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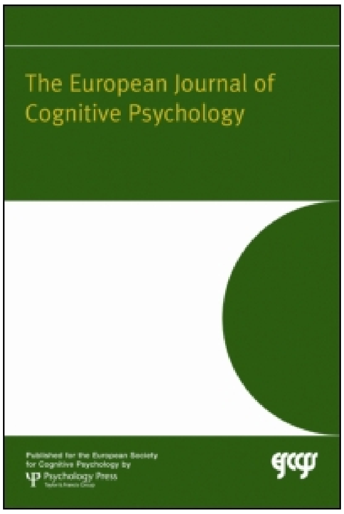

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Attentional capture by motion onsets is spatially imprecise

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Attentional capture by motion onsets is spatially imprecise

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Using straight translatory motion of a visual peripheral cue in the frontoparallel plane, and probing target discrimination at different positions along the cue's motion trajectory, we found that target orientation discrimination was slower for targets presented at or near the position of motion onset (4.2° off centre), relative to the onset of a static cue (Experiment 1), and relative to targets presented further along the motion trajectory (Experiments 1 and 2). Target discrimination was equally fast and accurate in the moving cue conditions relative to static cue conditions at positions further along the cue's motion trajectory (Experiment 1). Moreover, target orientation discrimination was not slowed at the same position, once this position was no longer the motion onset position (Experiment 3), and performance in a target colour-discrimination task was not slowed even at motion onset (Experiment 4). Finally, we found that the onset location of the motion cue was perceived as being shifted in the direction of the cue's motion (Experiment 5). These results indicate that attention cannot be as quickly or precisely shifted to the onset of a motion stimulus as to other positions on a stimulus' motion trajectory.

Keywords: Vision; Attention; Motion; Cueing.

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The current study addresses the potential of motion to capture spatial attention.[1] Early research on this topic concerned the question whether motion captures attention only if it is task-relevant (cf. Folk, Remington, & Wright, 1994), or whether it also captures attention involuntarily (cf. Hillstrom & Yantis, 1994). More recently, however, the focus of the research has shifted towards discussing the power of motion onsets to capture attention (cf. Abrams & Christ, 2003; Franconeri & Simons, 2003, 2005; Kerzel & Müsseler, 2002; Kirschfeld & Kammer, 1999; Müsseler & Aschersleben, 1998). In particular, it has been observed that the starting point of an unanticipated moving stimulus is not perceived at its veridical position, but at a position shifted further in the motion direction.[2] This misperception is called the Fröhlich effect (named after the German physiologist Fröhlich who described the misperception in 1929).

A variety of explanations have been given for the misperception. According to the attentional account, the Fröhlich effect reflects the duration of an attention shift towards the moving stimulus: An attention shift would be necessary to consciously perceive the moving stimulus, but shifting attention takes time. Thus, if the observer cannot anticipate the position of the motion onset, attention can only catch up with the moving stimulus when the stimulus has already moved. As a consequence, the moving stimulus is not seen first at its veridical onset position but at a later position on its motion trajectory (cf. Müsseler & Aschersleben, 1998). Other possibilities are that backward masking of motion onsets by later adjacent stimulation (cf. Kirschfeld & Kammer, 1999) or different degrees of spatiotemporal integration at successive motion stimulus positions (cf. Eagleman & Sejnowski, 2007) could be creating the Fröhlich effect.

Consider backward masking: According to Kirschfeld and Kammer (1999), backward masking by a subsequent adjacent stimulus most strongly diminishes the visibility of the first position of a moving stimulus and less so the visibility of its later positions. The reason is that only the motion onset does selectively suffer from backward masking (i.e., a reduction of its

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[1] "Attentional capture by motion" denotes the attraction of an observer's spatial attention by a moving stimulus. Note that this is not the same as "motion capture", a term sometimes used to denote (a) the recording and translating of movement into a digital model in computer animation, or (b) a form of perceived illusory motion in a static stimulus that is presented adjacent to a moving stimulus.

[2] The illusion is sometimes also in the other direction. The onset repulsion effect denotes that a moving object can be memorised as being shifted in the direction opposite to that of its motion direction (cf. Hubbard & Motes, 2002; Thornton, 2002). So far, it is not fully clear what factors account for whether a Fröhlich effect or an onset repulsion effect is found but one likely moderating variable seems to be the predictability of the target onset position, with the Fröhlich effect being typical for better predictable targets and onset repulsion effects for less predictable targets (cf. Müsseler & Kerzel, 2004; but see Müsseler, Stork, & Kerzel, 2008).

visibility) by the subsequent adjacent stimulation without compensatory priming by preceding adjacent stimulation. For all stimulus positions further along the motion trajectory, priming partly outweighs masking. Next consider spatiotemporal integration: Perception takes time and perception's inertia means that temporally extended stimulation is not necessarily spatiotemporally resolved in the representation of an image (cf. Eagleman & Sejnowski, 2007). In particular, the first image of a moving stimulus could be feeding into a representation integrated across several stimulus positions. As a consequence, a moving stimulus at motion onset would be perceived as being shifted in the motion direction and in addition potentially also as being blurred (or "smeared"), as Fröhlich also believed (see also Kirschfeld & Kammer, 1999).

Whatever the correct explanation of the Fröhlich effect, if the onset of a moving stimulus is misperceived, it follows that attentional capture to the motion onset position could be also diminished. This prediction most obviously follows from the attentional account, because a failure of attentional capture to the motion onset position is assumed to explain the Fröhlich effect in the first place. Spatiotemporal integration, however, could be also having the same negative consequences for the spatial precision of attentional capture towards motion onset positions: If a moving stimulus at motion onset is perceived as being shifted and additionally as being blurred (or "smeared" because it is integrated over a region encompassing more than one stimulus position), as Fröhlich believed (see also Kirschfeld & Kammer, 1999), then we might also find a less accurate shifting of attention towards the position of the motion onset than towards subsequent positions along a stimulus' motion trajectory, because an invisible onset or a blurred motion onset would be also providing a less confined spatial signal than a stimulus position near the end of stimulus motion, at which latter point a moving stimulus is visible and might also no longer be integrated across as many successive positions. Only in the case that masking accounts for the mislocalisation of motion onsets, it seems, the spatial precision of attentional capture could be kept. This is suggested by studies demonstrating attentional capture by masked stimuli (cf. Scharlau, 2002; Scharlau & Ansorge, 2003).

The spatial precision of attentional capture by motion onsets has so far only been studied once in an experiment by Müsseler and Aschersleben (1998). In that experiment observers failed at detecting a brief pattern change at motion onset but were better at detecting the change at positions further along the stimulus' motion trajectory (Exp. 5 of Müsseler & Aschersleben, 1998). This finding seems to require a mediating role of a lesser spatial precision of attentional capture to the motion onset to explain how pattern discrimination could have been lower at motion onset.

However, this conclusion is not certain because a number of influences besides the spatial precision of attentional capture by a motion onset could have diminished pattern discrimination near the motion onset. First, *visibility* could be accounting for the lower discrimination performance. Müsseler and Aschersleben (1998) presented the discriminated pattern only briefly as a feature of the moving stimulus. Thus, lower visibility of a motion onset alone could have diminished pattern visibility near motion onset. On such an account, there is no need to refer to attentional capture to understand the lower pattern discrimination because factors such as backward masking could be equally accounting for the low visibility of motion onsets as was explained earlier.

Second, a lower pattern discrimination performance near motion onset could reflect an *increasing predictability of the pattern's position over time.* Because the number of positions where the pattern could be shown was inversely proportional to the distance already covered by the moving stimulus, the number of the possible positions where the pattern could be found steadily decreased with the duration of stimulus motion. Discrimination would have benefited most from this uncertainty reduction over time if the pattern was presented near the moving stimulus' end position, whereas discrimination would have benefited least from this uncertainty reduction over time for patterns near the moving stimulus start position.

Third and related, *interference by coding the stimulus' motion (direction)* could have substantially decreased pattern discrimination near motion onset. If both coding (the direction) of stimulus motion and discrimination of a visual spatial pattern rely on a similar mechanism, coding the cue's motion could have more strongly competed with pattern discrimination near motion onset and less so the further the stimulus moved, simply because from pattern onset on the relative duration of the stimulus motion decreased and, thus, the time or capacity needed for coding the motion's direction.

Finally, the interval between motion onset (as well as stimulus onset) and pattern was consistently longer the further the pattern was presented away from motion onset. Thus, a better discrimination of patterns presented further along the stimulus motion trajectory could have also reflected a spatially unspecific temporal waning effect of stimulus onset.

In light of these procedural confounds and the theoretical possibility that motion onsets could be capturing attention in a spatially precise manner, the current study aimed to corroborate that shifting of attention to a motion onset stimulus is not quick enough to code the onset and, thus, spatially inaccurate. We used a spatial cueing paradigm, in which a moving stimulus served as an attention-capturing cue but measured the cue's effect on processing of a subsequently presented static target of sufficient duration (1 s) to be seen. Concerning the cueing procedure, if a relevant to-be-discriminated target's position cannot be anticipated, a cue at one of the potential target positions facilitates discriminating or identifying at least some of the target's features (cf. Posner, 1980). This facilitation is found in comparison to a neutral condition without a cue or a condition with a cue at a position away from the target. The cueing effect is thought to reflect the shifting of attention. The cue captures attention and, thus, if at target position it shortens the duration for discriminating the target by the time that would otherwise be necessary for shifting attention to the target (cf. Posner, 1980). Note that this prediction only holds true for target features like shape or orientation which require a prior shifting of attention for being successfully discriminated. Other features like colour that can be found without a prior shifting of attention to the position of the feature accordingly are not affected by an advance cueing (cf. Treisman, 1988).

For these reasons, we expected facilitation of discrimination of target patterns (here: target orientations) by cueing the targets with a moving stimulus. However, on the basis of the observations of Müsseler and Aschersleben (1998), we also expected less of such facilitation of discrimination for targets cued by a motion onset than for targets cued by a moving cue that has already moved further along its motion trajectory. Attentional capture by the motion onset, if it occurs at all, should be at least spatially less precise than capture by a moving stimulus that has moved further along its motion trajectory.

In comparison to the procedure used in Experiment 5 of Müsseler and Aschersleben (1998), our cueing procedure has the advantage that the static target can always be seen. As a consequence, one of the potential alternative accounts of the expected performance difference can be ruled out: Any effects of the phase of the moving cue (onset vs. later positions of the cue) on discriminating target orientation that we might find cannot be ascribed to different degrees of target visibility. Cueing the static target with a moving cue might lead to invisibility of the cue but not of the target. The moving cue might affect the precision of discriminating the target's orientation and, thus, create response time (RT) differences for discriminating the target at different positions of the moving cue. However, the static 1 s target will be visible under all of the conditions. Therefore, in our Experiments 1–2 (presented later), the expected less efficient discrimination of target orientations cued by motion onsets cannot be ascribed to an invisibility of the corresponding features themselves but must be due to a diminished cueing effect. Also, step by step, we rule out in the subsequent experiments all conceivable effects of the cue but its attentional capture effect as potentially accounting for the expected performance differences.

In Experiment 2, we rule out that different degrees of target predictability could be accounting for different cueing effects by motion onsets versus motion offsets. In Experiments 2 and 3, we will also rule out that the expected diminished orientation discrimination of targets cued with a motion onset could have reflected coding of the (direction of the) cue's motion. In Experiment 4, we use colour discrimination, which does not require a prior shifting of attention to the colour stimulus, and show that under these conditions, cueing by motion onsets versus offset, for example, does not alter target discrimination performance, an observation fully in line with the attentional explanation of the cueing effect. Finally, in Experiment 5 we demonstrate that the moving cue is seen shifted in the direction of its motion, thus, providing converging independent evidence for a diminished spatial precision of spatial coding at motion onsets.

EXPERIMENT 1

With a cueing approach we wanted to demonstrate that attention shifts to the motion onset of a stimulus are indeed less accurate than towards positions further along the motion trajectory of the stimulus. Our cueing approach, allowed directly pitting the power of a moving cue to capture attention against that of a static abrupt-onset cue at the same position. Our observers had to discriminate whether an upward or a downward pointing arrow was shown to them as a static visual target. This target was shown unpredictably at one of several alternative positions to the left or to the right of screen centre. Crucially, 85 ms prior to the target we presented a peripheral cue which moved in one blocked condition but was static in the other blocked condition. The static cue validly indicated the target's position (in 100% of the trials). Performance under static cue conditions provided a baseline against which we measured the ability of the moving cue to capture attention to different positions along its motion trajectory. Based on previous findings, we expected participants to attend to the static informative cue and to accordingly shift their attention towards the target position in anticipation of the target (cf. Müller & Rabbitt, 1989; Posner, 1980).

