



Changes (but not differences) in motion direction fail to capture attention

Erik Van der Burg^{a,b,c,*}, John Cass^d, Jan Theeuwes^{a,c}

^a Department of Experimental and Applied Psychology, Vrije Universiteit Amsterdam, Amsterdam, Netherlands

^b School of Psychology, University of Sydney, Australia

^c Institute for Brain and Behaviour, Amsterdam, Netherlands

^d School of Social Sciences & Psychology, Western Sydney University, Australia

ARTICLE INFO

Keywords:

Attention
Visual search
Attentional capture
Vision
Motion

ABSTRACT

In this study we investigated under what conditions motion direction changes pop out in continuously moving target/distractor environments. Participants were presented with vertically oriented Gabor patches whose carrier components drifted at a constant speed from left to right and then reversed direction. On any given trial, one of these elements was nominated as the *target* and the remaining elements were *distractors*. Distractor elements all changed direction simultaneously. The distractors either moved in a homogeneous manner (i.e. all moved in the same direction), or in a heterogeneous manner (i.e. direction was randomized). The target moved with a similar spatio-temporal trajectory as the distractors from left to right (or vice versa), but changed direction asynchronously with respect to the distracting elements. The participants' task was to locate this deviant (*target*) Gabor patch. We show that a motion direction change pops out (as indicated by the absence of a set size effect) when the surrounding distractors move in a homogeneous direction. When the distractors moved in heterogeneous directions, a similar pop out effect was observed when the set size was small (≤ 5 elements), but not when it was large. This suggests that motion direction changes capture attention only when the change results in a unique direction of motion. Consistent with this finding we also show that a moving target (without direction change) captures attention in cases in which all distractors recently changed direction. This corroborates the idea that, in addition to direction cues, the temporal uniqueness of a change in an object's direction (or absence, thereof) relative to surrounding objects is a cue capable of capturing attention.

It is often difficult to ignore objects that stand out from the environment. For example, a uniquely red object captures attention when it is surrounded by green objects, even when the red object is not relevant to the observers' goal (Theeuwes, 1992). Moreover, it is also known that differences in visual properties such as object shape, orientation, size and luminance can attract attention (see e.g. Jonides & Yantis, 1988; Theeuwes, 2010; Theeuwes & Van der Burg, 2007, 2008; Treisman & Gelade, 1980; Wolfe & Horowitz, 2004). Whereas these and many other studies have investigated attentional capture in static environments, they say little about capture in more dynamic environments.

Other studies have investigated visual attention in static environments in which one object is dynamic (see e.g. Abrams & Christ, 2003; Franconeri & Simons, 2003). For instance, Franconeri and Simons (2003) examined whether different types of moving stimuli among static stimuli can capture attention. They reported that some moving stimuli, e.g. looming objects (dynamic increases in object size), but not

all moving stimuli, can capture attention. Franconeri and Simons concluded that a moving object among static objects can, in principle, capture attention. Abrams and Christ (2003) also investigated whether motion can capture attention, but came to a different conclusion, finding no evidence for such search benefits when the target was the only moving item among other static items. They did, however, find an advantage for targets that had started to move recently. On this basis, Abrams and Christ (2003) suggested that it is the sudden onset of motion in a previously static object that captures attention rather than its motion *per se* (see also Abrams & Christ, 2005; but see Franconeri & Simons, 2003; Franconeri & Simons, 2005).

To date, very little is known about whether a moving object - among other moving objects - captures attention when, for example, one or more objects within the visual array change direction. In certain circumstances it may be crucial to notice changes in motion direction as these may signal the trajectory of an ecologically significant object (e.g. predator or prey). Pratt, Radulescu, Guo, and Abrams (2010)

* Corresponding author at: Vrije Universiteit Amsterdam, Faculty of Behavioural and Movement Sciences, Van der Boechorststraat 1, 1081 BT Amsterdam, Netherlands.

E-mail address: vanderburg.erik@gmail.com (E. Van der Burg).

<https://doi.org/10.1016/j.visres.2019.09.008>

Received 13 December 2018; Received in revised form 27 September 2019; Accepted 29 September 2019

Available online 23 October 2019

0042-6989/ © 2019 Elsevier Ltd. All rights reserved.

investigated whether motion direction changes can capture attention in a continuously moving environment. In their study, participants saw four objects on the screen that moved pseudo-randomly. In the ‘inanimate’ motion condition, periodically moving objects collided with each other or with the surrounding frame. In the ‘animate’ motion condition, one specific object changed direction without a collision with other objects. Subsequently, one of the four objects vanished from the display and participants were asked to make a speeded response as soon as they saw the object disappear. Responses to the target were faster when that vanishing object recently underwent direction changes consistent with ‘animate’ motion, compared to when it recently made an ‘inanimate’ direction change. Based on these results, Pratt et al. (2010) concluded that a motion direction change captures attention, but only when this motion change is not due to an external event – i.e. when it is consistent with ‘animate’ motion.

Howard and Holcombe (2010) used a slightly different design to investigate whether a motion direction change captures attention. In their task, participants saw four moving Gabor patches, each with continuously changing orientation. Participants were instructed by a pre-cue to attend to and to track two of the four Gabor patches and to ignore the other two distractor Gabor patches. Periodically, one of these distractors changed direction by either bouncing against a visible or an invisible frame. After a certain time, all Gabor patches disappeared from the display and participants saw a probe corresponding to the location of one of the two target Gabors. Participants were asked to report the orientation of the Gabor patch indicated by the probe. Interestingly, even though participants were asked to track only the two target Gabor patches (and ignore the two others), participants made greater errors in reporting the orientation of the target Gabor patch when a distractor Gabor patch recently changed direction due to a collision against an invisible frame than when it changed direction against a visible frame. In line with Pratt et al. (2010), Howard and Holcombe concluded that, even though irrelevant to the observers’ goal, motion direction changes can capture attention, but only when these changes are not visibly due to an extrinsic cause (and therefore, consistent with an intrinsic ‘animate’ cause of direction change).

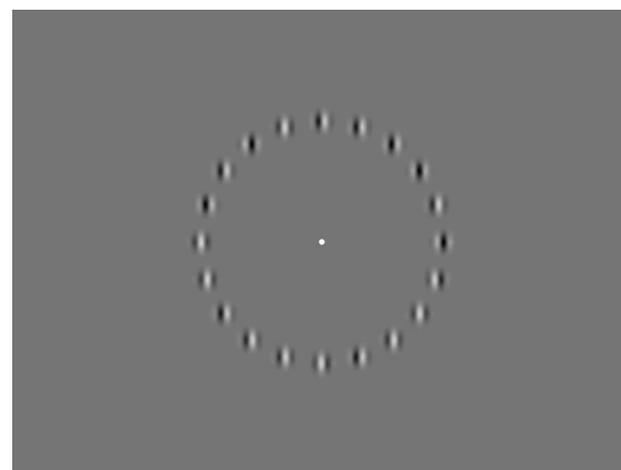
In the present study, we investigated why a motion direction change pops out when embedded amongst other continuously moving objects. Whereas Pratt et al. and Howard and Holcombe used pseudo-randomly moving stimuli involving continuous and abrupt shifts in the locations of object across time, we move only the carrier components of our vertical Gabor stimuli (preserving the location of the envelope) to: (a) limit the direction of each object (i.e. left and right); and (b) to minimize the influence of any luminance and eccentricity effects (see the General Discussion in the Howard and Holcombe study on p. 2093 for a related discussion on luminance and eccentricity effects in their study).

