking conditions. A two-way ANOVA, with condition (slow, medium, or fast blinking target) and set size (9, 17, or 33) as factors, revealed a trend for a main effect for condition, $F(2, 12) = 3.36$, $MSE = 179{,}481.76$, $p = .07$. Participants tended to be overall somewhat faster in the slow blinking target condition. However, there was no interaction with set size, $F(4, 24) = 1.25$, $MSE = 95{,}323.25$, $p >$

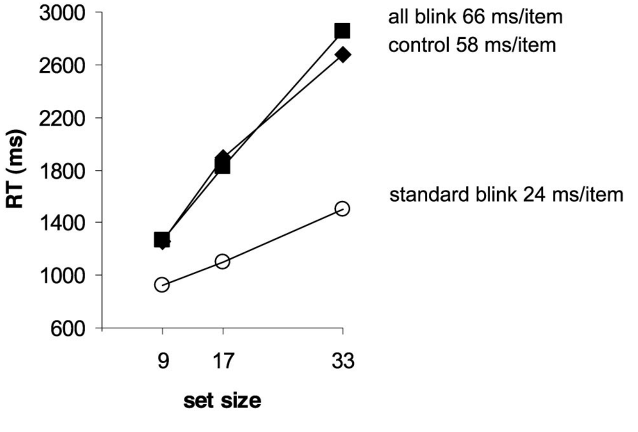

Figure 6. Mean reaction times (RT) for each condition of Experiment 5 (control, all blink, and standard blink) as a function of set size. For each condition, the mean search slopes are provided.

.3, indicating that search efficiency was very similar across these conditions. Therefore, we pooled the three versions of the all blinking conditions together. A similar analyses on the three versions of the standard blinking conditions (in which only the distractors blinked) revealed no main effect for condition, $F(2, 12) = 0.73$, $MSE = 22{,}709.42$, $p > .50$, but a marginally significant interaction of condition and set size, $F(4, 24) = 2.80$, $MSE = 7{,}069.59$, $p = .049$. Closer analyses revealed that search was somewhat less efficient when the distractors were blinking at the same rate as in the medium blinking target condition (28.8 ms/item vs. 20.9 ms/item and 23.0 ms/item, respectively, for the equivalent controls for the slow and fast blinking target conditions). Because of this difference, we also compared each of the slow, medium, and fast standard blinking conditions with their equivalent counterparts of the all blinking conditions. These pairwise comparisons revealed that observers were always faster and always more efficient when the target was static (standard blinking condition) compared with when it was blinking (all blinking condition; all ps $< .015$). Therefore, because all three standard blinking conditions appeared to behave in more or less the same way relative to the all blinking conditions, we decided to pool them together to form one standard blinking condition.

A two-way ANOVA, with these pooled conditions (all blinking, standard blinking, or control) and set size (9, 17, or 33) as factors, revealed a main effect for condition, as RTs were shortest in the standard blinking condition followed by the control and the all blinking conditions, $F(2, 12) = 18.20$, $MSE = 239{,}352.54$, $p < .001$, a main effect for set size, as RTs increased with increasing set size, $F(2, 12) = 25.37$, $MSE = 301{,}088.77$, $p < .001$, and a significant interaction, indicating shallower search slopes in the standard blinking condition than in the all blinking and control conditions, $F(4, 24) = 9.04$, $MSE = 58{,}809.39$, $p < .001$. Separate comparisons between the conditions revealed that RTs were faster and search slopes were shallower in the standard blinking condition compared with the control and with the all blinking condition: condition, $F(1, 6) = 23.58$, $MSE = 262{,}164.93$, $p < .005$; $F(1, 6) = 17.73$, $MSE = 387{,}533.10$, $p < .01$; and Condition × Set Size, $F(2, 12) = 6.90$, $MSE = 89{,}844.89$, $p < .05$; $F(2, 12) = 18.44$, $MSE = 49{,}712.61$, $p < .001$, respectively. RTs and search slopes did not differ significantly between the all blinking condition and the control condition (ps $> .24$).

Discussion

The results indicate that participants could not make use of the unique target frequencies when all items blinked, even when these frequencies were linearly separable from the distractor frequencies. This finding indicates that the unique frequency aided little to nothing. We concluded that it is not just any temporal difference that may guide attention but that it is specifically the target being static that allows for efficient search.