In the moving cue condition, the cue also validly predicted the side on which the target was shown. However, after its onset the cue moved horizontally towards the screen centre (i.e., centripetally) or towards the screen's periphery (centrifugally) with 1° lateral movement per each of five consecutive refreshes of the computer screen (with a refresh duration of 17 ms). Most importantly, the target was equally likely presented at each of the five different positions along the moving cue's motion trajectory. Thus, we gave our participants an incentive to attend to the motion onset and to direct their attention to the side of the screen at which the motion onset occurred. However, we did not provide an incentive to willingly attend to one particular position along the motion trajectory because the target was presented equally likely at each of the positions on the trajectory. Note also that we took care to equate the interval between each particular position of the moving cue and the target. This interval was always 85 ms. As one further favourable consequence of the particular interval we chose, static cues as well as moving cues and targets were always presented in succession: Even at the earliest time that a target could have been presented, the moving cue had been turned off.

Our predictions were straightforward. If it is true that capturing of attention by the motion onset is spatially not precise, then performance should be worse when the target position is precued by a motion onset than when it is precued by a static cue. However, assuming that attention shifts to the moving cue become more precise as it further moves along its motion trajectory, we would expect performance to improve for cueing the target by positions of the moving cue after the motion onset position.

Here a side remark might be in order: True, not only motion onsets but also motion offsets can be perceived as shifted in the direction of motion ("representational momentum"; for a review see Hubbard, 2005). Also, representational momentum can transfer to a subsequent static stimulus, like the static target in the current experiment. However, representational momentum does not reflect a spatially less confined capture of attention to any of the positions at or near motion offset. Therefore, there is no reason to expect that a distorted localisation of the moving cue or a consequential mislocalisation of the subsequent static target at the cue's motion offset, even if it occurs, should decrease our observers' ability for discriminating target orientation.

Thus, with an increasing distance from motion onset the probability increases that attention catches up with the moving cue, so that the processing of a static target at that particular position would benefit from an advance shifting of attention to the position of the moving cue. Note that this prediction holds on the attentional account of the Fröhlich effect but also if perceived blur of the cue would be inversely proportional to motion duration or if motion onset positions of the cues were invisible because of perceptual inertia and spatiotemporal integration: Attentional capture should then be also either only possible towards the end of the cue's motion trajectory where the cue can be seen or it should be at least spatially more precise if blur would be lesser for positions further along the cue's motion trajectory.

In addition, to get a fine-grained estimate of the cueing effect under the different conditions, we also varied and analysed cue eccentricities. Some authors found, for example, a less accurate localisation of an outward moving relative to an inward moving stimulus (cf. Müsseler & Aschersleben, 1998). Since it is at present unknown whether these differences in the Fröhlich effect reflect spatial inaccuracies of shifts of attention, we incorporated eccentricity as an additional variable.

Method

Participants. Twelve students (10 female, 2 male) with a mean age of 27 years participated in Experiment 1. Here and in later experiments, they were naïve with respect to the hypotheses under investigation.

Apparatus. The experiment was controlled by a computer that also served for data registration. Stimuli were presented on a 15-inch colour monitor. A serial mouse was used to register responses. Participants pressed the left or right mouse button with the index finger of the corresponding hand, and latencies were measured from the beginning of the target to the nearest millisecond. The participants sat in a dimly lit room, 65 cm in front of the screen, with their line of gaze kept straight ahead by a headrest.

Stimuli and procedure. Figure 1 depicts an example of the stimuli in Experiment 1. All stimuli were presented in grey (24 cd/m^2) on a black background (<1 cd/m^2). Each trial started with the presentation of a fixation cross centred on the screen for 800 ms. Next the cue was shown. It consisted of an outline circle (side thickness 2 pixels) with a diameter of 1°. In the moving cue condition, the cue appeared at a screen location 4.2° left or right of fixation, and was presented for altogether 85 ms. It consistently moved centripetally or centrifugally by 1° with each refresh of the screen and covered a distance of altogether 4°, leading to a presentation duration of 85 ms. In the static cue condition, the cue was presented at only one of the five possible positions for the duration of a single refresh. Thus, the static cue was shown for 17 ms, which corresponds to the duration that the moving cue was presented at each single location along its motion trajectory. In the static cue conditions, the time interval between the cue at the target's position and the target was also 85 ms. After the cue vanished, the target was presented stationary for 1 s. The target was an upward or a downward pointing arrow. In the static cue condition, the target always appeared at the position of the cue, whereas in the moving cue condition, the target was equally likely presented at one of the five positions along the motion trajectory of the moving cue.

Note that this means that static and moving cue conditions differed from one another in terms of the observer's certainty about the target position (see also Figure 1). Directly after a moving cue was presented, each position of the moving cue contained the target equally likely. Thus, the moving cue indicated the exact target location with 20% likelihood, whereas the static cue informed about the target position with 100% certainty. Static and moving cue conditions differed also in terms of the overall duration of the cue (static cue: 17 vs. moving cue: 85 ms) and in terms of the variability and the average length of the interval between the cue onset/motion onset and the target onset (static cue: 85 ms vs. moving cue: 85–170 ms).

These drawbacks of the present procedure were accepted to keep the duration of the moving cue at each particular position and that of the static cue the same, and also to keep the interval between the moving cue at a particular position and the target at that very cue position as well as the interval between the static cue and the target constant across different cue

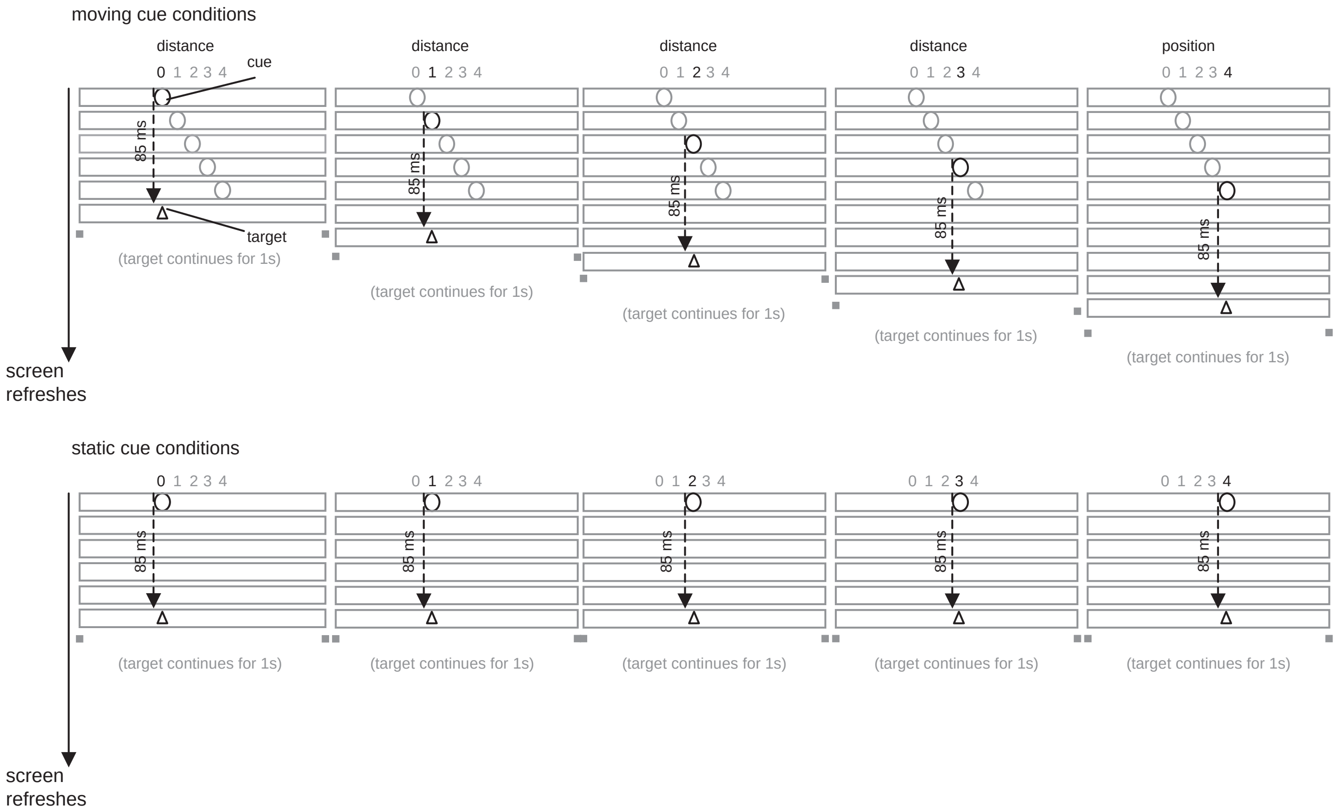

Figure 1. (*See facing page for caption*).

Figure 1 (opposite). Depicted are schematic illustrations of moving cue conditions (upper rows) and static cueing conditions (lower rows) of Experiment 1. From top to bottom, each line represents one refresh of the computer screen. Within each frame, the stimulus could have occupied 1 out of 20 positions (2 sides × 10 eccentricities). In the Figure, only 5 different positions are indicated numbered 0 to 4 corresponding to their distance in degrees of visual angle relative to the 4.2° reference position. For each of the columns in the upper rows, the cue shifted by 1° per each refresh of the computer screen for altogether 5 frames creating apparent motion of the cue. The lowest line in each of the upper rows' columns shows an example of a target (here: an upward pointing arrow head). From the leftmost column to the rightmost column of the upper rows, the target is presented with an increasing distance to the moving cue's motion onset position at 4.2° (in the upmost line of the upper row).

For each of the columns in the lower rows, the cue was presented at the same position (but shifted by different degrees to the reference point at 4.2°) for a single frame creating a static cue. From left to right, columns of the lower rows depict the corresponding static cueing conditions to control for each of the respective moving cue conditions. Again, the lowest line in each of the lower rows' columns shows an upward pointing arrow head as an example of a target.

The black arrows on the left depict the direction of time; the black dotted arrows within the columns depict the cue-target interval, which was kept the same for all cue-target position combinations. The dots at the final lines of all upper rows' and all lower rows' columns stand for the continuation of the target. Targets and the (first) target-preceding cue at the target's position are highlighted (black). Stimuli are not drawn to scale.

conditions. The confounded factors were controlled for in turn in subsequent Experiment 2 (see later) in which we accepted the complimentary confound of using different exact intervals between, on the one hand, the moving cue at motion onset and the target at the cue's motion onset position versus, on the other hand, the moving cue at motion offset and the target at the moving cue's motion offset position.

Participants had to press the left key for an upward pointing arrow and the right key for a downward pointing arrow, or vice versa. The different stimulus–response (S-R) mappings were balanced across participants. In case of an inadequate response, feedback was presented for 700 ms at the screen centre. For an incorrect response the message read "*Falsche Taste!*" ("Wrong key!"), for a response slower than 1250 ms "*Schneller reagieren!*" ("Respond faster!"), and for a response faster than 100 ms, "*Langsamer reagieren!*" ("Respond slower!"). The intertrial interval was 2100 ms.

Moving and static cue conditions were run in separate blocks, with the order balanced across participants. Within blocks, each of the two targets was equally likely at each of the 20 positions (10 possible target locations on each side of the screen). Different conditions were pseudorandomised within blocks. After a few practice trials, each participant worked through altogether 400 trials, with 10 repetitions of the target at each of its positions in each of the two blocks. This took approximately 45 minutes.

There were three variables of interest: cue type (moving cue vs. static cue), distance of target to starting position of the moving cue (target is 0°, 1°, 2°, 3°, or 4° centripetally or centrifugally shifted from the 4.2° motion onset position as a point of reference),[3] and direction of target position relative to motion onset (target position shifted centripetally or centrifugally, both relative to the 4.2° starting position of the moving cue). Repeated-measures ANOVAs of the means of individual medians of correct RTs and arc-sine transformed error rates were conducted with these three variables. Where appropriate, degrees of freedom were adjusted by Greenhouse Geisser's ε and the corrected significance levels are reported.

Results

See Figures 2 and 3 for the results. Out of all responses, 1.3% was discarded because they were faster than 100 ms or slower than 1 s. The ANOVA calculated over the mean RTs showed significant main effects of cue type,

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[3] Under static cue conditions, trials with targets presented at 4.2° were arbitrarily subdivided in halves for providing two baselines, one for the targets at 4.2° under motion cueing conditions with a centripetally moving cue, the other one for the targets at 4.2° under motion cueing conditions with a centrifugally moving cue.