1. Experiment 1

The aim of Experiment 1 was to investigate whether a motion direction change is capable of producing pop out search performance in a dynamic environment. Participants were presented with twenty vertically oriented Gabor patches whose carrier components moved periodically from left to right and reversed with a frequency of 0.39 Hz. Nineteen of these Gabor patches were used as distractors and one was the target. The distractors all changed direction simultaneously, moving in either a homogeneous manner (i.e. all distractors moved in the same direction) or in a heterogeneous manner (i.e. the direction was randomized). Fig. 1 illustrates a snapshot of the search display used in the present study. See also Movie 1 and Movie 2 for an example trial in which the distractors moved in a homogenous and heterogenous manner, respectively (target-distractor interval is 500 ms).



Fig. 1. Snapshot of the search display used in the present study.



Movie 1.



Movie 2.

The target moved with an identical temporal frequency (0.39 Hz) as the distractors from left to right and reversed, but its direction change (reversal) either preceded or followed the direction reversals of the distractors (target-distractor interval was 25, 50, 75, 100, 125, 250, or 500 ms). The interval between the target and distractor changes was manipulated to investigate the boundary condition under which a motion direction change can pop out from its dynamic environment. The participants were asked to localize the deviant Gabor patch (i.e. the target) by making an unspeeded response. After the termination of the

trial, participants saw a response screen with twenty circles (spatially aligned with the twenty Gabor patches). Each circle contained a randomly determined letter (a–t) and participants were instructed to press the (a–t) key corresponding to the location of the target Gabor patch.

We assume that the temporally deviant target might pop out from its environment in one of two ways (or possibly a combination of both). First, it is possible that the *sudden direction change* (i.e. the temporally unique event) pops out from its dynamic environment. If this sudden event indeed captures attention, then we expect to observe good performance (i.e. high localization accuracy) independent of the relative direction of the surrounding distractors' movement (homogeneous or heterogeneous) because the target direction change is temporally separated from the distractor direction changes (i.e. the target-distractor interval). Second, it is feasible that it is the temporarily unique direction of motion of the target object that recently changed direction compared to the direction of motion of the surrounding distractors that is principal determinant of attentional capture. If a *motion direction change* indeed captures attention because of its unique direction, then we expect to observe better performance (i.e. higher localization accuracy) in cases where the distractors move homogeneously relative to the heterogeneous distractor condition, since in the latter condition the target direction will never be unique within the display.

1.1. Method

1.1.1. Participants

Eight students (6 female; mean age 21.6 years; ranging from 18 to 29 years) who were naive as to the purpose of the experiment participated in Experiment 1. Participants were paid €8 an hour. Informed consent was obtained from each participant. The experiment was approved by the local ethics committee of the Vrije Universiteit Amsterdam. Experimental procedures adhered to the declaration of Helsinki.

1.1.2. Stimuli and apparatus

The experiment was programmed and controlled by using E-prime software. Participants were seated approximately 80 cm from the monitor (120 Hz refresh rate; 1024x768 pixels). A trial started with a presentation of a white fixation dot (radius = 0.13°; luminance 92.3 cd m⁻²) in the middle of the screen for a fixed period of 500 ms. The luminance of the dark-gray background was kept constant at about 9.6 cd m⁻². Subsequently, the search display appeared with twenty vertically oriented Gabor patches (radius = 0.7°; color one = black, < 0.5 cd m⁻²; color two = light gray, 51.5 cd m⁻²; background = average color 9.6 cd m⁻²; spatial frequency = 0.75 cycles/degree; standard deviation of the Gaussian envelope = 10 pixels; initial spatial phase was randomly determined by steps of 51/360°) equally spaced around the fixation dot on an imaginary circle with a radius of 5.2°. The Gabor patches were all equally spaced to avoid any eccentricity effects. See Fig. 1 for the layout of the search display. The search display was presented for 7650 ms, and during this period the grating of each Gabor patch moved from left to right or reversed by varying the spatial phase of the sinusoidal grating (51/360° degree per 25 ms) with a frequency of 0.39 Hz. In other words, each trial contained six motion direction changes (i.e. consistent with 3 cycles of 2550 ms each). At the beginning of each trial, the initial spatial phase of the sinusoidal grating for each Gabor patch was randomly determined so that a pop out cannot be attributed to a luminance change or a pop out of the target when the display appeared (see Fig. 1 for a snapshot of the display used in the present study). Nineteen Gabor patches were used as distractors, and one was designated as the target. The distractors were always synchronized in such a way that they all changed direction simultaneously. On half of the trials, the distractors moved in a homogeneous manner (i.e. all distractors moved in the same direction). On the other half of the trials, the distractors moved in a heterogeneous manner (i.e. the direction of each distractor was randomly determined). The

temporal frequency of the target's direction reversal was identical to that of the distractors' (0.39 Hz), but its direction change either preceded or followed the distractor motion direction changes. The target-distractor interval was either 25, 50, 75, 100, 125, 250 or 500 ms. The participants were asked to localize the deviant Gabor patch (i.e. the target). After the termination of the trial, participants saw a response screen with twenty circles (spatially aligned with the twenty Gabor patches). Each circle contained a randomly determined letter (a–t) and participants were instructed to press the (a–t) key corresponding to the location of the target Gabor patch. The location of the target Gabor patch was randomly allocated on each trial. The next trial was initiated after a response was given.

1.1.3. Design and procedure

Participants were instructed to remain fixated on the central fixation point during the course of a trial. The independent variables were target-distractor interval (25, 50, 75, 100, 125, 250 or 500 ms), target-distractor order (target leads vs. target follows) and distractor condition (homogeneous vs. heterogeneous). Each participant performed one practice block and eight experimental blocks of 28 trials each. All conditions were randomized within blocks. Participants received feedback about their overall mean percentage target localization after each block.

1.2. Results

The results of Experiment 1 are presented in Fig. 2. Data from the practice block were excluded. All data were subjected to a repeated-measure Univariate Analysis of Variance (ANOVA) with distractor condition (homogeneous vs. heterogeneous), target-distractor order (target leads vs. target follows) and target-distractor interval (25, 50, 75, 100, 125, 250 or 500 ms) as within-subject variables. The reported values for *p* are those after a Huynh-Feldt correction for sphericity violations with alpha set at 0.05.

1.2.1. Percentage target localization

Overall mean percentage target localization was 59.8%. The ANOVA yielded a reliable main effect of target-distractor interval, $F(6, 42) = 65.9$, $p < .001$, as overall percentage target localization increased with increasing target-distractor interval. Important, overall

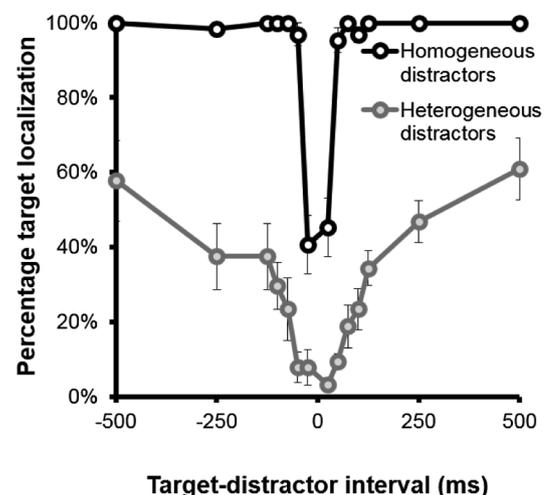


Fig. 2. Results of Experiment 1. Overall mean percentage target localization as a function of target-distractor interval, target-distractor order (target leads vs. target follows) and distractor condition. Note that a negative target distractor interval indicates that the target change preceded the distractor changes, and that a positive value indicates that the target change followed the distractor changes. The error bars reflect the overall standard errors of the individuals' mean percentage target localization.