Of course, our results may heavily depend on the range of frequencies we have used. Perhaps the difference between the target frequency and the distractor frequencies in the all blinking conditions was simply not large enough? The fastest rate contained one blink every 150 ms (a frequency of 6.67 Hz), and the slowest rate contained one blink every 350 ms (a frequency of 2.86 Hz), with the other rates falling in between at steps of 50 ms. The problem is that if we would extend this range much further, the dynamic items become practically undistinguishable from static items. That is, if we made the rate much slower, then in its on period, an item is on for so long that it might be regarded as a static item. In this respect, we were especially careful not to let items be on for longer than one would normally expect observers to start generating a response (i.e., around 400 ms). If we would make the rate much faster, then subsequent frames will be merged into a single percept, again making it virtually static. In this respect, we were careful not to choose a frequency at which the blinking object might be perceptually treated as one and the same object across frames (i.e., faster than once every 100 ms; Yantis & Gibson, 1994), a point to which we will return in the General Discussion. Finally, psychophysical studies have shown that observers are quite sensitive to frequency and phase differences below 10 Hz (as used in the present study), with relative difference thresholds of around 0.1 (Mandler, 1984; Mowbray & Gebhard, 1955; see also Forte, Hogben, & Ross, 1999). This means that observers should be able to distinguish the 50-ms differences between rates. Thus, it deserves pointing out that our conclusions are limited to the frequency range used here but that this range is not unreasonable.

Experiment 6: Luminance Offsets Versus Complete Object Offsets

In Experiments 1–5, we showed that participants are able to find a static among blinking items, and by elimination of other explanations, we concluded that it is indeed the static nature of the target that allows for relatively efficient search. This is in line with Theeuwes's (2004) account but contradicts Davis and Leow's (2005) claim that search for a static target among dynamic distractors is not possible unless the distractors exhibit some form of motion. They based this claim on their finding that search was inefficient for a static target among distractors that abruptly changed both color and luminance from frame to frame. Thus, a question remains how our results can be brought into accordance with Davis and Leow's findings. An important difference between our experiments and Davis and Leow's experiments is that in our blinking conditions, the blinking distractors completely disappeared and reappeared. In Davis and Leow's experiment, the distractors changed in luminance and color but did not disappear. A possible explanation for the discrepancy between our results and Davis and Leow's results, then, could be that luminance change of the distractors is not enough for relatively efficient search but that complete on- and offsets of the distractors are required. There is substantial evidence that the effectiveness of luminance transients depends not only on the relative increase or decrease in luminance but also on whether a new perceptual object is being created (Cole, Kentridge, & Heywood, 2004; Enns, Austen, DiLollo, Rauschenberger, & Yantis, 2001; Yantis & Hillstrom, 1994). A second reason why search may have been less efficient in Davis and Leow's displays is that the luminance changes were accompanied by a color change. It has been found that simultaneous changes in color, on the one hand, and dynamic properties such as motion or orientation changes, on the other hand, are not always perceived as simultaneous (Clifford, Arnold, & Pearson, 2003; Moutoussis & Zeki, 1997). The same asynchrony may apply to color and luminance changes, possibly obscuring the dynamic signal. Moreover, the color changes are likely to have activated the color-sensitive parvocellular pathway. There is evidence that the parvocellular pathway inhibits the magnocellular pathway thought to be sensitive for dynamic information such as luminance transients (Breitmeyer & Williams, 1990; Tassinari, Marzi, Lee, DiLollo, & Campara, 1999; Yeshurun, 2004; Yeshurun & Levy, 2003).

To investigate these possibilities, in Experiment 6, we presented participants with four conditions: a twinkle condition in which the distractors underwent luminance changes but never disappeared from the display (comparable with Davis and Leow's, 2005, displays but without a color change); two blinking conditions; and a control condition. In the twinkle condition, distractors abruptly changed luminance between 33% and 100% of the maximum against a black background of zero luminance. In the bright blinking condition, the distractors also abruptly switched between 33% and 100% of the maximum luminance but now against a gray background of 33% luminance. In the dark blinking condition, the distractors abruptly changed between 0% and 67% of the maximum luminance against a zero luminance background. This way, both the absolute luminance change and the luminance change relative to the background were controlled for.

If complete object disappearances and reappearances are important, then we would expect efficient search only in the blinking conditions and not in the twinkle condition, where luminance changes were equivalent but the distractors did not disappear. Furthermore, unlike in Davis and Leow's (2005) study, the distractors in our twinkle condition did not undergo a color change. If color changes were the main reason for inefficient search in their study, then we might expect efficient search in our twinkle condition.