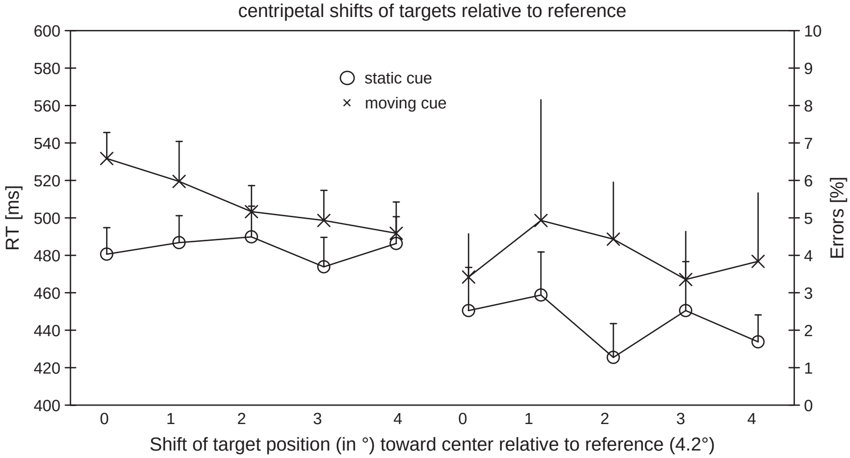

Figure 2. Mean reaction times (RTs) in milliseconds (ms) and mean error rates in percent (crosses; circles), and the corresponding standard errors (vertical lines), as a function of cue type (moving cue vs. static cue) and target position ($-0°$, $-1°$, $-2°$, $-3°$, $-4°$) shift in the direction of screen centre relative to the reference point at 4.2° of Experiment 1.

$F(1, 11) = 7.92$, $p < .05$, distance, $F(4, 44) = 7.48$, $p < .01$, and direction, $F(1, 11) = 10.25$, $p < .01$. Most importantly, we observed a significant Cue type × Distance interaction, $F(4, 44) = 2.83$, $p < .01$. The remaining interactions were not significant, all Fs < 1.00. Responses to targets under moving cue

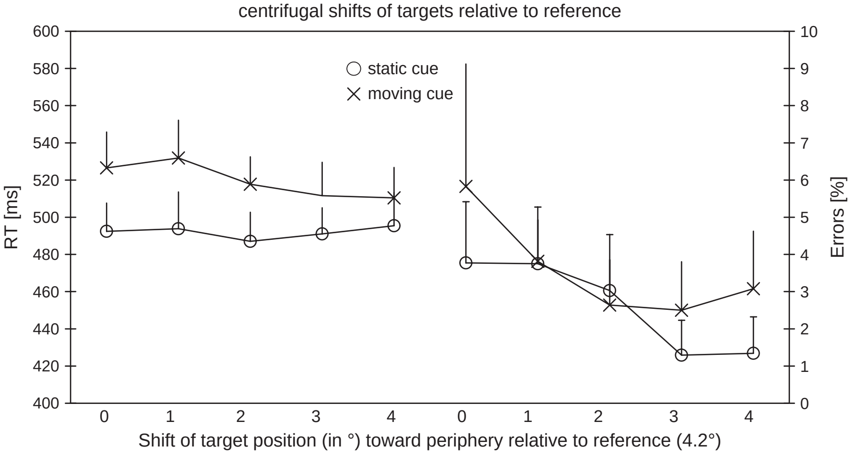

Figure 3. Mean reaction times (RTs) in milliseconds (ms) and mean error rates in percent (crosses, circles), and the corresponding standard errors (vertical lines) as a function of cue type (moving cue vs. static cue) and target position ($+0°$, $+1°$, $+2°$, $+3°$, $+4°$) shift in the direction of the screen's periphery relative to the reference point at 4.2° of Experiment 1.

conditions were delayed ($\text{RT} = 514$ ms) relative to static cue conditions ($\text{RT} = 488$ ms). However, significant RT delays were restricted to the first four positions along the cue's motion trajectory (moving cue: target at 4.2° $\text{RT} = 529$ ms; target 1° away from 4.2° $\text{RT} = -3$ ms; target 2° away from 4.2° $\text{RT} = -19$ ms; target 3° away from 4.2° $\text{RT} = -24$ ms; static cue: target at 4.2° $\text{RT} = 487$ ms, target 1° away from 4.2° $\text{RT} = +3$ ms; target 2° away from 4.2° $\text{RT} = +2$ ms; target 3° away from 4.2° $\text{RT} = -4$ ms), all four $t\text{s}(11) > 2.10$, all four $p\text{s} < .05$, one-tailed. By contrast, no significant delay for target RTs under moving cue conditions relative to static cue conditions resulted for targets presented at the cue's motion offset (moving cue: target 4° away from 4.2° $\text{RT} = 501$ ms; static cue: target 4° away from 4.2° $\text{RT} = 491$ ms), $t(11) < 1.00$. Besides, responses to targets closer to the screen centre were faster ($\text{RT} = 496$ ms) than responses to targets in the periphery ($\text{RT} = 506$ ms).

There was a tendency towards a significant main effect of cue type in a corresponding ANOVA of the arc-sine transformed error rates, $F(1, 11) = 2.95$, $p = .11$, reflecting an inflated error rate under moving cue conditions (error rate = 3.8%) relative to static cue conditions (error rate = 2.4%). The remaining main effects and interactions were not significant, all $F\text{s} < 1.50$, all $p\text{s} > .25$.

Discussion

The results of the first experiment are tentatively in line with the assumption that capturing of attention by the onset of a moving stimulus is spatially less accurate than the alignment of attention with positions further along the trajectory of a moving stimulus (and with the position of a static stimulus): We found the fastest responses for targets under static cue conditions and that discrimination responses to targets cued by motion onsets was significantly slower relative to the corresponding static cue conditions. By contrast, discrimination responses for targets presented at the cue's motion offset position were not delayed relative to the static cue condition. In addition, under the moving cue conditions, from motion-onset position to motion-offset position, performance became faster (see Figure 2).

Besides, we observed somewhat slower responses for the more peripheral targets than for the more central ones. This is a standard finding in visual discrimination tasks that presumably reflected the decreasing spatial resolution of the eyes' retinae with an increasing distance from the fovea (cf. Daniel & Whitteridge, 1961; Rentschler & Treutwein, 1985). Remember that participants had to discriminate between two target orientations, a task that requires relatively fine visuospatial resolution. To note, a less accurate localisation of the peripheral cues than of the central cues and an even less accurate localisation of the outward moving relative to the inward moving cue (corresponding to a similar difference in the Fröhlich effect; cf. Müsseler & Aschersleben, 1998) might have also contributed to the effect, but the three-way interaction failed to confirm a stronger eccentricity effect for the moving cues than for the static cues.

According to our main research question, the results could have reflected an imbalance in the shifting of attention to the precise position of the moving cue during its different motion phases: The moving cue at its motion onset would have not captured attention as precisely as the static cue or it would have not captured attention at all. Yet at the later positions along its motion trajectory the moving cue, too, served as a valid cue for targets presented there. The likely origin of the lower attentional effect of the moving cue at motion onset is that the motion onset is only badly localised or not at all and that a moving cue is better localised during later phases of its motion.

In comparison to the findings of Müsseler and Aschersleben's (1998) Experiment 5, Experiment 1 ruled out two alternative explanations of the effect. First, we presented a static target long enough that it could always be seen. Still, we found an RT difference for discriminating target orientation at the cue's motion onsets relative to targets cued by positions further along the cue's motion trajectory. Thus, a lower visibility of targets at motion onset can be ruled out as a potential explanation for the diminished discrimination of target orientations cued by motion onsets.

Second, the findings of Müsseler and Aschersleben's (1998) Experiment 5 could have reflected more temporal warning by stimulus onsets preceding target patterns at later motion positions than for patterns at motion onset. If less temporal warning would be accounting for the lower discrimination performance of targets at motion onset, however, we should have found a better performance with targets cued by (a) motion offsets (cue onset-to-target interval = 170 ms) than by (b) static cues (cue onset-to-target interval = 85 ms). This was not found. Therefore, we think that it is unlikely that different temporal warning intervals since stimulus onset are the sole major responsible factor for the target discrimination differences in the present experiment or in Experiment 5 of Müsseler and Aschersleben (1998).

Still, the lower cueing effect of motion onsets could have had origins different from a spatially less precise attentional capture. Experiments 2–4 provided altogether three different control conditions to rule out all alternative interpretations of our results.

EXPERIMENT 2

In the introduction, we noted that a lower cueing effect for targets cued by motion onsets relative to targets cued by positions further along the motion trajectory could not only reflect a spatially less precise capture of attention but also less warning time after stimulus onset, interference by coding the cue's motion direction, or a lower predictability of the target position immediately after the moving cue than with each additional frame after cue offset (i.e., the number of positions decreased by 1 every 17 ms after the moving cue was turned off, meaning that the highest predictability existed for targets presented at the motion offset position of the moving cue). Note that all these differences, but one, also existed between conditions in which cueing was by motion onsets and conditions in which cueing was by static cues. (The one exception was the temporal interval between the particular cued position at which the target was shown and the target: This interval was the same in motion onset cue conditions and in static cue conditions.)

In Experiment 2, we ruled out these alternative explanations. To show that changes of the moving cue's predictive value for the target's most likely position did not account for the major findings of Experiment 1, we aimed at demonstrating inferior discrimination of targets cued by motion onsets than by motion offsets, when both of these moving cue conditions predict the target position equally well, right from the onset of the motion cue and throughout the trial. To that end, we only used motion onset cueing and motion offset cueing and realised these two different conditions in separate blocks. As a consequence, once the moving cue had had its onset observers knew exactly where the target appeared. For instance, in a block in which targets were always shown at the cue's motion onset position and a left-moving cue was at 4.2° left of fixation, the observer knew that the target was also shown at 4.2° left of fixation. Likewise, in a block in which targets were always shown at the end position of the cue's motion, with a left-moving cue presented 4.2° left of fixation, the observer knew that the target was shown at 8.2° left of fixation.

If focusing or shifting of attention is spatially less accurate for motion onsets than offsets, target discrimination responses if cued by motion onset should be again slower than if cued by motion offset. However, if the lower prediction of the target's position by the motion onset cue than by the motion offset cue accounted for a slow discrimination of targets cued by motion onset, then there should be no differences in discrimination performance between Experiment 2's moving cue conditions.

To rule out that a longer interval between cue onset/motion onset and target onset in conditions with motion offset cues (interval = 175 ms) than in conditions with motion onset cues (interval = 85 ms) accounted for the slower discrimination of targets cued by motion onsets, the interval between the cue onset/motion onset and the target was kept the same (interval = 85 ms) in both of the moving cue conditions (see Figure 4).

If different intervals accounted for target discrimination differences, no such differences were to be expected in the present experiment. By contrast, if spatially less precise attentional capture by motion onsets than offsets was responsible for the results, we expected to again find a better performance for target orientation discrimination if targets are cued by motion offsets than onsets.

To rule out that more coding of motion direction in-between motion onset and response than in-between motion offset and response accounted for the discrimination differences we used static cue control conditions. If our reasoning is correct that spatial attentional capture by the motion onset more or less failed and that a motion offset can capture attention precisely to its position, we can mimic the effect between the two different moving cue conditions by simply eliminating all of the moving cue but its presence at the final position: In this control condition, we should be able to mimic the target discrimination differences by showing a static cue at the end position of the motion trajectory (at 0.2° or 8.2°) and either present the target away from that cue at 4.2° (corresponding to the motion onset cue condition) or at the position of that cue (at what corresponds to the motion offset cue position).

If it is true that the motion onset cue fails to capture attention and the motion offset cue fully captures attention, we expected to replicate the findings from the moving cue conditions under these static cue conditions. We expected slower responses for targets presented away from the static cue (i.e., for conditions mimicking target discrimination at motion onset position) relative to targets presented at the static cue (i.e., for conditions mimicking target discrimination at the cue's motion offset position). Note that under these static control conditions, different amounts of interference by coding the cue's motion direction were effectively ruled out.

Therefore, if interference by coding the cue's motion direction in-between motion onset and response contributed to the slower discrimination of targets cued by motion onsets relative to targets cued by motion offsets, we expected to find a smaller difference between the different static cue conditions than between the different moving cue conditions. The reason is that the different static cue conditions only mimicked the attentional difference between the two different moving cue conditions. In the extreme, if coding of cue motion direction in-between the cue's motion onset and the response alone accounted for the slow discrimination of targets cued by motion onsets, no such slowing might be observed in the static cue control conditions at all.

Note, of course, that everything else had to be and was the same in the static cue conditions as it was in the moving cue conditions of the present experiment. For instance, the different static cue conditions were also realised in separate blocks. Therefore, all of the cueing conditions, static as well as moving cue conditions, were strictly comparable to one another in terms of the cue's prediction of the upcoming target's location.