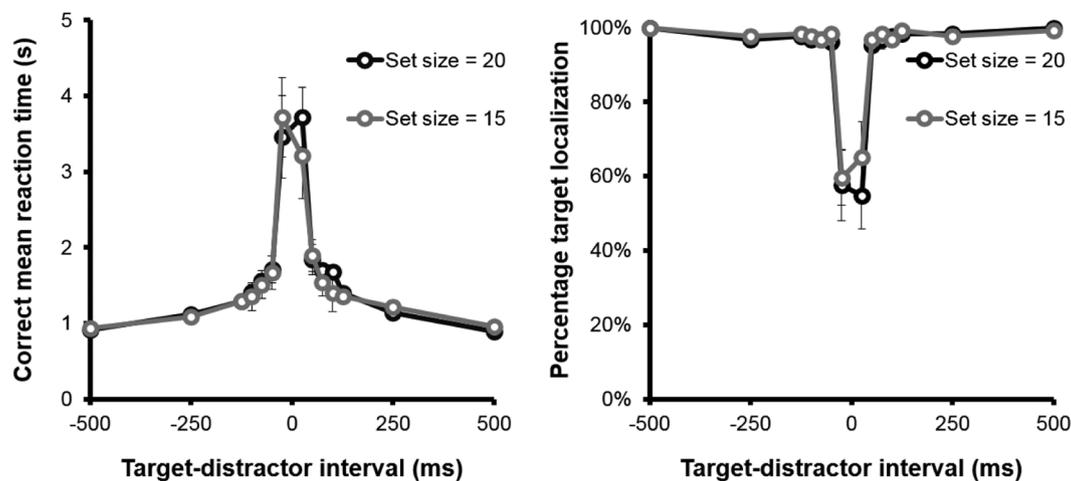


Fig. 3. Results of Experiment 2. Left panel) Correct mean reaction time (RT) as a function of set size, target-distractor interval, and target-distractor order (target leads vs. target follows). The error bars reflect the overall standard errors of the individuals mean correct reaction time. Right panel: Overall mean percentage target localization as a function of set size, target-distractor interval, and target-distractor order (target leads vs. target follows). The error bars reflect the overall standard errors of the individuals' mean percentage target localization. Note that a negative target-distractor interval indicates that the target change preceded the distractor changes, and that a positive value indicates that the target change followed the distractor changes.

percentage target localization was better when the surrounding distractors moved homogeneously (91.0%) than when the distractors moved heterogeneously (28.5%), $F(1, 7) = 383.2, p < .001$. The target-distractor interval \times distractor condition interaction was highly significant, $F(6, 42) = 12.2, p < .001$, and further examined by separate ANOVAs for each distractor condition. In the heterogeneous distractor condition, percentage target localization improved with increasing target-distractor interval, $F(6, 42) = 21.4, p < .001$. Importantly, even though participants had multiple chances to detect the target because it changed six times per trial, performance was rather low and never approached 100% (60.9% at best). Therefore, these results suggest that the target event did not pop out from its dynamic environment. In the homogeneous distractor condition, percentage target localization increased with increasing target-distractor interval, $F(6, 42) = 63.4, p < .001$. In contrast to the heterogeneous distractor condition, performance was high (99.0%) and approached 100% correct when the interval between the target and distractors was > 25 ms, suggesting that the target event did pop out from its homogeneously moving environment. In the homogeneous condition, the highly significant target-distractor interval effect failed to reach significance when we excluded the shortest target-distractor interval (25 ms) from the analysis, $F(5, 35) = 1.3, p = .29$. This confirms the idea that performance was at ceiling over all target distractor intervals (excluding the 25 ms condition). Furthermore, all other effects were not reliable (all $F_s < 1$).

The results are clear. Whereas a target motion direction change did not pop out when it was surrounded by heterogeneously moving distractors, target localization performance was significantly better when embedded amongst homogeneously moving distractors. However, even though percentage correct approached ceiling (i.e. 100% correct target localization) this does not necessarily mean that the target popped out in the homogeneous condition. For instance, on each trial, participants had multiple chances to detect the target because it changed six times per trial (see the Method Section for more details). Therefore, it is unclear whether the first target direction change resulted in pop out or whether performance was based on subsequent motion direction changes. In Experiment 2 we investigated whether the target popped out by asking participants to make a speeded response as soon as they saw the target.

2. Experiment 2

The aim of Experiment 2 was to investigate whether a target direction change pops out when embedded within distractor environments composed of Gabors drifting with homogenous directions of motion. Therefore, we manipulated the number of elements in the display (15 or 20 Gabor patches) and asked participants to make a speeded response by pressing the spacebar as soon as they detected the target. After each trial, participants were again required to identify the target (like in Experiment 1) to make sure that they responded to the target event. If a motion direction change does pop out among homogeneously moving distractors, then we expect to observe search times independent on the number of moving objects in the display.

2.1. Method

2.1.1. Participants

Ten students (8 female; mean age 19.4 years; ranging from 18 to 21 years) participated in Experiment 2.

The experiment was identical to the previous experiment except that the participants were asked to make a speeded response by pressing the spacebar when they saw the target. To make sure that participants indeed responded to the target Gabor patch we asked them (similar to Experiment 1) to localize the target after they made the speeded response. The distractors were always moving and changing direction in a homogeneous manner. On half of the trials the search display contained 15 Gabor patches and on the remaining trials the search display contained 20 Gabor patches.

The independent variables were target-distractor interval (25, 50, 75, 100, 125, 250 or 500 ms), target-distractor order (target leads vs. target follows) and set size (15 vs. 20 objects). Each participant performed one practice block and thirteen experimental blocks of 28 trials each. All conditions were randomized within blocks. Participants received feedback about their overall mean percentage target localization and overall mean RT after each block.

2.2. Results

The results of Experiment 2 are presented in Fig. 3. Data from the practice block and trials on which participants responded too slow (> 20 s) were excluded (0.3%). Correct mean reaction time (RT) and percentage target localization were subjected to an ANOVA with set

size (15 vs. 20 elements), target-distractor order (target leads vs. target follows) and target-distractor interval (25, 50, 75, 100, 125, 250, 500 ms) as within-subject variables.

2.2.1. Percentage target localization

Overall mean percentage target localization was 95.3%. The ANOVA on percentage target localization yielded a significant target-distractor interval main effect, $F(6, 54) = 38.04$, $p < .001$, as the percentage target localization increased with increasing target-distractor interval. The main effect of set size was not significant, $F(1, 9) = 1.67$; $p = .228$. All other effects were not reliable (all $F_s < 1$).

2.2.2. Reaction time

The ANOVA on RTs yielded a significant target-distractor interval effect, $F(6, 54) = 28.77$, $p < .001$, as the RTs decreased with increasing target-distractor interval. Importantly, consistent with the accuracy data, the main effect of set size was not significant, $F < 1$. All other effects were not reliable (all $F_s < 3.36$, $p_s > 0.1$).