Method

Sixteen participants, ranging in age from 18 to 33 years ($M = 12.0$ years), took part as paid (7€ per hour) volunteers. The apparatus, stimuli, and procedure were the same as in Experiment 1, except for the following changes. There were four conditions: the control condition in which all elements stayed on the screen with a luminance of 59.99 cd/m^2 (CIE x, y coordinates = .286, .305, respectively), and the background had zero luminance; the bright blinking condition in which the target remained on the screen with a luminance of 59.99 cd/m^2 (CIE x, y coordinates = .286, .305, respectively), the background had a luminance of 20.13 cd/m^2 (CIE x, y coordinates = .291, .305, respectively), and the tilted elements alternated between these two luminances; the dark blinking condition in which the target remained on the screen with a luminance of 40.13 cd/m^2 (CIE x, y coordinates = .285, .305, respectively), the background had zero luminance, and the tilted elements alternated between these two luminances; and the twinkle condition in which the target remained on the screen with a luminance of 59.99 cd/m^2 (CIE x, y coordinates = .286, .305, respectively), the background had zero luminance, and the tilted elements alternated between a luminance of 59.99 cd/m^2 (CIE x, y coordinates = .286, .305, respectively) and a luminance of 20.13 cd/m^2 (CIE x, y coordinates = .291, .305, respectively). The experiment consisted of five clusters of four blocks; each block consisted of 36 trials. The first cluster of four blocks was disregarded as practice. Within each cluster, the blocks had a fixed order. This order was counterbalanced among participants.

Results

Error percentages were overall low (see Table 1). An ANOVA, with condition and set size as factors, revealed no significant main effects but a significant effect for the interaction, $F(6, 90) = 2.35$, $MSE = 9.35$, $p < .05$. Further analyses revealed that errors increased more with set size in the control condition, especially in comparison with the dark blink condition. Because this pattern did not go against the pattern of RTs, we excluded the possibility of a speed–accuracy trade-off, and we concentrated on RTs.

Trials on which RTs were two and a half standard deviations away from the mean were excluded from analysis, resulting in a loss of less than 3% of the trials. See Figure 7 for a graphical depiction of the findings. The results were analyzed in the same way as in the previous experiments. Separate comparisons between the conditions revealed that RTs were faster and search slopes were shallower in the dark blinking condition, the bright blinking condition, and the twinkle condition compared with the control condition: condition, $F(1, 15) = 93.94$, $MSE = 179{,}734.26$, $p < .001$; $F(1, 15) = 101.56$, $MSE = 203{,}462.42$, $p < .001$; $F(1, 15) = 93.82$, $MSE = 60{,}607.43$, $p < .001$, and Condition × Set Size, $F(2, 30) = 68.53$, $MSE = 31{,}922.70$, $p < .001$; $F(2, 30) = 71.62$, $MSE = 37{,}418.55$, $p < .001$; $F(2, 30) = 17.59$, $MSE = 26{,}071.62$, $p < .001$. Also RTs were faster and search slopes were shallower in both the dark blinking condition and the bright blinking condition compared with the twinkle condition: condition, $F(1, 15) = 53.12$, $MSE = 55{,}985.96$, $p < .001$; $F(1, 15) = 65.39$, $MSE = 71{,}416.13$, $p < .001$, and Condition × Set Size, $F(2, 30) = 26.89$, $MSE = 23{,}970.92$, $p < .001$; $F(2, 30) = 34.03$, $MSE = 27{,}118.90$, $p < .001$. Overall, participants were somewhat faster in the bright blinking than in the dark blinking condition, $F(1, 15) = 32.53$, $MSE = 5{,}680.51$, $p < .001$, and participants had shallower search slopes (by 4 ms/item) in the bright blinking than in the dark blinking condition, $F(2, 30) = 10.32$, $MSE = 2{,}420.00$, $p < .001$.