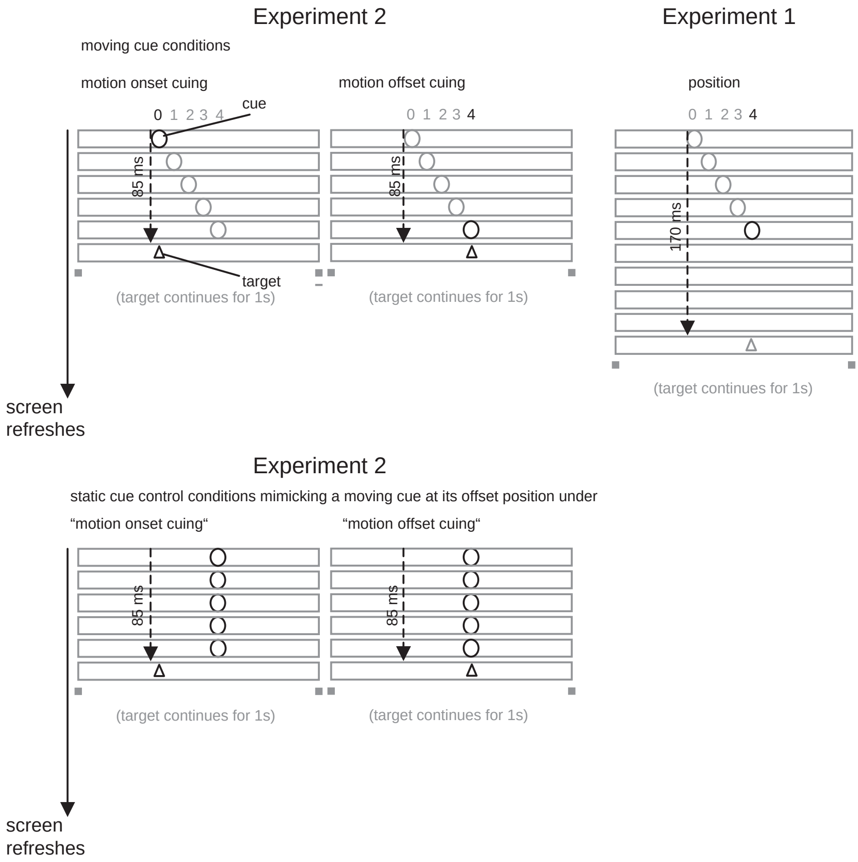

Figure 4. (*See facing page for caption*).

Method

Participants. Fifteen students (11 female, 4 male) with a mean age of 24 years participated in Experiment 2.

Apparatus, stimuli, and procedure. See also Figure 4. These were the same as in Experiment 1, with the following exceptions. First, only two kinds of moving cue conditions were realised. The target was either shown at the motion onset position of the moving cue (with 4.2° eccentricity) or at the end position of the moving cue (with 0.2° or 8.2° eccentricity).

Second, only two kinds of static cue conditions were realised. Mimicking cueing by a motion onset, the static cue was shown either 0.2° or 8.2° left or right of fixation and the target was shown 4.2° on the same side of fixation as the cue.

Figure 4 (opposite). Depicted are schematic illustrations of moving cue conditions (upper rows) and static cueing conditions (lower rows) of Experiments 2 (on the left) and 1 (at top right). From top to bottom, each line represents one refresh of the computer screen. Within each frame, the stimulus could have occupied 1 out of 20 positions (2 sides × 10 eccentricities). In the Figure, only 5 different positions are indicated numbered 0 to 4 corresponding to their distance in degrees of visual angle relative to the 4.2° reference position. For each of the columns in the upper rows, the cue shifted by 1° per each refresh of the computer screen for altogether 5 frames creating apparent motion of the cue. The lowest line in each of the upper rows' columns shows an example of a target (here: an upward pointing arrow head). The left column of the upper row depicts a condition with the target presented at the motion onset position of the moving cue. The middle column of the upper row depicts the target presented at the motion offset position of the moving cue. The right column of the upper row depicts a condition of Experiment 1, with a target at the motion offset of the moving cue. As can be seen one major difference between the experiments concerns the interval between motion onset and target. In Experiment 1, different moving cue conditions are equated for the motion onset to target interval (instead of being equated for the cue-target interval for the moving cue at target position as was the case in Experiment 1).

The left column in the lower row shows the static cue shifted by 4° relative to the reference point (i.e., the point at 4.2° eccentricity corresponding to the motion onset position of the moving cue) and the static target at the reference point. The right column in the lower row shows the static cue as well as the static target shifted by 4° relative to the reference point. As it can be seen, the two different position relations between static cue and target in the lower rows were thus replications of the two different position relations between the moving cue's final motion position and the target position in the upper rows.

The black arrows on the left depict the direction of time; the black dotted arrows within the columns depict the interval between motion onset or cue onset and target, which was kept the same for all conditions. The dots at the final lines of all upper rows' and all lower rows' columns stand for the continuation of the target. Targets and the (first) target-preceding cues are highlighted (black). Stimuli are not drawn to scale.

Mimicking cueing by motion offset, the static cue was shown either 0.2° or 8.2° left or right of fixation, and the target was presented at the same position as this cue. Note also that we took the opportunity to equate overall static and moving cue durations. Both of these cues were now presented for 85 ms. This was not expected to alter the results under the static cue conditions because we assume that the static cue's attentional effect depends entirely on its onset (as assumed in Experiment 1) with little additional influence of its duration.

Third, each of the four different cueing conditions (two moving cue conditions and two static cue conditions) was realised in a separate block.

Fourth, the interval between the onset of the cue and the static target as well as the duration of the cue was 85 ms under all conditions. Thus, the procedure equated the static cue conditions and the moving cue conditions in these two respects in which the cue type conditions differed in the preceding experiment. This procedure has one drawback: In the moving cue conditions, it creates a longer interval between the cue's motion onset and the target at that very position (i.e., an interval of 85 ms) than between the cue's motion offset and the target at that very position (i.e., an interval of 17 ms). This is the "complementary" confound to that of Experiment 1 in which the procedures were equated for the interval between the moving cue at the target's position and the target but not for the interval between the onset of the moving cue and that of the static target. However, we accepted the present confound because we wanted to rule out that the difference in the interval between cue onset/motion onset and the target which existed between different moving cue conditions in Experiment 1 could have been the responsible factor for the slower responses for targets presented at the cue's motion onset position. Precisely, in Experiment 1 the interval between cue onset/motion onset and target was 85 ms if targets were cued by motion onsets but it was 170 ms if targets were cued by motion offsets, whereas in Experiment 2 this interval between cue onset/motion onset and target was 85 ms for both of the moving cue conditions.

The order of the different blocked cueing conditions was balanced across participants.

Results

Out of all responses, 0.9% was discarded because they were faster than 100 ms or slower than 1 s. In a repeated-measures ANOVA of the means of individual medians of correct RTs, we found a significant effect of distance, $F(1, 13) = 52.55$, $p < .01$. The effect reflected better performance for targets shifted relative to the starting point of the moving cue at 4.2° (RT = 442 ms) than for targets being presented at the starting point of the moving cue at 4.2° (RT = 476 ms). This position effect was found in moving cue conditions (distance of target 4° from 4.2° RT = 441 ms/error rate = 2.1%; target at 4.2° RT = 479 ms/error rate = 1.9%) and in static cue conditions (distance of target 4° from 4.2° RT = 443 ms/error rate = 1.7%; target at 4.2° RT = 474 ms/error rate = 1.5%); $F < 1.00$ for the Cue type × Distance interaction. The main effect of cue type was not significant, $F < 1.00$. A corresponding ANOVA of the arc-sine transformed error rates led to no significant effects, all Fs < 1.00, ruling out that a speed–accuracy tradeoff accounted for the RT effects.

Discussion

The data supported the conclusion that attentional capture to the position of the cue's motion onset was virtually absent. We again observed a slower orientation discrimination response for static targets cued by motion onsets relative to static targets cued by motion offsets. This difference was found although the two moving cue conditions were realised in separate blocks and with equally long intervals between the cue onset/motion onset and the static target. Thus, the different moving cue conditions were similar to one another in terms of the precision with which the cue informed the observer about the position of the upcoming target and in terms of the time since a hypothetically interfering or warning cue or motion had had its onset. Therefore, it can be ruled out that the different degrees of certainty about the target location delivered by the moving cue at different positions of its motion trajectory or the time since a warning (or an interfering) cue or motion had had its onset were the major factors responsible for the performance difference between the different moving cue conditions.

Moreover, using static cues and static targets that mimicked the attentional effect of a moving cue at motion offset, we were able to replicate the performance difference from the moving cue conditions. This means that the results in the moving cue conditions can be understood in terms of a lack of attentional capture by motion onset cues and by attentional capture by motion offset cues. The fact that the performance difference between the two static cue conditions (RT difference = 38 ms) was numerically almost equal to that under the two moving cue conditions (RT difference = 34 ms) is highly suggestive of that it is only attentional capture by the cue at motion offset and nothing else that produces the difference between conditions with a target cued by motion onset versus a target cued by motion offset: The results, thus, indicate that interference by coding of the cue's motion direction in motion onset cue conditions does not substantially contribute to the performance difference between the two different moving cue conditions. Otherwise, we would have expected a smaller performance difference between the two static control conditions than between the two moving cue conditions because the two static conditions only mimicked the attentional effect.

EXPERIMENT 3

Again, we tested whether spatially less precise attentional capture by the motion onset cue accounted for the slow orientation discrimination of targets cued by motion onset in the preceding Experiments 1 and 2, or whether interfering motion (direction) coding, or a low predictability of the target's position better accounted for the results.

To that end, we created conditions similar to Experiment 1 with one notable exception: The moving cue now started to move either at 8.2° or at 0.2° left or right of fixation. Thus, by the time that the moving cue passed over its former motion onset position (i.e., at 4.2°), it was already moving for 85 ms (see also Figure 5). Still, as in Experiment 1, from 4.2° onward, the moving cue had another 85 ms or five positions to go before the static target was shown. Also, as in Experiment 1, targets were only presented at one of the final five positions along the moving cue's trajectory. Therefore, all differences in terms of interfering motion (direction) coding or degrees of target predictability that existed between on the one hand motion onset cueing and on the other hand motion offset cueing (as well as between motion onset cueing and static cueing) that existed in Experiment 1 were again realised. This means that under the modified conditions of Experiment 3, again the same results as in Experiment 1 could be expected if one of these realised factors accounted for the slow orientation discrimination of targets at 4.2°.

The only factor that was ruled out as slowing the discrimination of target orientation responses at 4.2° was a spatially less precise attentional capture by motion onsets: With motion onsets of the moving cue preceding the cue at position 4.2°, attentional capture by a moving cue at position 4.2° and at later positions on the cue's motion trajectory should be more equal to one another: As the moving cue at position 4.2° already moved since five frames, the spatial precision of attentional capture by a moving cue at 4.2° was not expected to drastically differ from the spatial precision of attentional capture to positions further along the cue's motion trajectory. Therefore, only on the basis of an attentional explanation of the target discrimination, the cueing effect is expected to be the same for a moving cue cueing a target at 4.2° (at the former motion onset position) and for a moving cue cueing the target at subsequent positions on the moving cue's trajectory.[4]

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[4] Note that the procedural change of Experiment 3 means that the temporal interval between the cue onset/motion onset and the static target was again changed in comparison to (a) the preceding Experiments 1 and 2, and (b) the static cue conditions. This interval was 85 ms for moving cues and static cues in Experiment 2, for example, but it was at least 170 ms for moving cues (if cueing was by motion onsets) in the present experiment. One might argue that we therefore should have taken one of two measures. Either, we should have decreased the interval in the moving cue condition also to 85 ms by having the cue shifting with a rate of 2° per frame. Or we should have increased the interval between the static cue's onset and the target to 170 ms, too.

In practice, however, neither of these measures was necessary nor advised. It was not necessary because the comparison of the results of the preceding Experiments 1 and 2 already demonstrated that the interval between cue onset/motion onset and target per se was not the major factor responsible for target discrimination speed. It was also not advised for two interrelated reasons. First, the crucial condition we wanted to replicate is the preceding experiments' motion onset cueing condition, with a moving cue at position 4.2° and a static target at the very same position. This was the one condition creating slow target orientation discrimination responses in Experiments 1 and 2, and this was the one condition that we now wanted to change in such a way that the moving cue at that position could capture attention. Because Experiment 1 suggested that the moving cue had to move for 85 ms (i.e., in the motion offset cue condition) before its attentional capture effect had the size of that of a static cue, we had to measure the moving cue's effect at 4.2°, with a head-start of cue motion of 85 ms before reaching the position at 4.2°. Therefore, increasing the moving cue's motion speed was not an option. This would have shortened the interval between cue onset/motion onset and the moving cue at 4.2° and, therefore, undermined the rationale of our manipulation. Second and in addition, in the current experiment we had to compare the moving cue's effect on target discrimination at 4.2° with the attentional effect of the static cue on target discrimination at 4.2°. Because the crucial interval between the moving cue at 4.2° and the target at 4.2° was 85 ms, we had to use the same interval for the static cue conditions. Therefore, increasing the interval between cue onset and target in the static cue conditions was also not an option.