The results are clear. There was no set size effect in terms of RTs or percentage target localization, suggesting that the target direction change may have popped out among homogeneously moving distractors. However, the overall long search times (> 1000 ms) may raise doubts about whether the target event really pops out from its environment. In contrast to other studies who have used static singletons (like a colour, or orientation singleton that stands out from its environment), we have used a dynamic singleton that only deviates temporally from its environment (see also Cass, Van der Burg, & Alais, 2011; Van der Burg, Olivers, Bronkhorst, & Theeuwes, 2008b; Van der Burg, Olivers, Bronkhorst, & Theeuwes, 2009, for a similar finding and discussion regarding temporally salient events). Therefore, observers had to wait for the first target event, which occurred on average 637 ms after the display onset. The effective RTs are in fact 637 ms faster than is plotted in Fig. 3. Furthermore, it is possible that on some trials, participants made eye-movements or blinks and therefore missed the first target motion direction change so that they must wait for the subsequent target direction change (1275 ms later). Therefore, to gain more information about whether the target may have otherwise popped out from its environment we plotted the RT distributions for each condition (see Fig. 4). Here the proportion of responses is plotted as a function of normalized RT (bin width is 150 ms) for each target-distractor interval. The normalized RT is the time to respond to the visual target from the first target event (collapsed over set size).

It is clear from Fig. 4 that a target direction change does not pop out when the target-distractor interval is short (i.e. 25 ms). In this case the RT distribution demonstrates multiple peaks (i.e. serial search) indicating that participants were not always able to respond to the first target direction change. Therefore, one can conclude that when the target-distractor interval is short, participants required multiple direction changes of the target Gabor patch to detect it (explaining the multiple peaks). By contrast, in the other conditions, there was one clear peak indicating that participants responded on most trials within a certain time window. Importantly, participants responded on 89.1% of the trials before the second target motion direction change occurred (compared to 39.2% of the trials in the case the target-distractor interval was 25 ms). Fig. 5 illustrates the percentage of responses in which participants responded before the second target motion direction change. We suggest, therefore, that when the temporal separation between the target and distractor changes is sufficiently long (> 25 ms), the target Gabor patch pops out among homogeneously moving distractor Gabor patches.

In Fig. 4, when the target event preceded the distractor event (left panels), the RT distribution peaked at ~ 700 ms from onset of the target event (i.e. the target's direction change). In contrast, when the target event followed the distractor changes (Fig. 4 right panels), the peak was closer to the target event when the target-distractor interval was sufficiently long. More specifically, the peak was at ~ 200 ms when the

distractor-target interval was 500 ms. Interestingly, in this condition participants responded before the target changed direction on 14% of the trials. This indicates that when the distractor motion direction changes preceded the target motion direction change, the target Gabor patch did not pop out due to the target direction change (since this did not happen), but due to the distractor direction changes instead. In other words, a constantly moving Gabor patch seems to pop out also when all the distractors change direction towards the opposite direction of the target Gabor patch. This supports the notion that a target direction change can pop out when the direction of the moving target is unique compared to the direction of the moving distractors.

3. Experiment 3

So far, in Experiments 1 and 2, the deviant Gabor patch was always relevant to the task. Therefore, it is unclear whether a deviant Gabor patch in the previous experiments captured attention in an automatic, stimulus-driven fashion or not. The aim of the present experiment is to investigate whether a motion direction change or multiple motion direction changes can lead to automatic capture of attention. In Experiment 3, participants saw ten Gabor patches moving homogeneously to either the left or to the right. After a randomized interval, one of the Gabor patches became deviant in terms of its motion direction compared to the motion direction of the other Gabor patches. This was achieved in two different manners. On half of the trials, one Gabor patch changed towards the opposite direction so that this Gabor patch was deviant compared to the direction of the surrounding Gabor patches (i.e. the deviant change condition). On the other half of the trials, we tested whether a constantly moving Gabor patch captures attention when all the distractors change direction towards the opposite direction of the target Gabor patch. Thus, in this condition, all Gabor patches except the deviant Gabor patch changed direction (i.e. the distractor changes condition). 150 ms after the disappearance of the Gabor patches, nine Gabor patches were replaced by black circles and one by a green or red circle (i.e. the probe). Participants were asked to respond as fast and accurately as possible to the color of the probe. On 10% of the trials, the probe appeared at the same location of the deviant Gabor patch, and on the remaining 90% of the trials, the probe appeared at the location of one of the distractor Gabor patches. Note that, in this way, each Gabor patch had an equal probability to be probed (i.e. on chance level; 10%). If the deviant Gabor patch attracts attention in a stimulus-driven manner, then we expect that participants will be faster when the probe appeared at the location corresponding to the deviant Gabor patch than when the probe appeared at the location corresponding to a distractor (i.e. non-deviant) Gabor patch (see also Nakayama & Mackeben, 1989; Posner, 1980; Van der Burg, Olivers, Bronkhorst, & Theeuwes, 2008a).

3.1. Method

3.1.1. Participants

Ten participants participated in Experiment 3 (7 female; 21.6 years; ranging from 18 to 27 years). The data from one participant was excluded from further analyses, as he, or she was using the mobile phone.

The Experiment was similar to Experiment 2 except for the following changes. Participants saw ten homogeneously moving Gabor patches on the screen (either moving to the left or right). The start direction was randomly determined and mixed within blocks. After a randomly determined interval (575–875 ms), one of the Gabor patches became deviant, as this Gabor patch moved in the direction opposite that of the other Gabor patches. This was established in two different ways. On half of the trials, one Gabor patch changed towards the opposite direction so that this Gabor patch was deviant compared to the direction of the surrounding Gabor patches (i.e. the deviant change condition). On the other half of the trials all Gabor patches, except the deviant Gabor patch, changed towards the opposite direction (i.e. the