Discussion

The results from Experiment 6 again showed that search for a static target among on- and offsets is relatively efficient. The main finding is that search for a static target among distractors changing only in luminance without offsets was considerably less efficient, even when the extent of the luminance change was the same as in the on- and offset conditions in either relative or absolute terms. This finding implies that the change of luminance of distractors is not enough for efficient search. Instead, the distractors need to

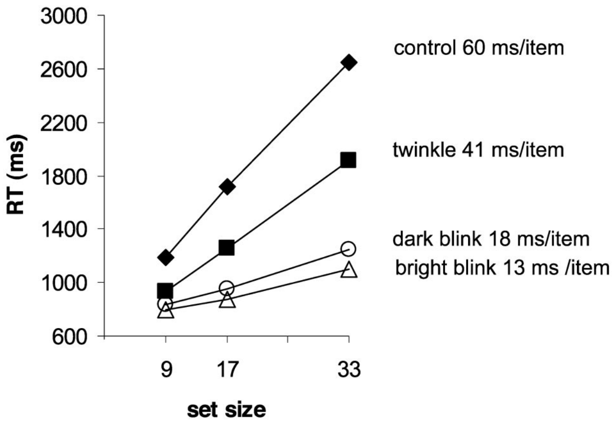

Figure 7. Mean reaction times (RT) for each condition of Experiment 6 (control, twinkle, bright blink, and dark blink) as a function of set size. For each condition, the mean search slopes are provided.

completely disappear and reappear to allow the visual system to fully separate the distractors from the static target.

Our results are in accordance with the hypothesis that the crucial difference between our experiments and Davis and Leow's (2005) search task is the complete on- and offsets of the distractors. When items change in luminance but produce no on- or offsets, participants are less able to efficiently detect a static target. In contrast to Davis and Leow's experiment, in our task, there were no color changes, yet the results were very much comparable. This evidence suggests that the color change probably played little to no role in causing the inefficient search in Davis and Leow's displays. This result furthermore implies that Theeuwes's (2004) original account is not entirely correct. Participants are not always able to rapidly find a static target among dynamic distractors. They can do so when the distractors are moving or blinking but not when the distractors are only changing in luminance. Note, though, that there were nevertheless some benefits in the twinkle condition relative to the control condition, suggesting that the observers made some (but limited) use of the luminance changes. The implications of these findings are elaborated on in the General Discussion.

General Discussion

This work started with the question of whether observers are able to efficiently detect a static target among dynamic distractors. Others have claimed that such efficiency may only be confined to the case of moving distractors (Davis & Leow, 2005). However, here we have shown that relatively efficient search may also be achieved when the distractors are characterized by multiple asynchronous abrupt onsets and that this search is equally efficient or even slightly more efficient than when the distractors are moving, lending support to Theeuwes's (2004) claim that, in general, static information may be detected relatively rapidly from among dynamic information. In Experiment 1, we showed that search for a static target among blinking distractors is performed efficiently and that this search is as efficient as for a static target among moving distractors. In Experiment 2, average or momentary luminance differences between the target and the distractors were ruled out as an explanation. In Experiment 3, long-range apparent motion was also dismissed as a possible cause, as was temporal grouping on the basis of common onset frequencies. Experiment 4 showed that preknowledge of the dynamic nature of the distractors is not needed for efficient search of the static target. The results of Experiment 5 showed that it is not just any unique frequency that results in efficient search. Experiment 6 made clear that a luminance change alone is not enough for efficient search. It does improve search efficiency, but the largest improvement in search efficiency arises when the blinking objects fully disappear and reappear. The results of this last experiment suggest that neither Theeuwes (2004) nor Davis and Leow were entirely correct. Participants cannot efficiently find a static target among dynamic distractors, regardless of the dynamic nature of the distractors. They can do so when the distractors move or blink on and off completely but not when the distractors only change in luminance (though luminance changes per se appear to contribute too).

Note that so far we have discussed improvements in performance in the dynamic conditions in terms of relative efficiency. It deserves mentioning that, even though search became substantially more efficient when distractors were dynamic in nature, search slopes were not completely flat, indicating that the target was usually not found entirely in parallel across the display. This finding contrasts with the flat search slopes usually found when participants search for a dynamic target among static distractors (Hillstrom & Yantis, 1994; Watson & Humphreys, 1995; Yantis & Egeth, 1999). However, Müller and Found (1996) showed that participants after intensive practice were as efficient in finding a static target among moving distractors as the reverse. It could be that in our experiments, with more extensive practice, participants would have shown parallel search.

In any case, contrary to Davis and Leow's (2005) claim, the present results show that motion is not unique in allowing for relatively efficient search. Instead, we agree with Pashler (2001) that dynamic differences between stimuli, such as abrupt onsets, are just another aspect on which these stimuli can be discriminated and prioritized for attentional selection. The question remains as to how the visual system performs this discrimination.