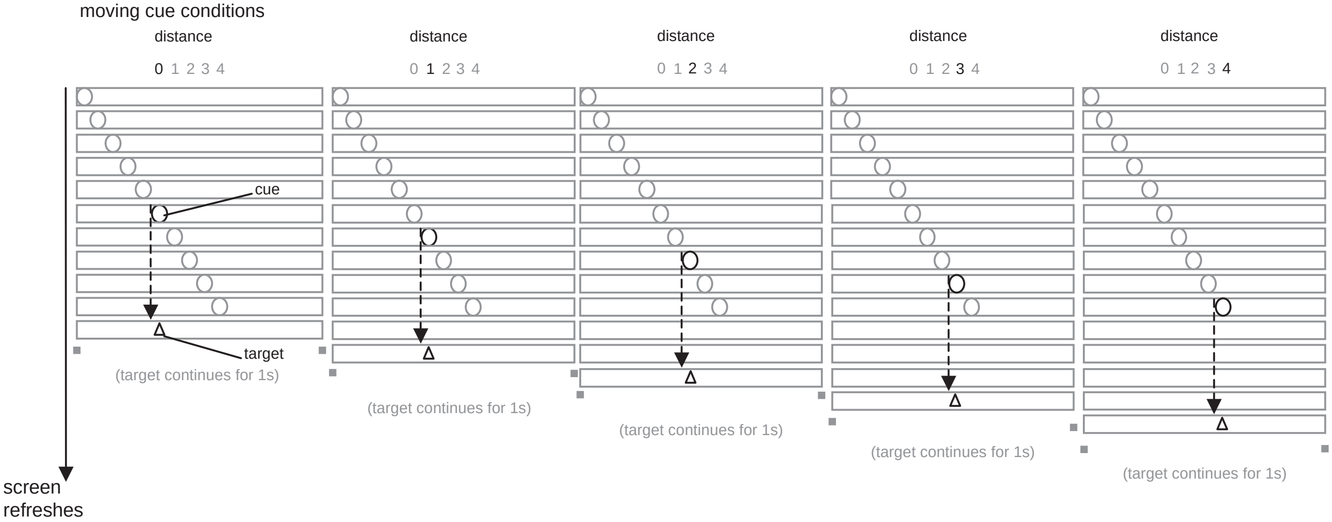

Figure 5. Depicted are schematic illustrations of moving cue conditions of Experiment 3. (Static cueing conditions were the same as in Experiment 1.) From top to bottom, each line represents one refresh of the computer screen. Within each frame, the stimulus could have occupied 1 out of 20 positions (2 sides × 10 eccentricities). In the Figure, only the final 5 different positions at which the moving cue appeared are numbered 0 to 4 corresponding to their distance in degrees of visual angle relative to the 4.2° reference position. Note that these positions were the possible target positions and that they were the same as in Experiments 1 and 2.

For each of the columns, the cue is shifted by 1° per each refresh of the computer screen for altogether 10 frames creating apparent motion of the cue. The lowest line in each of the columns shows an example of a target (here: an upward pointing arrow head). From the leftmost column to the rightmost column, the target is presented with an increasing distance to the moving cue's motion onset position at 4.2° (in the upmost line of the upper row). Note that in contrast to Experiment 1, the cue started more peripheral (at 8.2°) or more central (at 0.2°) so when the moving cue was at 4.2°, it was moving for already 5 frames (or 85 ms). Thus, a target at 4.2° was no longer at the position of motion onset.

The black arrow on the left depicts the direction of time; the black dotted arrows within the columns depict the cue-target interval, which was kept the same for all cue-target position combinations. The dots at the final lines of all upper rows' and all lower rows' columns stand for the continuation of the target. Targets and the target-preceding cues at the target's position are highlighted (black). Stimuli are not drawn to scale.

Method

Participants. Twenty-four students (16 female, 8 male) with a mean age of 28 years participated in Experiment 3.

Apparatus, stimuli, and procedure. These were the same as in Experiment 1, except as noted (see Figure 5). In the moving cue conditions, each cue moved for 10 instead of only 5 successive refreshes of the computer screen. Centripetally moving cues started 8.2° left or right of the screen centre, and centrifugally moving cues started 0.2° left or right of screen centre. Under both conditions, targets were presented only at one of the final five positions on the moving cue's motion trajectory. In all other respects, Experiment 2 was exactly like Experiment 1.

Results

See Figures 6 and 7 for the results. Out of all responses, 1.7% was discarded because they were faster than 100 ms or slower than 1 s. A repeated-measures ANOVA of the means of individual median correct RTs was conducted as in Experiment 1. This ANOVA revealed significant main effects of distance, $F(4, 92) = 14.32$, $p < .01$, and direction, $F(1, 23) = 10.46$, $p < .01$, and significant interactions of Cue type × Direction, $F(1, 23) = 9.02$, $p < .01$, and Distance × Direction, $F(4, 92) = 4.73$, $p < .01$. In contrast to

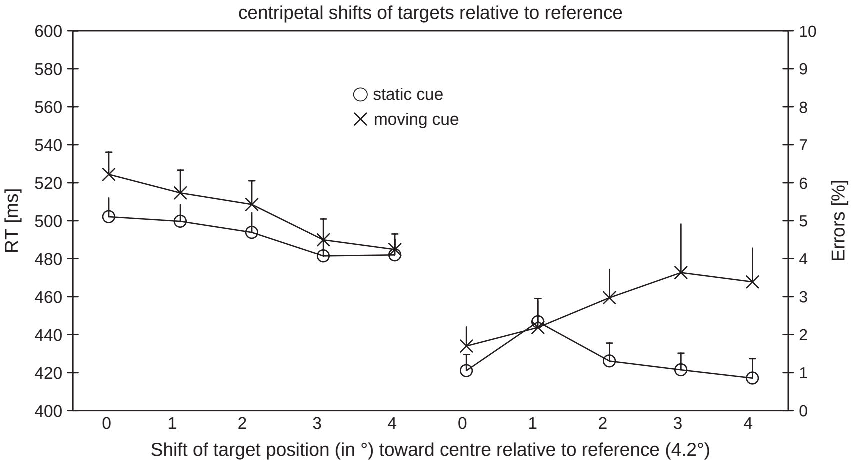

Figure 6. Mean reaction times (RTs) in milliseconds (ms) and mean error rates in percent (crosses; circles), and the corresponding standard errors (vertical lines), as a function of cue type (moving cue vs. static cue) and target position (−0°, −1°, −2°, −3°, −4°) shift in the direction of screen centre relative to the reference point at 4.2° of Experiment 3.

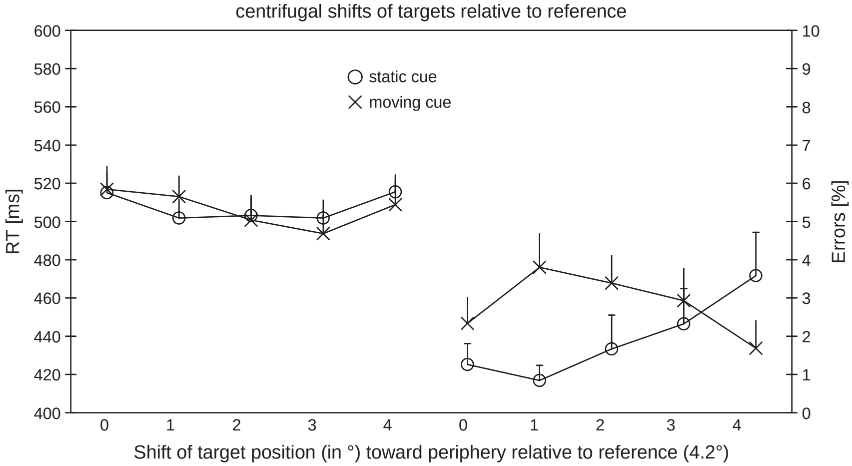

Figure 7. Mean reaction times (RTs) in milliseconds (ms) and mean error rates in percent (crosses; circles), and the corresponding standard errors (vertical lines), as a function of cue type (moving cue vs. static cue) and target position (+0°, +1°, +2°, +3°, +4°) shift in the direction of the screen's periphery relative to the reference point at 4.2° of Experiment 3.

Experiment 1, the main effect of cue type, $F < 1.00$, and the interaction of Cue type × Distance, $F(4, 92) = 1.87$, $p = .12$, failed to become significant. This was the case although we had doubled the number of participants in comparison with Experiment 1. (The three-way interaction was also not significant, $F < 1.00$.) Responses to targets closer to screen centre were faster (RT = 498 ms) than responses to targets in the periphery (RT = 507 ms). On closer inspection, this pattern could only be confirmed under static cue conditions, in which RTs to the more peripheral targets were on average 16 ms slower (RT = 508) than RTs to more central targets (RT = 492 ms), $t(23) = 4.60$, $p < .01$. By contrast, under moving cue conditions, responses to the more peripheral targets (RT = 507 ms) and to the more central targets (RT = 505 ms) were about the same, $t < 1.00$. Finally, the two-way interaction between distance and direction reflected that responses were slower only for targets presented at the two most peripheral (target at 7.2° RT = 498 ms; target at 8.2° RT = 512 ms) relative to the respective two most central positions (target at 1.2° RT = 486 ms; target at 0.2° RT = 483 ms), both $ts(23) > 3.10$, both $ps < .01$.

We also conducted an additional repeated-measures ANOVA for correct RTs to targets presented at 4.2°, with the two within-participant variables cue type and direction as before, and the between-participants variable experiment/motion onset position (Experiment 1/motion onset at 4.2° vs. Experiment 3/motion onset at 0.2° or 8.2°). This ANOVA led to a significant interaction of Cue type × Experiment/motion onset position and, thus, confirmed that slower responses to targets at 4.2° were only observed if that was also the cue's motion onset position (Experiment 1) but not if the cue's motion onset was lying 85 ms in the past (Experiment 3).

A repeated-measures ANOVA of the arc-sine transformed error rates of Experiment 3, with the variables cue type, distance, and direction, led to a significant main effect of cue type, $F(1,\ 23) = 7.10$, $p < .05$, and to a significant three way-interaction of Cue type × Distance × Direction, $F(4,\ 92) = 4.76$, $p < .01$. Error rate was higher under moving cue conditions (error rate = 2.8%) than under static cue conditions (error rate = 1.6%). Importantly, the three-way interaction reflected that with targets presented at a position on the centripetally moving cue's trajectory, increased error rates under moving cue conditions (relative to static cue conditions) were restricted to target positions further along the cue's motion trajectory (positions 1.2° and 2.2°), both $t\text{s}(23) > 1.80$, both $p\text{s} < .05$, one-tailed. By contrast, error rates for targets near or at the former motion onset position of Experiment 1 were *not* inflated under moving cue conditions relative to static cue conditions (target at positions 2.2°, 3.2°, and 4.2°), all three $t\text{s}(23) < 1.50$, all three $p\text{s} > .16$. This pattern of results, however, was slightly different for targets presented at positions along the centrifugally moving cue's motion trajectory. Under the latter conditions, we also observed increased error rates for target positions further along the motion trajectory of the cue under moving cue relative to static cue conditions (target at positions 6.2° and 8.2°), both $t\text{s}(23) > 1.70$, both $p\text{s} < .05$, one-tailed. Additionally, however, a similarly increased error rate under moving cue relative to static cue conditions was obtained for targets at and near 4.2°—that is, at the former motion onset position of Experiment 1 and directly adjacent to it (target at positions 4.2° and 5.2°), both $t\text{s}(23) > 1.70$, both $p\text{s} < .05$, one-tailed.

In the additional error analysis for targets at position 4.2°, including the between-participant variable experiment/motion onset position, we found neither a significant main effect, nor a significant interaction, all $F\text{s} < 2.40$, all $p\text{s} > .11$. In particular and in line with the greater similarity of the error rates than RTs for targets at 4.2° under the conditions of Experiments 1 and 3, we did not observe a significant Cue type × Experiment/motion onset position interaction, $F < 1.00$. A comparison between on the one hand Figures 2 and 3 and on the other hand Figures 6 and 7, however, makes it clear that, if anything, between the experiments error differences were in the same direction as RT differences: The diminished discrimination performance under moving cue conditions relative to static cue conditions for targets at 4.2° was more pronounced under conditions in which motion onset was at 4.2° (Experiment 1) than under conditions in which the motion onset was lying 85 ms in the past (Experiment 3). In conclusion, neither a speed–accuracy tradeoff between the experiments nor an insufficient power of Experiment 3's significance tests does better account for the change of the speed of a correct discrimination of target orientations cued by a moving cue at 4.2° in Experiment 3 relative to Experiment 1.