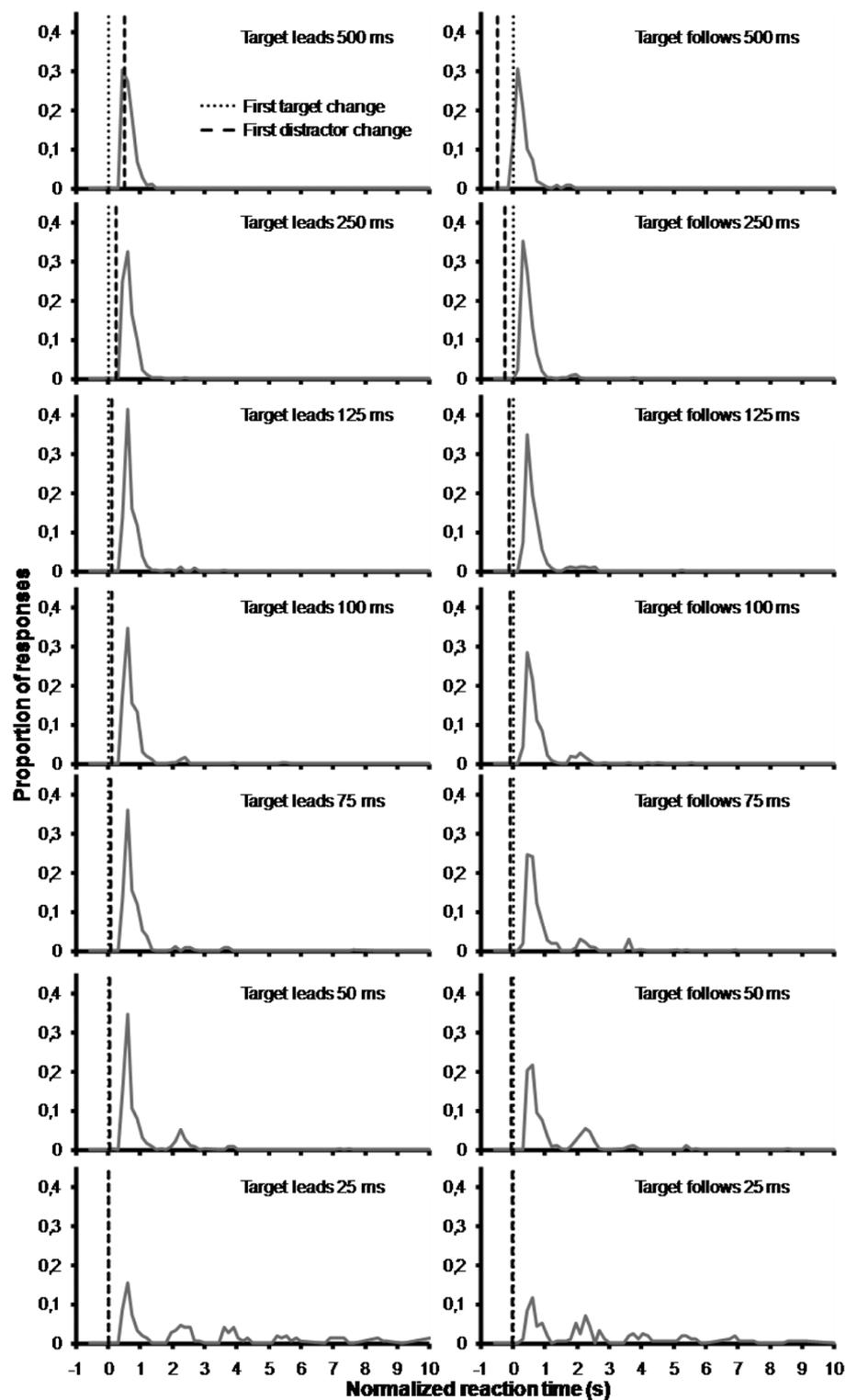


Fig. 4. RT distributions of Experiment 2. Here proportion of responses is plotted as a function of normalized RT (bin width is 150 ms) for each target-distractor interval. The normalized RT is the time to respond to the visual target from the first target event (collapsed over set size). The left panels indicate that the target direction change preceded the distractor direction changes. The right panel indicates that the distractor direction changes preceded the target direction change.

distractor changes condition). Subsequently, 150 ms later, nine Gabor patches were replaced by black circles ($< 0.5 \text{ cd m}^{-2}$; radius = 0.65°) and one Gabor patch by a green (10.8 cd ; radius = 0.65°) or red (15.5 cd ; radius = 0.65°) circle (i.e. the probe). Participants were asked to respond as fast and accurate as possible to the color of the probe by pressing the z- or m-key when they saw a red or green probe, respectively. On 10% of the trials, the probe appeared at the same location as

the deviant Gabor patch, and on the remaining 90% of the trials, the probe appeared at the location as a distractor Gabor patches. Note that in this way each Gabor patch had an equal probability to be probed. After two practice blocks, participants did nine experimental blocks of 40 trials each. Deviant type (deviant change vs. distractor changes) and probe color were randomly determined and presented within blocks. The probe was presented at the deviant location on 10% of the trials

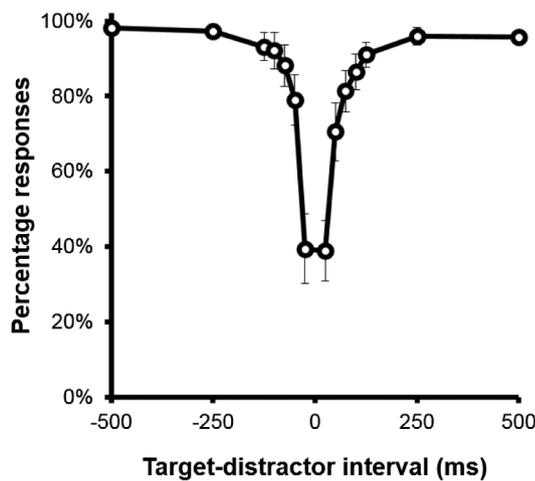


Fig. 5. Percentage of responses before the second target direction change (i.e. responses faster than 1225 ms from the first target direction change) as a function of target-distractor interval, and target-distractor order (target leads vs. target follows) collapsed across set size. The error bars reflect the overall standard errors of the individuals' mean percentage of responses. Note that a negative target-distractor interval indicates that the target change preceded the distractor changes, and that a positive value indicates that the target change followed the distractor changes.

and on the 90% of the trials the probe appeared at a randomly determined distractor location (see also Cass et al., 2011; Theeuwes & Van der Burg, 2007, for a similar procedure). The location of the probe was randomly determined and presented within blocks. Participants received feedback about their overall mean RT and error rate after each block.

3.2. Results

The results of Experiment 3 are presented in Fig. 6. Data from the practice blocks and trials on which participants responded too slow (> 1200 ms) were excluded (2.1%). Correct mean reaction time (RT) and Errors were subjected to an ANOVA with probe location and deviant type (deviant change vs. distractor changes) as within-subject variables.

3.2.1. Reaction time

There was a trend towards a reliable main effect of deviant type, F

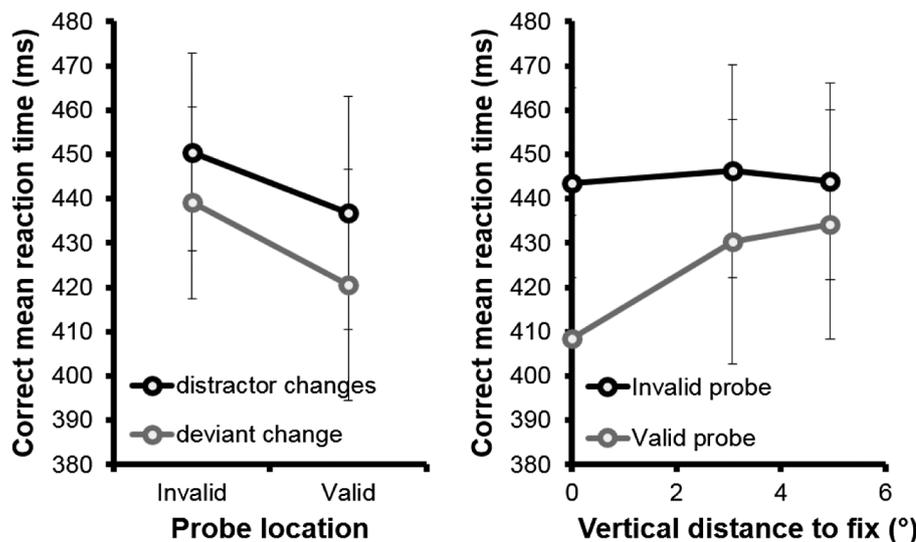


Fig. 6. Results of Experiment 3. Left panel) Correct mean reaction time (RT) as a function of probe location and deviant type (deviant change vs. distractor changes). Note that the location of the probe was irrelevant to the participants' task. Right panel: Correct mean reaction time as a function of probe validity and the vertical position of the target relative to the fixation dot. 0° indicate that the target appeared on the left and right of fixation whereas 4.9° indicates that the target appeared above and below fixation. The error bars reflect the overall standard errors of the individuals mean correct reaction time.