Memory

One way the visual system might discriminate static from dynamic stimuli is by building up a memory representation of the successive frames of the changing displays. By taking a series of complete snapshots and comparing them, the visual system may then filter out the only item that is present in every single snapshot. Such snapshots may be taken from iconic memory, a large-capacity initial storage of visual information (Sperling, 1960). However, various studies have now shown that not much visual information survives from one snapshot to the next, at least not across brief interruptions or eye movements (Irwin, 1991; O'Regan, Rensink, & Clark, 1999; Pashler, 1988; Phillips, 1974; Simons, 1996). Illustrative in this respect are the change blindness studies showing that observers often fail to detect large changes between two separate displays when the transients accompanying these changes are eliminated (see Rensink, 2002, for a review). Closer to the present study, Theeuwes (2004) presented two successive displays in which all elements changed, except the target, which remained identical. When the second display followed the first without interruption, the target was easily found. However, when a blank display was inserted between the two frames, search for the one nonchanged element became very effortful. Taken together, the evidence indicates that a high-level memory representation of the displays offers an implausible explanation of the efficient detection of static among dynamic elements. Instead, just as efficient detection of a changing target appears to rely on the presence of transients at its location, efficient detection of a static target appears to rely on the presence of transients at the distractor locations. This evidence appears to point to an important role of relatively earlier visual transient detection mechanisms.

Transient Versus Sustained Channels

The dynamic properties of the stimulus are already distinguished at the level of retinal ganglion cells. One group of cells, the so-called *X* cells (or β/B cells), have relatively slow conduction velocity, and they show sustained firing to predominantly stationary stimuli. The *Y* cells (or α/A cells) have faster conduction velocities, and they show transient bursts of firing in response to abrupt changes in the stimulus, such as onset and motion (Cleland, Dubin, & Levick, 1971; Enroth-Cugell & Robson, 1966; Leventhal, Rodieck, & Dreher, 1981; Stone & Fukuda, 1974). This division is thought to lie at the basis of what have been referred to as the magno- and parvocellular pathways at the physiological level, or transient and sustained channels of visual processing at a more functional level, and it extends into (and probably beyond) the primary visual cortex (e.g., Breitmeyer & Ganz, 1976; Livingstone & Hubel, 1988; Todd & Van Gelder, 1979).

The relatively independent transient and sustained subsystems may provide a direct explanation for the efficient discrimination of static and dynamic information. When searching for a dynamic target, the visual system only has to look for activity in the transient (magno) channel. When looking for a static target, as in the present experiments, the registration of activity in the sustained (parvo) channel is sufficient. The fact that dynamic targets are usually somewhat faster and more efficiently detected than static targets may then be explained by a slight preference of the visual system for the transient channel or by the fact that the transient neurons have faster conduction velocities. Note, however, that the transient-sustained dichotomy at a pure retinal level cannot account for the data. In the twinkle condition of Experiment 6, the distractors featured abrupt luminance changes equivalent to those in the blinking conditions but without completely disappearing from the displays. Retinal cells should have responded equally in these conditions, yet search was much more effortful when the distractor offsets were not complete. Thus, the crucial distinction between changing and nonchanging elements appears to be whether a new object has been created relative to its background, rather than a simple luminance change. Such new object comparisons relative to its surroundings are more likely to be made at higher levels, for instance in the primary visual cortex (V1), where center-surround cells provide important information about the background. Moreover, V1 cells respond to both moving and blinking stimuli but do not distinguish between them (Andersen, 1997). This would explain why performance in our motion and blinking conditions was so similar. In contrast, the higher up motion-sensitive area, the middle temporal area of the extrastriate visual cortex (MT), responds only weakly or not at all to blinking stimuli (Andersen, 1997). Thus, V1 may provide the necessary initial mechanisms for both motion processing and temporal segmentation of static and dynamic stimuli (Fahle, 1993; Forte et al., 1999).

Attentional Capture

A somewhat surprising aspect of our findings is that search for a static item among blinking items is efficient, despite the fact that the distractors are characterized by repeated abrupt onsets. As mentioned in the introduction, there is substantial evidence that, under the right circumstances, abrupt onsets automatically capture attention (Yantis & Jonides, 1984). As also mentioned earlier, moving stimuli appear to be less strong attentional captors (Hillstrom & Yantis, 1994; Yantis & Egeth, 1999). So in our blinking conditions, why were observers not continuously distracted by the abrupt onsets of the blinking distractors?