Discussion

In Experiment 3, we found that the slower orientation discrimination responses for targets at 4.2° under moving cue conditions relative to static cue conditions that we observed in Experiment 1 crucially depended on that the moving cue had its motion onset at that very position. In the current experiment, in which the cue started to move 85 ms earlier, the slower orientation discrimination for targets at 4.2° was at least less severe than in Experiment 1. A spatially less precise attentional capture by motion onsets is the best fitting account for this pattern of results. The reason for this is that motion onsets were manipulated in the present experiment compared to Experiment 3. They were no longer at 4.2°: The cue's motion onset preceded the moving cue at 4.2° by 85 ms.

By contrast, each of the other conceivable factors, an interfering coding of the cue's motion (direction) and a low prediction of the upcoming target position by a moving cue at 4.2°, were the same as in Experiment 1. These factors both depend on the stimulation after the moving cue has been at 4.2°. Because the conditions of the present experiment were, however, identical with those of Experiment 1 with respect to all the stimulation occurring after the moving cue has been at 4.2°, the present results demonstrate that the aforementioned alternative factors were insufficient to produce the full slowing of the discrimination of target orientations at 4.2°. In other words, with spatial precision of coding the position of the moving cue and, hence, attentional capture by that cue better equated at positions 4.2°, 0.2°, and 8.2° (by having the motion onset further shifted into the past), a significant slowing of orientation discrimination responses for targets at 4.2° is no longer observed.

Note that the failure to observe a significant slowing of discrimination responses for targets at 4.2° in the present experiment could not have been due to an insufficient power of the significance test because the ANOVA was based on 24 participants in the present experiment as compared to only 12 participants used for showing the significant difference in Experiment 1. The weaker RT costs between conditions with moving cues and static targets at 4.2° in the present experiment as compared to Experiment 1 were also confirmed by an ANOVA across Experiments 1 and 3, demonstrating a significant interaction between the discrimination performance under moving cue conditions at 4.2° and the variable experiment. In conclusion, the present results confirm our interpretation that attentional capture to the onset of a moving stimulus is less precise.

Like in Experiment 1, we also found an effect of direction, with better performance for targets at central relative to peripheral positions. However, this pattern was only clearly observed as a difference between the most distant target positions (0.2° vs. 8.2°). The pattern was also restricted to static cue conditions and was not found under moving cue conditions. This is important, because the static cue conditions were exactly like those in Experiment 1, whereas in the moving cue condition, the onset of the cue now preceded that of the target by 170–255 ms rather than by 85–170 ms. Given that the static cue was the same in Experiments 1 and 3, any effects of the cue depending upon the delay between onset of the cue and onset of the target could be examined only for the moving cue condition. The exact origin of this unexpected difference between the direction conditions is not certain. We believe that the cue had a cue–target interval dependent warning function for an upcoming target (Posner & Boies, 1971). If so, a longer prewarning for an upcoming target by the onset of the moving cue in Experiment 3 (as compared to Experiment 1) evidently allowed the participants to counteract the differences of processing peripheral relative to central targets.

Note, that the changed temporal warning effect under moving cue conditions does not call into question our interpretation concerning the better spatial coding of the moving cue at 4.2° and its stronger attentional capture in the present experiment compared to Experiment 1. First, the crucial interval to be compared between the moving cue conditions of Experiments 1 and 3 is that between the moving cue at 4.2° and the static target at 4.2°. This crucial interval was kept the same in the present experiment's moving cue conditions and static cue conditions as well as in the motion onset cue conditions of the preceding Experiments 1 and 2. Second, in Experiment 2, we demonstrated that the interval between cue onset/motion onset and static target by itself was not the responsible factor for a slow orientation discrimination of targets cued by motion onset cues at 4.2°.

EXPERIMENT 4

On the basis of a spatially lower precision of attentional capture by motion onset stimuli, Müsseler and Aschersleben (1998) predicted that discrimination of target colours at motion onset positions should be better than discrimination of target orientations. The reason for this prediction is that shape, pattern, or orientation discrimination, but not or less so colour discrimination depends on a prior focusing of attention at the target's position (Treisman, 1988). It is a standard finding that simple colour features can be searched for in parallel across different locations, such that search times for a colour-defined target among differently coloured distractors are not largely affected by the number of distractors in the display (cf. Green & Anderson, 1956). This parallel or efficient search performance has been attributed to either an attention-independent search for colour (Treisman & Gelade, 1980) or, more plausibly, to a distributed attention mode (cf. Bravo & Nakayama, 1992). Corroborating this assumption as well as the attentional effect of peripheral cues, it has been found that colour discrimination of targets is not significantly affected by an advance cueing of target positions (Treisman, 1988).

Based on Müsseler and Aschersleben's (1998) assumptions, we expected that if the task is to discriminate between target colours, less attention is necessary for accurately discriminating the target. Therefore, a spatially less accurate attentional shifting to the cue's motion onset position (or focusing of attention on it) should be without consequences for target colour discrimination performance. This hypothesis was tested in Experiment 4.

Method

Participants. Twenty-four students (13 female, 11 male) with a mean age of 27 years participated in Experiment 4.

Apparatus, stimuli, and procedure. These were the same as in Experiment 1, except for the following differences. As a target, we used a small outline box instead of the upward and downward pointing arrows used in the preceding experiments. This target box was equally likely white or red. Participants had to respond with a right keypress to a red target and with a left keypress to a white target, or vice versa. The different S-R mapping rules were balanced across participants.

Results

See Figures 8 and 9 for the results. Out of all responses, 1.7% was discarded because they were faster than 100 ms or slower than 1 s. A repeated-measures ANOVA, with the same variables as in Experiments 1 and 3 led to significant main effects of cue type, $F(1, 23) = 5.64, p < .05$, distance, $F(4, 92) = 4.94, p < .01$, and direction, $F(1, 23) = 11.14, p < .01$. Responses to targets in the moving cue conditions were slower (RT = 456 ms) than in the static cue conditions (RT = 438 ms). Also, responses were again faster to central targets (RT = 444 ms) than to peripheral targets (RT = 450 ms). This effect is small but bearing on the relatively large number of participants and, thus, a high power of the test, turned out to be significant. Finally, RTs decreased with an

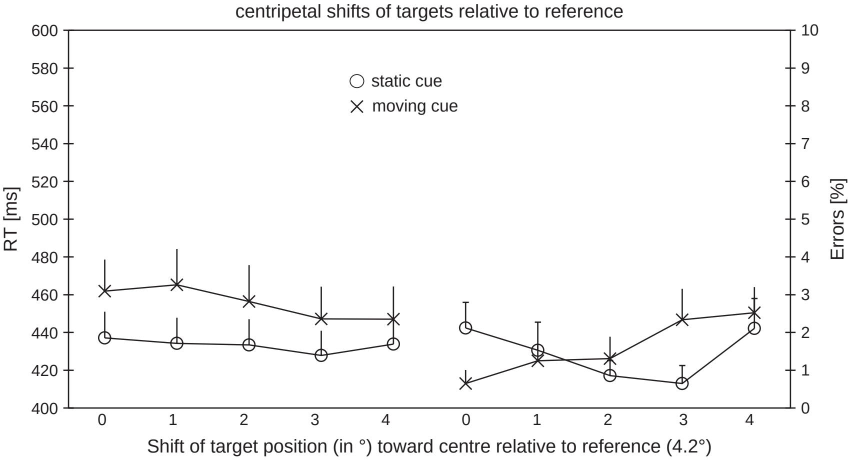

Figure 8. Mean reaction times (RTs) in milliseconds (ms) and mean error rates in percent (crosses; circles), and the corresponding standard errors (vertical lines), as a function of cue type (moving cue vs. static cue) and target position (–0°, –1°, –2°, –3°, –4°) shift in the direction of screen centre relative to the reference point at 4.2° of Experiment 4.

increasing distance from 4.2° (4.2°: RT = 453 ms; target distance 1° from 4.2° RT = 450 ms; target distance 2° form 4.2° RT = 449 ms; target distance 3° from 4.2° RT = 443 ms; target distance 4° from 4.2° RT = 442 ms).

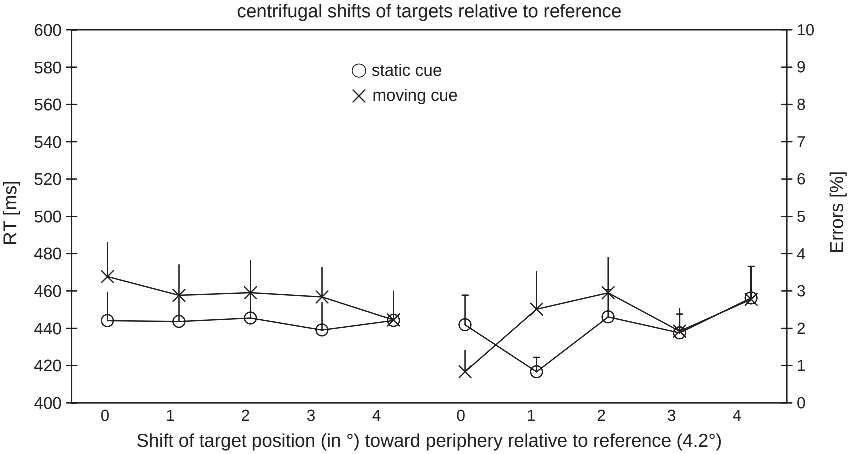

Figure 9. Mean reaction times (RTs) in milliseconds (ms) and mean error rates in percent (crosses; circles), and the corresponding standard errors (vertical lines), as a function of cue type (moving cue vs. static cue) and target position (+0°, +1°, +2°, +3°, +4°) shift in the direction of the screen's periphery relative to the reference point at 4.2° of Experiment 4.

Yet, although we doubled the number of participants and thereby increased the power of our significance test in Experiment 4 (24 participants) as compared to Experiment 1 (12 participants), the Cue type × Distance interaction only tended towards significance, $F(4, 92) = 2.14$, $p = .08$. However, this tendency seemingly reflected a data pattern similar to that in Experiment 1: That is, target discrimination performance for targets under moving cue conditions relative to static cue conditions was most strongly slowed at the cue's motion onset position.

Even more to the point, however, this marginally significant trend towards a better RT performance under static than under moving cue conditions for targets at 4.2° had a different origin in the current experiment than in Experiment 1: It reflected a speed–accuracy tradeoff. This was revealed in a corresponding ANOVA of the arc-sine transformed error rates. In this analysis, we observed a significant interaction of Cue type × Distance, $F(4, 92) = 2.57$, $p < .05$, with a higher accuracy under moving cue conditions (error rate = 0.7%) than under static cue conditions (error rate = 2.1%) for targets at 4.2°, $t(23) = 2.34$, $p < .05$.

Besides this interaction, we also found a significant main effect of direction, $F(1, 23) = 7.28$, $p < .05$, due to an increased error rate for targets presented at one of the positions of the centrifugally moving cue (error rate = 2.1%) in comparison with targets presented at one of the positions of the centripetally moving cue (error rate = 1.5%), and a trend towards a significant effect of distance, $F(4, 92) = 2.26$, $p = .07$. With respect to the latter, errors tended to increase as a function of the distance to the 4.2° position (target at 4.2°: error rate = 1.4%; distance of target 1° from 4.2° error rate = 1.5%; distance of target 2° from 4.2° error rate = 1.9%; distance of target 3° from 4.2° error rate = 1.7%; distance of target 4° from 4.2° error rate = 2.6%). Thus, the slowing of RTs with an increasing distance of the targets from the 4.2° reference position was also reflecting a speed–accuracy tradeoff. All other main effects and interactions of the error analysis were not significant, all other Fs < 1.00.

Discussion

In Experiment 4, we used a colour discrimination task requiring less attention to be directed at the targets than in the orientation discrimination task of Experiments 1 to 3 (cf. Treisman & Gelade, 1980). On the basis of Müsseler and Aschersleben's (1998) hypothesis that diminished target orientation discrimination performance at motion onset position reflected a spatially less precise capture of attention, we expected less slowing of colour discrimination of targets cued by motion onsets in the present Experiment 4 relative to the slowing of orientation discrimination of targets cued by motion onsets in Experiments 1 and 2. The results mainly supported this prediction. Although we increased the power by using twice the number of participants than in Experiment 1 to replicate Experiment 1's slower discrimination responses for targets cued by motion onsets (in a Distance × Cue type interaction), we only found a nonsignificant slowing of the colour discrimination RTs for targets at motion onset that even more to the point turned out to reflect a speed–accuracy tradeoff. Therefore, in Experiment 4, a tendency towards slower discrimination responses for targets cued by motion onsets reflected a bias of the observers to trade a higher accuracy of colour discrimination for a lower discrimination speed. This bias is not the same as the generally inferior orientation discrimination performance for targets cued by motion onsets relative to targets cued by motion offsets (or by static cues) we found in Experiment 1.