(1, 8) = 5.33, $p = .050$, indicating that participants responded faster overall to the probe when a single Gabor patch changed direction (430 ms) than when all the Gabor patches (except the deviant) changed direction (444 ms). Importantly, for the purpose of the present study, participants responded faster when the probe appeared at a deviant location (429 ms) than when the probe appeared at a non-deviant distractor location (445 ms), $F(1, 8) = 8.74$, $p = .018$. This capture effect was independent of the deviant type as the two-way interaction between probe location and deviant type was far from reliable, $F < 1$.

3.2.2. Errors

The overall rate was 5.0%. The ANOVA on Errors did not result in any significant effects (all $F_s < 3.23$; $p_s > 0.110$).

Responses to a probe were faster when the probe appeared at a deviant location than when the probe appeared at a distractor (non-deviant) location. Even though the probe location was irrelevant for the participants' task, a deviant Gabor patch captured attention in an automatic manner. Whereas other studies reported that a single motion direction change can capture attention (Howard & Holcombe, 2010; Pratt et al., 2010), here we show that a constantly moving object (without a motion direction change) can also capture attention when all the other objects change in the opposite direction to that of the target.

Although the data support the notion that motion direction changes can capture attention, one might argue that observers can perform the task on the basis of apparent shape changes in the ring of stimuli caused by the fact that motion causes position judgments to be offset in the direction of carrier motion, the so-called DeValois effect (De Valois & De Valois, 1991). That is to say, rather than the motion direction being the principle cue driving attentional capture in the above experiments, it is conceivable that performance may instead be informed by apparent motion-induced deformations in the geometry of the virtual ring defined by the positions of the iso-eccentric Gabor elements surrounding fixation.

To examine whether the motion direction deviant appears to be offset of the ring of distractors we conducted a post-hoc analyses. The deviant Gabor could have appeared at three different possible locations on the vertical plane relative to the fixation dot. That is, on the same location as fixation (i.e., on the left or right from fixation; 0°), 3.1° and 4.9° above and below fixation. If it is indeed the offset to the left or right of the ring of distractors, then we expect the validity effect to be contingent upon the location of the deviant Gabor. For instance, a deviant Gabor located at the far left or right of the display is likely to elicit a strong deformation of the virtual ring of distractors as the motion direction is orthogonal to the tangent of the ring. By contrast a deviant

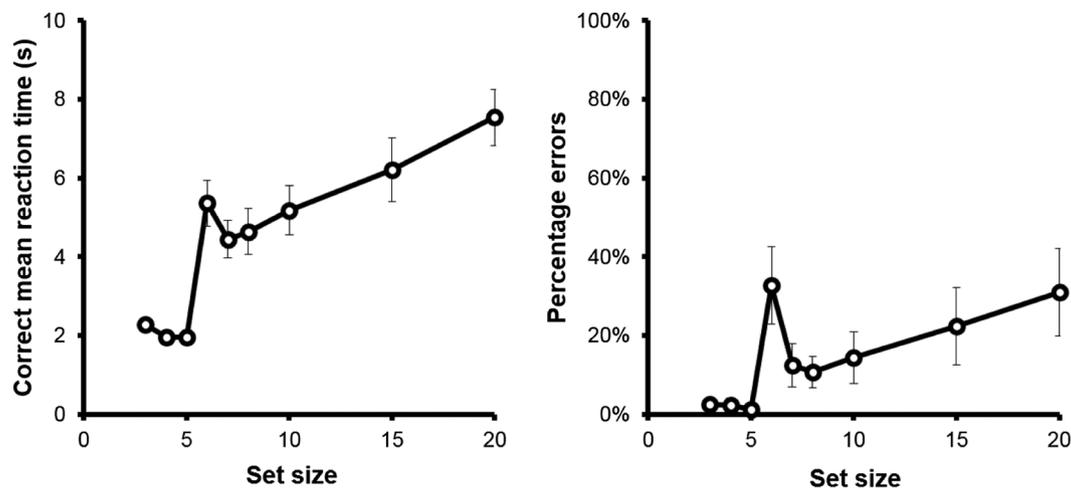


Fig. 7. Results from Experiment 4 (collapsed over target-distractor interval). Left panel: Correct mean RT as a function of set size. The error bars reflect the overall standard errors of the individuals mean correct reaction time. Right panel: Error rate as a function of set size. The error bars reflect the overall standard errors of the individuals mean error rate.

Gabor located at the top and bottom of the distractor display is unlikely to generate as strong a deformation, as the motion direction more closely approximates the tangent of the virtual ring.

Fig. 6 (right panel) illustrates the correct mean reaction times as a function of probe validity and vertical distance of the cue compared to the fixation dot (0° , 3.1° and 4.9° above and below fixation). An ANOVA with probe validity (valid: probe appeared at the same location as the deviant Gabor; invalid: probe appeared at a different location as the deviant Gabor) and vertical distance as within subject variables yielded neither a distance effect, $F(2, 16) = 1.73$, $p = .209$, nor a distance \times probe validity effect, $F(2, 16) = 0.32$, $p = .733$. The probe validity effect was reliable, $F(1, 8) = 7.0$, $p = .029$. Taken together, the results confirm the idea that the position of the deviant Gabor had no significant impact on the validity effect.

4. Experiment 4

So far, we have shown that a motion direction changes pop-out, and even captures attention in an automatic fashion when the deviant Gabor is embedded among homogeneously moving distractors, but not among heterogeneously moving distractors. This latter finding stands in stark contrast with studies showing that a motion direction change captures attention among randomly moving distractors (Howard & Holcombe, 2010; Pratt et al., 2010). One of the key differences in those studies compared ours is that they used a small set size (i.e., four objects), whereas we always used a relatively large set size of up to 20 objects. This may be an important difference, as we know from the multiple object tracking literature that participants can track about four objects simultaneously (see Cavanagh & Alvarez, 2005, for a review; Pylyshyn & Storm, 1988). Interestingly, similar capacity limits have been reported in visual search studies. For instance, several studies have shown that about four flashed locations can be prioritized in search (Van der Burg, Awh, & Olivers, 2013; Wright, 1994; Yantis & Johnson, 1990). Therefore, it might be possible that in both the Howard & Holcombe and Pratt et al. studies, participants were actually attending to all objects, possibly explaining why they found a ‘capture’ effect. This is very unlikely to occur in our case as the set size was simply too large to attend to all the objects.

In Experiment 4 we manipulate the number of distractor Gabors (i.e., 3, 4, 5, 7, 8, 10, 15 and 20 elements) in the search display to examine whether the number of elements in the display plays a crucial role for a deviant motion direction change to pop out among heterogeneously moving distractors. Like in Experiment 2, participants were asked to make a speeded response by pressing the spacebar as soon as

they detected the target. After each trial, participants were again required to identify the target (like in Experiments 1–3) to make sure that they responded to the target event. If participants are able to track a small set of objects in parallel, then we expect to observe search times to be both fast and relatively stable for the small set sizes. By contrast, if the number of elements in the display exceeds the attentional capacity limit then we expect search times to linearly increase with increasing elements in the display. A similar pattern of results is expected for the error rate.