One possible explanation is that after the first abrupt onset, subsequent onsets become much less salient. As has been suggested before, what appears to make an abrupt onset so salient is the appearance of a new object (Yantis & Hillstrom, 1994). Relevant to this finding is a study by Kahneman, Treisman, and Gibbs (1992), who found that features were recognized faster when they had been part of one and the same object across time relative to when they had switched objects. Kahneman et al. suggested that whenever a new object appears, an object file is created, storing the object properties as long as the spatiotemporal continuity is preserved. The creation of this object file requires attention. In our experiments, continuously appearing items failed to attract attention. Perhaps, then, the blinking line segments were not seen as new objects but as one and the same object simply disappearing and reappearing. However, a study by Yantis and Gibson (1994) argued against this account. In one of their experiments, they used a visual search task in which one of the items briefly disappeared. When it reappeared, it could be the target, although it was more likely to be a distractor. The amount of attentional capture was determined as the relative efficiency of search when the blinking item was indeed the target. Yantis and Gibson (1994) found that the blinking item automatically captured attention as long as the temporal interval between the offset and onset was more than about 100 ms. In the same study, the same interval was also found crucial in determining the percept of bistable apparent motion displays (so-called Ternus displays, in which part of the array may be seen as stationary or moving depending on the interval between frames). Yantis and Gibson (1994) concluded that a spatiotemporal discontinuity of around 100 ms is sufficient for an object to be regarded as new. In the present study, the distractor items were always switched off for at least 150 ms (and up to 350 ms). Thus, according to Yantis and Gibson's (1994) measure, these items should be regarded as new and, in principle, capable of capturing attention.

Another possibility is that abrupt onsets only capture attention when they are the only onset in the display. In the same vein, the creation of new object files may only be limited to a small number of items (perhaps because of the limited attentional resources available for such creation). In other words, single onsets may capture attention, but multiple onsets, when distributed evenly across the visual field, may not. Like other features such as color or orientation, abrupt onsets may become more salient the more unique they are. Some support for this idea comes from a study by Chastain and Cheal (1999), who found that a single onset precue shows all the characteristics of involuntary attentional capture (rapid attentional build-up followed by rapid attentional decay across longer precue to target delays) but that an onset of multiple precues shows the characteristics of voluntary attentional control (slow attentional build-up and no attentional decay with longer time between precue and target). However, other studies suggest that multiple onsets can still capture attention. For instance, Yantis and Johnson (1990; see also Yantis & Jones, 1991) found just as strong attentional capture in displays of up to 16 items, half of which were defined by abrupt onsets. Similarly, Donk and Theeuwes (2003) found that in a visual search task, participants prioritized up to 14 new elements (as defined by an abrupt onset) over up to 14 interspersed old elements, even when the target was twice as likely to be old. Thus, the presence of multiple onsets in itself does not appear to necessarily prevent attentional capture. Note further that, in our displays, the blinking items appeared and disappeared at different rates, making them at least locally relatively unique.

It appears, then, that observers can at least exert some control over the attentional capture by abrupt onsets (see also Pashler, 2001; Yantis & Jonides, 1990). Attention may be initially captured by one of the blinking items (or sometimes even the target, because it too is initially defined by an onset), but soon observers are able to ignore them and actually use the difference between transient and sustained signals to direct their attention to the target. This account may be regarded as in between the automatic capture account (Theeuwes, 1992; Yantis & Jonides, 1984), which states that some stimuli capture attention regardless of the tasks and goals of the observer, and the contingent capture account (Folk et al., 1992; Folk, Remington, & Wright, 1994), which states that capture is dependent on the attentional set of the observer. In the case of multiple onsets, attention may initially be captured automatically, but it is then quickly overridden by top-down goal settings to prevent further interference.

A final finding worth returning to, now in relation to attentional capture, is the fact that search for a static target was relatively inefficient when the dynamic distractors only changed luminance, without disappearing (Experiment 6). Recently, Enns et al. (2001) reported a related finding: An item featuring a maximum luminance change (i.e., a polarity reversal: changing from black to white on a gray background) did not get as much priority in search as an item that newly appeared in an empty location (i.e., whose luminance changed from the gray background to either black or white). Enns et al. concluded, as we do here, that the visual system is biased toward new object appearances rather than luminance changes. In our experiments, in terms of attentional capture, one might actually have expected search to be easier when the distractors only changed luminance, because they would draw less attention. The fact that search was actually more difficult means that the effect of new object appearances cuts both ways: They draw more attention when they are unique in the display, but they can also be more easily discriminated and rejected when they constitute the distractors.

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