In particular, researchers have repeatedly emphasised that different levels of processing, sensory, and decisional levels, can contribute to cueing effects (cf. Downing, 1988; Pashler, 1998). However, one should be aware of the fact that the use of the same term "attention" for both of these effects then denotes two different effects and two different levels of processing: A real performance diminution (or improvement) reflecting the degree of the cue's attentional capture to one of several positions impacting on the sensory level of processing a target at one of these positions (as in Experiments 1 to 3); or a bias in which a performance diminution in form of an RT slowing is the cost incurred by a higher accuracy of target discrimination reflecting a decision level effect of the cue for applying different criteria of caution to discriminate targets at differently cued regions of the visual field (as in the present experiment).

In contrast to the preceding Experiments 1 and 3, we also observed a second speed–accuracy tradeoff concerning the distance effect in the RTs. The fact that such a bias for the processing of the target at 4.2° existed in the present but not in the preceding experiments is additional indirect evidence that participants used the cue's motion onset differently in the present as compared to the preceding Experiments 1 and 3.

EXPERIMENT 5

So far, in the current study, we have only assumed but not measured that localisation of the motion onset of the cues is not precise. Based on the existing literature, one might think that this should be the case—that is, there should be a Fröhlich effect. However, Fröhlich effects are not observed under all conditions (cf. Kerzel & Müsseler, 2002; Müsseler & Kerzel, 2004; Müsseler, Stork, & Kerzel, 2008). Therefore, in Experiment 5 we tested whether the moving cue was indeed mislocalised under the current conditions. Such mislocalisation would provide independent converging support for our conclusion that the motion onset was spatially not precisely coded. Alternatively to this interpretation one might argue that localisation of the moving cue at motion onset was in our experiments simply delayed or that cue contrast was weaker at motion onset but that the cue was otherwise seen at its veridical location and that this sort of spatially precise but weak or delayed position coding of motion onsets was reflected in a slower orientation discrimination of the targets cued by motion onsets in Experiments 1 and 2.

In the final experiment, we therefore tested whether the moving cue was mislocalised at motion onset. Procedure and set-up were similar to that of Experiment 1, but now our participants had to judge where they perceived the onset position of the moving cue, with the stimulus that was being used as a target in Experiment 1 (the arrow) now serving as a reference stimulus for a categorical judgement about where the moving cue was first seen in one of the judgement conditions (see later). Under the changed task conditions of the present experiment, we expected a Fröhlich effect—that is, that the observers frequently see and, thus, judge the onset position of the moving cue as being shifted in the direction of its motion.

Method

Participants. Twenty-four students (11 female, 13 male) with a mean age of 27 years participated in Experiment 5.

Apparatus, stimuli, and procedure. These were the same as in the moving cue condition of Experiment 1, except for the following differences. Half of the participants had to give a relative judgement about the moving cue's onset position. After each trial, they had to judge where they perceived the onset of the cue relative to the position of the static arrow (that was being used as a target in Experiment 1). In other words, the former target now served as a spatial reference for judging whether the cue was perceived (a) at this reference position, (b) left of this reference, or (c) right of this reference. In a fourth judgement category, participants were allowed to indicate that they were uncertain about what they saw and, thus, wanted to abstain from a judgement on the current trial. To that end, different keys of the numeric keypad of a standard keyboard were used. Participants were asked to press the central key ("5") if they saw the onset of the moving cue at the reference position, the left key ("4") if they saw the onset of the moving cue left of the reference, and the right key ("6") if they saw the onset of the moving cue right of the reference. If uncertain of what they saw, participants were asked not to press any of these keys. In the following, we restricted our analysis to the above judgements (b) and (c), and recoded left and right positions as being either positions in the direction of the cue's motion (i.e., if the cue moved centrifugally onset position was judged to be more peripheral than the reference; if the cue moved centripetally onset position was judged to be more central than the reference) or positions shifted against the direction of motion (i.e., if the cue moved centrifugally onset position was judged to be more central than the reference; if the cue moved centripetally onset position was judged to be more peripheral than the reference).

The other half of the participants received static and moving cues as before, and had to give a categorical judgement. They had to decide at which of its five positions a static cue or a moving cue had had its onset. For that purpose, at the end of each trial, the moving cue was simultaneously presented in a static fashion at all of its five screen positions simultaneously, and the positions were numbered from 1 (onset position) to 5 (end position). Here, it was the observers' task to press that one of five number keys ("1" to "5") that had a number corresponding to that of the cue's perceived onset position. In detail, once the cue had been turned off, the numbers 1 to 5 were shown directly adjacent to the rings (cues) at the five positions that the moving cue had passed across, starting with the lowest number at the cue's starting position and an increment by 1 for each of the positions that the moving cue successively passed along its trajectory. If the cue moved from left to right, these numbers read from left to right, and if the cue moved from right to left, the numbers read from right to left. The participants were then asked to enter the number corresponding to the onset position via the horizontal numeric key band of a standard keyboard. Moreover, the same procedure was used with the static cues, with the only difference being that the positions that were available for the judgement of the onset of the static cue were taken from one of the moving cue conditions that encompassed the actual position of the static cue. For instance, if a static cue was shown at 6.2° left of the screen centre, the subsequent judgement display contained cues at left positions 4.2°, 5.2°, 6.2°, 7.2°, and 8.2°. Thus, we were able to compare the expected mislocalisation of the onset position of the moving cue to a baseline localisation performance with a static cue.

All participants in both of the tasks were instructed to take their time for the judgements as needed. No feedback about the speed of the judgements was given. Also, no feedback about the correctness of the judgements was provided, because we wanted to measure the misperception of the cue's motion onset position and did not want our participants to strategically compensate in their judgements for the expected misperception.

Results

Relative judgements. See Figure 10 for the results of the relative judgements. Prior to the analysis, trials in which observers were uncertain

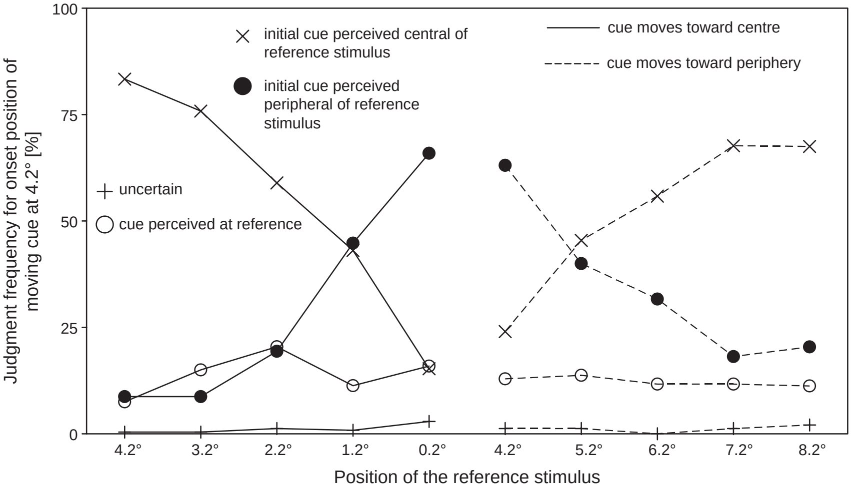

Figure 10. Judgement rates in percent as a function of judgement type (initial cue perceived central of reference stimulus; initial cue perceived peripheral of reference stimulus; uncertain; or cue perceived at reference stimulus) motion direction of the cue (cue moves toward centre; or cue moves toward periphery), and position of the reference stimulus (0.2°, 1.2°, 2.2°, 3.2°, 4.2°, 5.2°, 6.2°, 7.2°, 8.2°).

about what they saw (1.1%) and trials in which observers saw the moving cue at its veridical position (13.2%) were eliminated. The relative judgements were then analysed by a repeated-measures ANOVA of the frequencies of judgements under moving cue conditions, with the three variables judgement type (cue onset position perceived as shifted in motion direction vs. cue onset position perceived as shifted against motion direction), position (corresponding to the variable distance in the preceding experiments), and direction (as in the preceding experiments). The ANOVA led to significant interactions of Judgement × Position, $F(4, 44) = 21.15$, $p < .01$, Judgement × Direction, $F(1, 11) = 18.87$, $p < .01$, and Judgement × Position × Direction, $F(4, 44) = 10.05$, $p < .01$.

The Judgement × Position interaction reflected that with both types of direction (cue moves centripetally or centrifugally), the cue (starting at 4.2°) was perceived as starting at a position shifted in the direction of its motion. In detail, proceeding from low to high spatial distances between cue onset and the "target" as a point of reference, we discerned three different data patterns: First, when the "target" as a reference point was presented at or near the motion onset position (at positions 4.2°, and positions 1° away from 4.2°), the onset of the moving cue was frequently perceived as being shifted in the direction of motion, both ts$(11) > 3.10$, both ps $< .01$, one-tailed. Second, when the "target" as a point of reference was presented at a position further along the motion trajectory, the difference between the judgement frequencies was diminished towards a point of equilibrium between the two judgements' frequencies (at positions 2° away from 4.2°), $t(11) < 1.00$. This point of equilibrium of the frequencies of the two judgements provided the best approximate estimate of the spatial shift of the perceived onset position of the moving cue. Third, presenting the "target" as a reference at a position on the cue's motion trajectory that was even further away from the cue's motion onset, the frequencies of the two judgements reverted: For positions 3° and 4° away from the motion onset position at 4.2°, the frequency of the veridical judgements outweighed that of the wrong judgements, both $ts(11) > 1.90$, both $ps < .05$, one-tailed.

Besides these similarities between the two motion direction conditions, we also found a three-way interaction. It reflected that the mislocalisation of the motion onset position was more pronounced for centripetally moving cues than for centrifugally moving cues: The point of a first significant reverted difference (being diagnostic of a majority of accurate judgements) lay at 6.2° ("target" as a reference was 2° away from motion onset at 4.2°), $t(11) = 2.10$, $p < .05$, one-tailed, with a centrifugally moving cue, but at 0.2° ("target" as a reference was 4° away from motion onset at 4.2°) with a centripetally moving cue, $t(11) = 3.50$, $p < .01$. Likewise, the point of equilibrium of the frequencies of the two judgements was reached with a reference at 5.2° ("target" as a reference was 1° away from motion onset at 4.2°) if the cue moved centrifugally, whereas this point of equilibrium lay at 1.2° ("target" as a reference was 3° away from motion onset at 4.2°) if the cue moved centripetally, both $ts < 1.00$.

Categorical judgements. The categorical judgements were analysed by first calculating individual means of the degree of visual angle between the perceived cue's onset location and its veridical onset location. Shifts towards the centre of the screen were coded as negative values, and shifts towards the periphery of the screen were coded as positive. Four such measures were calculated, one each for the centrifugally moving cue, the centripetally moving cue, the static cue at one of the positions along the centrifugally moving cue's trajectory, and the static cue at one of the positions along the centripetally moving cue's trajectory. The moving cue's starting position was perceived as being shifted in the direction of motion. This was evident in altogether three comparisons between localisation performance for (1) centripetally moving cues (position = $-1.31°$) and static cues at one of the positions along that very same trajectory (position = $-0.36°$), $t(11) = 3.94$, $p < .01$; (2) centrifugally moving cues (position = 0.71°) and static cues presented at one of the positions along that very same trajectory (position = $-0.42°$), $t(11) = 5.94$, $p < .01$; and (3) centripetally moving cues and centrifugally moving cues' position, $t(11) = 5.55$, $p < .01$ (all tests

Bonferroni-corrected). By contrast, static cues that were presented at one of the positions of the centripetally moving cue were perceived with an approximately similar accuracy as static cues presented at one of the positions of the centrifugally moving cue, $t(11) < 1.00$.

Discussion

In line with previous research (Carbone & Pomplun, 2007; Kerzel & Müsseler, 2002; Kirschfeld & Kammer, 1999; Müsseler & Aschersleben, 1998), we found a mislocalisation of the initial position of a moving stimulus in the direction of its motion. In the relative judgements, this misperception was seemingly larger with centripetally than with centrifugally moving stimuli, which is the opposite of what is regularly reported in the literature (cf. Müsseler & Aschersleben, 1998). However, in the categorical judgements, we found the more frequently observed numerically (though not statistically) larger mislocalisation effect with centrifugally relative to centripetally moving cues. It is therefore possible that the "targets" that we used as reference markers here biased the relative judgements. Alternatively, a general bias to perceive all stimuli as being shifted in the direction of the screen centre could have contributed to the mislocalisation difference in the relative judgements. In general agreement with such a bias, in the categorical judgements we found a slight bias in the static cue control conditions for perceiving the veridical onset as being shifted towards the screen's centre. If such a bias also existed in the relative judgements (what we did not measure), it would explain the direction dependencies of the mislocalisation found in the relative judgements: The bias would have added to the motion onset mislocalisation with centripetally moving cues, but would have diminished the motion onset mislocalisation with centrifugally moving cues.