4.1. Method

4.1.1. Participants

Eight students (6 female; mean age 21.1 years; ranging from 18 to 26 years) participated in Experiment 4. All participants were naïve as to the purpose of the experiment.

The experiment was identical to Experiment 2 except for the following changes. The distractors were always drifting and changing direction in a heterogeneous manner. The target-distractor interval was 500 ms and kept constant during the experiment, but the target event was either leading or lagging the distractor events. The participants were asked to make a speeded response by pressing the spacebar when they saw the target. To make sure that the participants indeed responded to the target Gabor patch, we asked them to localize the target after they made the speeded response. The search display contained 3, 4, 5, 6, 7, 8, 10, 15, or 20 Gabor patches.

The independent variable was set size (3, 4, 5, 6, 7, 8, 10, 15, or 20 objects), which was randomized within blocks. Each participant performed one practice block and ten experimental blocks of 36 trials each. Participants received feedback about their overall mean percentage target localization and overall mean RT after each block. Note that for one participant the experiment crashed after he/she pressed the Windows key. As a result, this participant did 289 trials, whereas the others completed 360 experimental trials.

4.2. Results

The results of Experiment 4 are presented in Fig. 7 (collapsed over target–distractor interval). Data from the practice block and trials on which participants responded too slow (> 20 s) were excluded (1.2%). Correct mean reaction time (RT) and Errors were subjected to an ANOVA with set size as within-subject variable.

4.2.1. Reaction time

The ANOVA on RTs yielded a highly significant set size effect, $F(8,56) = 29.179$, $p < .0001$, as search times increased with increasing set size. Separate two-tailed t -tests were conducted to examine whether the RT for each set size was significantly different from the RT in the case there were only three elements in the display (the fewest elements used). The RT was significantly faster when the set size was 4 ($t(7) = 2.788$, $p = .027$), but not when the set size was 5 ($t(7) = 1.979$, $p = .088$), and significantly slower when the set size was > 5 (all t values > 4.720 , all p values $< .005$).

4.2.2. Error rate

The ANOVA on the error rates yielded a significant set size effect, $F(8, 56) = 6.541$, $p < .0001$, as the error rate increased with increasing set size. Separate two-tailed t -tests were conducted to examine whether the error rate for each set size was significantly different from the error rate in the case there were only three elements in the display (the fewest elements used). Participants made significantly more errors when the set size was 6, 9 and 20 (all p values ≤ 0.029), but not for the remaining set sizes (all p values > 0.65). Note that after Bonferroni correction is applied, none of these t -tests yielded a reliable effect.

As is clear from Fig. 7, there was no sign of a speed-accuracy trade-off, as the error data and RT data show a similar pattern. Consistent with Experiment 1, finding the target Gabor among heterogeneous distractors was rather difficult, and became more difficult and time consuming when the number of distractors increased. However, for small set sizes (3–5) the reaction time and error rate remained somewhat constant and independent of the number of distractors in the display. These results suggest that for small set sizes a deviant motion direction change among heterogeneously moving distractors can pop out. Interestingly, search for the deviant Gabor was more difficult and effortful when the set size was 6 compared to when the set size was 7. This was most pronounced in the error data, but also present in the RT data. It is unclear why search was more difficult for this specific set size condition. This may have something to do with the setup of the display, as this is a small set size condition where there are clearly three distractors presented in the left visual field and 3 in the right visual field. More research is needed to understand why a set size of 6 produced such apparently deviant results.

5. General discussion

In the present study, we investigated under what conditions a motion direction change can capture attention. In three experiments we found evidence that a motion direction change can capture attention, but only when this sudden change leads to a deviant motion direction compared to the direction of the other moving objects. Interestingly, we also found evidence for the opposite effect, indicating that a constantly moving object (without a motion direction change) captures attention when all the distractors suddenly change direction in the opposite direction (Experiments 2 and 3). This supports the idea that environmental changes can induce attentional object capture when the object's motion direction is deviant relative to the direction of the other objects within the visual array. Whereas the deviant object was always the target in Experiments 1 and 2, in Experiment 3 we showed that task-irrelevant objects can also capture attention in a stimulus-driven manner.

The present study is not the first study showing that a motion direction change can capture attention in a stimulus-driven manner (Howard & Holcombe, 2010; Pratt et al., 2010). Whereas these studies were successful when using pseudo-randomly moving objects, the present study extends these findings by showing that a motion direction change can, in principle, capture attention when movement only occurs within the carrier component of our vertical Gabor stimuli (whilst preserving the location of the envelope). Howard and Holcombe proposed that motion direction changes can capture attention, but only

when these changes are unexpected (like in animate motion; Pratt et al., 2010). In the present study, the motion direction change was always unexpected, since the motion direction change was not induced by a wall or other external event or object (like in the inanimate and expected condition in the Pratt et al and Howard and Holcombe study, respectively). Even though the motion direction changes were always unexpected, this did not necessarily lead to an attentional capture effect. It is possible that expectancy is important for a motion direction change to capture attention, but it is clear from the present study that the direction of the target compared to the direction of the surrounding objects is a key factor for producing a capture effect.

An intriguing question then is why were Howard and Holcombe and Pratt et al. able to find a capture effect when they used pseudo-randomly moving objects while we clearly failed to find any evidence for a capture effect when the distractors moved in a heterogeneous manner? With regard to the Howard and Holcombe and Pratt et al. study it is important to note that they used a relatively small set size (i.e. four moving objects). The presence of a capture effect might be explained by the capacity of the human brain to store and track multiple visual objects simultaneously. For instance, it is well known that people can track four or even more moving objects simultaneously (Franconeri, Jonathan, & Scimeca, 2010; Pylyshyn & Storm, 1988). In line with this, it is also known that up to four flashing objects can be attended in visual search (Van der Burg et al., 2013; Wright, 1994; Yantis & Johnson, 1990) and that the same number of objects can be stored in visual working memory (Awh, Barton, & Vogel, 2007; Cowan, 2001; Luck & Vogel, 1997). With regard to Howard and Holcombe and Pratt et al., it is feasible that participants may have tracked or monitored all four objects simultaneously, explaining why they observed a capture effect for the attended objects. This might also explain why we were not able to find any evidence for a capture effect when a task relevant object changed direction among our nineteen heterogeneously moving objects.

Whereas it is known that single luminance changes are able to capture attention in an automatic fashion (Theeuwes, 1995), the present findings cannot be explained by a luminance change for some good reasons. First, the initial spatial phase of the carrier grating associated with each Gabor patch in our displays was randomly determined, ensuring that luminance was not a reliable cue with which to segregate target and distractor objects. Second, the luminance changes were similar in the heterogeneous and homogeneous conditions, while a capture effect was only observed in the latter condition. This strengthens the idea that the direction is important for observing a capture effect, instead of a luminance change (see also Howard & Holcombe, 2010 for a discussion). Furthermore, the present study can also not be explained by eccentricity since all objects in our display were of equidistant from fixation.

It is worth mentioning that a previous visual search study has demonstrated that unique differences in direction of movement tend to dominate search performance when compared to unique differences in movement speed (Driver, McLeod, & Dienes, 1992). Whilst this is consistent with our finding of the predominance of directional information, our study extends this by showing that abrupt changes in direction alone are insufficient to capture attention if a unique direction of motion is also present, implying the predominance of direction over speed in visual search.

It should be noted that the RTs in the current experiments are relatively slower than previous pop-out studies (Cass et al., 2011; Theeuwes & Van der Burg, 2011; Theeuwes, Van der Burg, & Belopolsky, 2008). This may be due to several factors. On the one hand, responses are contingent upon the deviant Gabors changing direction, which on average occurred approximately 675 ms after the onset of the display. As a result, this requires that the participant must wait for this period (on average). On the other hand, the participant may occasionally miss this deviant direction change and must therefore wait for a subsequent direction change in this deviant item. Importantly, the

absence of a set-size effect between 3 and 5 items (Experiment 4) suggests that participants were able to track all items simultaneously in these displays, consistent with what is known regarding attentional capacity limitations. At larger set-sizes (6 and above) search becomes inefficient – as evidenced by a significant set-size effect) as increasing numbers of items compete for attentional selection.

How much of the attentional capture effect we observe in our homogeneous distractors was driven by the mere presence of a unique direction of motion is not clear. Future studies might examine this by systematically manipulating the proportion of distractor elements moving in a similar direction to the target. Indeed, we have characterised pop-out performance in our task as an all-or-none phenomenon. In reality, the distinction is likely to reflect a continuum of task difficulty. It is well established that search difficulty critically and continuously depends upon observers' ability to perceptually discriminate the features comprising a target (signal) from its distractor environment (noise) (e.g. Cass et al., 2011; Duncan & Humphreys, 1989; Van der Burg, Cass, Olivers, Theeuwes, & Alais, 2010; Wolfe & Horowitz, 2004). It is conceivable, for example, that the pop out performance observed in our homogeneous distractor conditions may become more difficult (and serial-like) if we were to reduce the overall speed and/or the proportion of motion noise (Braddick, 1995) associated with target and distractor elements. Indeed, as is clear from Fig. 5, a clear pop out was observed when the target-distractor interval was > 25 ms, but not when the interval was 25 ms. Conversely, one might assume that increasing the signal to noise might improve performance in conditions which otherwise yield serial search performance (our heterogeneous distractor conditions). Whilst this latter manipulation may be possible, at least in principle, future research is necessary to establish how this may be implemented.

In summary, we report clear evidence that motion direction changes can capture attention in a stimulus driven manner. However, this is only the case when a motion direction change results in a temporarily deviant motion direction relative to the direction of other objects within the visual array. Interestingly, we also found a capture effect for a constantly moving object (without change) when the motion of all the distractors shifted in the opposite motion direction. This further corroborates the notion that a deviant motion direction captures attention in a stimulus driven manner.

References

- Abrams, R. A., & Christ, S. E. (2003). Motion onset captures attention. *Psychological Science*, 14, 427–432.
- Abrams, R. A., & Christ, S. E. (2005). The onset of receding motion captures attention: Comment on Franconeri and Simons (2003). *Perception & Psychophysics*, 67, 219–223.
- Awh, E., Barton, B., & Vogel, E. K. (2007). Visual working memory represents a fixed number of items, regardless of complexity. *Psychological Science*, 18(7), 622–628.
- Braddick, O. (1995). Visual perception. Seeing motion signals in noise. *Current Biology*, 5(1), 7–9.
- Cass, J., Van der Burg, E., & Alais, D. (2011). Finding flicker: Critical differences in temporal frequency capture attention. *Frontiers in Perception Science*, 2(320), 1–7.
- Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. *Trends in Cognitive Sciences*, 9, 349–354.
- Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, 24, 87–185.
- De Valois, R. L., & De Valois, K. K. (1991). Vernier acuity with stationary moving Gabors. *Vision Research*, 31(9), 1619–1626.
- Driver, J., McLeod, P., & Dienes, Z. (1992). Motion coherence and conjunction search: Implications for guided search theory. *Perception & Psychophysics*, 51, 79–85.
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, 96, 433–458.
- Franconeri, S. L., Jonathan, S. V., & Scimeca, J. M. (2010). Tracking multiple objects is limited only by objects spacing, not by speed, time, or capacity. *Psychological Science*, 2(7), 920–925.
- Franconeri, S. L., & Simons, D. J. (2003). Moving and looming stimuli capture attention. *Perception and Psychophysics*, 65(7), 999–1010.
- Franconeri, S. L., & Simons, D. J. (2005). The dynamic events that capture attention: A reply to Abrams and Christ (2005). *Perception & Psychophysics*, 67(6), 962–966.
- Howard, C. J., & Holcombe, A. O. (2010). Unexpected changes in direction of motion attract attention. *Attention, Perception & Psychophysics*, 72(8), 2087–2095.
- Jonides, J., & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics*, 43, 346–354.
- Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, 390, 279–281.
- Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, 29, 1631–1647.
- Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, 32(1), 3–25.
- Pratt, J., Radulescu, P. V., Guo, R. M., & Abrams, R. A. (2010). It's alive! Animate motion captures visual attention. *Psychological Science*, 21(11), 1724–1730.
- Pylyshyn, Z., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision*, 3, 179–197.
- Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, 51, 599–606.
- Theeuwes, J. (1995). Abrupt luminance change pops out; abrupt color change does not. *Perception & Psychophysics*, 57(5), 637–644.
- Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychologica*, 123, 77–99.
- Theeuwes, J., & Van der Burg, E. (2007). The role of spatial and non-spatial information in visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 33(6), 1335–1351.
- Theeuwes, J., & Van der Burg, E. (2008). The role of cueing in attentional capture. *Visual Cognition*, 16(2–3), 232–247.
- Theeuwes, J., & Van der Burg, E. (2011). On the limits of top-down control of visual selection. *Attention, Perception & Psychophysics*, 73, 2092–2103.
- Theeuwes, J., Van der Burg, E., & Belopolsky, A. V. (2008). Detecting the presence of a singleton involves focal attention. *Psychonomic Bulletin & Review*, 15(3), 555–560.
- Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12, 97–136.
- Van der Burg, E., Awh, E., & Olivers, C. N. L. (2013). The capacity of audiovisual integration is limited to one item. *Psychological Science*, 24(3), 345–351.
- Van der Burg, E., Cass, J., Olivers, C. N. L., Theeuwes, J., & Alais, D. (2010). Efficient visual search from synchronized auditory signals requires transient audiovisual events. *PLoS One*, 5(5), e10664.
- Van der Burg, E., Olivers, C. N. L., Bronkhorst, A. W., & Theeuwes, J. (2008a). Audiovisual events capture attention: Evidence from temporal order judgments. *Journal of Vision*, 8(5) art: 2.
- Van der Burg, E., Olivers, C. N. L., Bronkhorst, A. W., & Theeuwes, J. (2008b). Pip and pop: Non-spatial auditory signals improve spatial visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 34(5), 1053–1065.
- Van der Burg, E., Olivers, C. N. L., Bronkhorst, A. W., & Theeuwes, J. (2009). Poke and pop: Tactile-visual synchrony increases visual saliency. *Neuroscience Letters*, 450(1), 60–64.
- Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience*, 5, 1–7.
- Wright, R. D. (1994). Shifts of visual attention to multiple simultaneous location cues. *Canadian Journal of Experimental Psychology*, 48, 205–217.
- Yantis, S., & Johnson, D. N. (1990). Mechanisms of attentional priority. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 812–825.