The important conclusion from Experiment 5 is that we were able to demonstrate the mislocalisation of the onset position of the moving stimulus: The moving stimulus was perceived as being shifted in the direction of motion, indicating that the moving cue was subject to the Fröhlich effect. The mislocalisation in the present experiment makes it clear that the slower orientation discrimination for targets at motion onsets in Experiments 1 and 2 was not due to an (equally) delayed but otherwise precise localisation of the moving cue at motion onset.

GENERAL DISCUSSION

Recent research suggested that attentional capture by moving stimuli could vary as a function of motion phase. The Fröhlich effect, for example, a perceived offset of the initial position of a moving stimulus in the direction of its motion, has been (at least by some authors) explained by the need of attention to be shifted to the moving stimulus and to catch up with the stimulus before this moving stimulus can be correctly localised and perceived at a particular position: According to this account, perception of the moving stimulus' location requires a prior shifting of attention to the moving stimulus. Yet, a shifting of attention takes time. As a consequence, attention catches up with an unanticipated moving stimulus only at a position further along the motion trajectory, and, hence, the moving stimulus' onset position is perceived as shifted (Müsseler & Aschersleben, 1998).

In the current study, we tested and confirmed one prediction that follows from the attentional account: Attentional capture by the onset of a moving stimulus should be spatially imprecise. Using a moving cue, we probed target orientation discrimination at different positions along the cue's motion trajectory. In line with the assumption of a spatially imprecise capture of attention to the position of a motion onset, we found that attentional cueing by the motion onset was less effective than cueing with a moving cue at a position further along the cue's motion trajectory. At the motion onset position of the moving cue (4.2° left or right of screen centre) target orientation discrimination was slower than in a condition with a static cue at the very same position (Experiment 1). In the same experiment, we found that the RTs for targets cued by moving cues steadily declined with an increasing distance of the target position from that of the cue's motion onset, an observation that is in line with the assumption that with an increasing duration of the (by then anticipated) cue's motion its position is coded with an increasing precision and attention has more and more likely caught up with the moving stimulus.

In line with this interpretation, using moving cues and static targets at the very same position of 4.2°, the delay of target orientation discrimination was significantly reduced, once the motion onset was shifted further into the past (Experiment 3). Shifting the onset of the moving cue further to the centre or to the periphery, the motion cue at 4.2° was no longer coincident with the motion onset. In line with the assumption that less capture by motion onsets was responsible for Experiment 1's slower orientation discrimination for targets cued by motion onsets at 4.2°, under the conditions of Experiment 3 a moving cue at 4.2° did not incur a slowing of responses for discriminating target orientations at that position. In addition, the generally weaker discrimination performance for targets cued by motion onsets was also eliminated, once a less attention-demanding colour discrimination task was used (Experiment 4). These findings support that the observed diminution of orientation discrimination of targets cued by motion onsets is at least partly of an attentional origin.

In addition, we were able to rule out various alternative explanations that could be given for our findings and the original observation made by

Müsseler and Aschersleben (1998, Exp. 5). First of all, Müsseler and Aschersleben had their participants discriminate the pattern of a moving stimulus itself. Therefore, it is possible to give an explanation of their findings without referring to attention at all. It could be that the low visibility of a target pattern near target motion onset accounted for their low discrimination performance for patterns near motion onset. Since the invisibility of a moving stimulus during motion onset must not be due to attention (i.e., it could be also, for example, reflect backward masking; cf. Kirschfeld & Kammer, 1999) it would be sufficient to explain both the mislocalisation of the motion onset and the lower pattern discrimination performance near motion onset by, for example, masking and the consequential stimulus invisibility. Yet in our experiments we used a moving cue preceding a subsequent static target of sufficient duration so that the target could be seen in all trials. Thus, the slower orientation discrimination of the static targets cued by motion onsets in the present Experiments 1 and 2 could not have been due to the invisibility of the corresponding target feature. (Note that this does not mean that the cue was seen at motion onset. In fact, we have verified that the cue was invisible at motion onset in Experiment 5.)

Other conceivable alternative explanations of the slower orientation discrimination for targets cued by motion onsets in the current study as well as a lower discrimination performance for patterns near the onset of a moving stimulus (cf. Müsseler & Aschersleben, 1998) were also ruled out. Two such alternative explanations were (1) the low predictability of the target's position at points in time early after motion onset, and (2) the interference by the coding of (the direction of) stimulus motion. These factors depend on the exposition of the moving cue after it has passed the 4.2° position in the present study. These factors were therefore not altered by changing the task (in the present Experiment 4), or by shifting the starting position of the motion of the moving cue to a point 85 ms further into the past, so that a moving cue at 4.2° was no longer coincident with the position of motion onset (in the present Experiment 3). Yet, although the two factors of motion coding and predictability were thus potentially still effective, slower responses to targets cued by a moving cue at 4.2° were either no longer observed (in Experiment 3) or they were reflecting a speed–accuracy tradeoff and, thus, were of a different origin than the real diminution of orientation discrimination of targets cued by motion onsets in our Experiments 1 and 2.

In addition, the time between the cue onset/motion onset and the target also turned out to be irrelevant for the slowing of responses to targets cued by motion onsets. In Experiment 1, we observed slow orientation discrimination responses for targets cued by motion onset but not for targets cued by motion offset when we kept the interval the same between (a) the moving cue at motion onset (or 4.2°) and the target at 4.2° and (b) the moving cue at motion offset (at a position 4° away from 4.2°, either 0.2° or 8.2°) and the target at the position of the cue's motion offset. Yet, keeping this interval the same meant that the interval was shorter between (a) the cue onset/motion onset (at 4.2°) and the target at the motion onset's position (i.e., with the target at 4.2° this interval was 85 ms) than between (b) the cue onset/motion onset (at 4.2°) and the target at the motion offset's position (i.e., with the target presented 4° away from 4.2°, this interval was 170 ms). Therefore, one alternative explanation of slower orientation discrimination for targets cued by motion onsets was the shorter temporal interval between cue onset/ motion onset and the target and the resultant lower temporal warning effect in motion-onset cueing than motion-offset cueing conditions. In a similar manner, such a difference of a shorter prewarning interval between stimulus onset/motion onset and target applied to the patterns near the motion onset in comparison to patterns at positions further along the motion trajectory in Müsseler and Aschersleben's (1998) Experiment 5.

However, in our present Experiment 2, we observed slow orientation discrimination responses for targets cued by motion onset but not for targets cued by motion offset when we kept the interval the same (a) between the cue onset/motion onset (at 4.2°) and the target at the motion onset's position (i.e., with the target at 4.2° this interval was 85 ms) and (b) between the cue onset/motion onset (at 4.2) and the target at the motion offset's position (i.e., with the target 4° away from 4.2°, this interval was also 85 ms). Thus, a shorter interval between cue onset/motion onset and the target cued by the motion onset and a resultant lower temporal prewarning was not responsible for the slow orientation discrimination of a target cued by a motion onset.

Because the differences between motion onset and motion offset cueing were also observed with motion onset cueing and motion offset cueing being realised in separate blocks, it is also clear that the onset cue's low predictive value for the position of the upcoming target was not responsible for the slow discrimination of the orientation of targets cued by motion onsets: In the moving cue conditions of Experiment 2 both motion onset cues and motion offset cues were equally predicting the target location with 100% certainty, right from cue onset on throughout the whole trial.

Finally, the attentional interpretation of the slow discrimination of targets cued by motion onsets was also backed up by the static cue control conditions of Experiment 2. We reasoned that if the moving cue at motion onset (at 4.2°) failed to capture attention and that the moving cue at motion offset (at 4° distance from 4.2°) captured attention, then we should be able to replicate the pattern of slow orientation discrimination responses for targets cued by motion onsets relative to targets cued by motion offsets by simply presenting one static cue at 8.2° or 0.2° (i.e., one of the potential motion offset positions) and comparing orientation discrimination RTs for a target at 4.2° (on the same side of the monitor as the cue, i.e., at one of the potential motion onset positions) to orientation discrimination RT for a target at the same position as the cue (i.e., one of the potential motion offset positions). Under these conditions, we found an RT difference between the two static cue conditions that was even numerically almost identical with the RT difference between the two moving cue conditions, a result which suggests that the RT difference between the two different moving cue conditions was reflecting only attentional capture by the motion offset cue and nil attentional capture by the motion onset cue.

By the way, this finding from the static cue control condition of Experiment 2 corroborated that interference by coding the moving cue's motion (direction) did not substantially contribute to the slow responses for discriminating targets cued by motion onsets. Otherwise, the RT difference between the static cue control conditions should have been smaller than that between the two moving cue conditions because the static cue control conditions mimicked only the moving cues' attentional effect but not the moving cue's motion-dependent effects.

Finally, one might question whether attentional capture by the motion onsets was indeed spatially less precise or whether attentional capture by the motion onsets was spatially veridical and precise but delayed. One piece of evidence that definitely rules out this alternative interpretation of our results that we found is that the moving cue was indeed not accurately located at motion onset (Experiment 5). Thus, the moving cue at motion onset is not perceived at its veridical position (but delayed). Instead the moving cue at motion onset was perceived as being shifted in the direction of its motion. In summary, the results thus supported that (a) spatial coding of the motion onset position was imprecise and that (b) spatial precision of attentional capture by the motion onset was compromised accordingly.

Relation to Fröhlich's observations

Our results show that a less precise spatial coding of motion onset coincides with a weaker spatial capture effect to the exact position of the motion onset. In principle, two sorts of explanations can account for these findings. First, attention could be taking time to catch up with the moving cue. As a consequence, the perception of the starting position of the cue that critically hinges on a prior shifting of attention could be spatially imprecise—that is, shifted in the direction of motion. Likewise, fine-grained discriminations of other features that also depend on a prior shifting of attention (i.e., orientation discrimination) would suffer from the same shortcoming of attention not being shifted to the exact motion onset position if being presented at the position of a motion onset.

Second, the moving stimulus at motion onset could be perceived as being more blurred or smeared because information about its position is integrated over a number of successive frames. Likewise, the moving stimulus at motion onset could not be perceived at all because of the representations inertia or because of backward masking of the motion onset position by subsequent adjacent stimulation. As one further consequence of this general loss of spatial detail about the motion onset position, an attention shift to this position could be also hampered. On the basis of the existing literature, the absence of attentional capture by a backward masked stimulus is maybe least supported as several studies have successfully demonstrated that backward masked cues can capture attention (Scharlau, 2002; Scharlau & Ansorge, 2003; Scharlau, Ansorge, & Horstmann, 2006).

However, taking a methodological perspective we cannot easily tell whether the misperception is the reason for the lack of attentional capture or the consequence of the lack of attentional capture. In the current study, we only demonstrated that a lack of an attentional effect of the moving cue at motion onset coincided with the mislocalisation of the cue's motion onset. Thus, the attentional effect could be the origin of the misperception but it could always be the other way round, too, with misperception being the reason for the diminished attentional effect. In any case, that discrimination of features besides position (here target orientation) suffered at motion onset can only be explained by a mediating role of attention for discriminating the target. This might have been doubted in Müsseler and Aschersleben's (1998) Experiment 5. However, in the present study we have ruled out the alternative conceivable explanations of their findings and supported their conclusion.

In addition, we want to emphasise that an account of the Fröhlich effect might require more than the attentional explanation. Fröhlich noted phenomenal characteristics besides a mere shifting of the perceived onset position of a moving stimulus. In particular, Fröhlich (1929) found that the motion stimulus is also perceived as being smeared and lighter than it objectively is during its onset phase. At least the explanation of these phenomenal characteristics might require mechanisms in addition to the working of attention. For instance, directing attention to a moving visual stimulus boosts perceived stimulus speed (Carraso, Ling, & Read, 2004; Turatto, Vescovi, & Valsecchi, 2007) and, this, in turn could increase perceived smear. (At least, it is not obvious how a delayed shifting of attention can account for the other phenomenal characteristics reported by Fröhlich.)

Finally, alternative explanations of the Fröhlich effect have also received some support. This is true for backward masking of the first position of the motion stimulus by the temporally trailing, laterally adjacent motion stimulus at its next position. Kirschfeld and Kammer (1999) rightly noted that these conditions are ideal for backward masking. In line with Kirschfeld and Kammer's two-mechanism account, attributing the Fröhlich effect to a combination of lacking advance cueing of the motion stimulus' first position (by the same stimulus at a preceding motion position) and backward masking of the same stimulus, we recently found an asymmetric amount of the mislocalisation in the Fröhlich effect, depending on whether a moving stimulus increased or decreased in size. Specifically, we found that the mislocalisation for increasing stimuli was larger than that for decreasing stimuli, and that this asymmetry was contingent on the contrast between the adjacent stimuli. These effects can most likely be understood only under the perspective that backward masking contributed to the mislocalisation effect (Carbone & Ansorge, 2008).

CONCLUSION

During the recent years psychological research on attention successively incorporated more and more aspects of ecologically valid scenarios into the well-controlled laboratory setting such as the use of real-word pictures as stimuli (e.g., Henderson, 2003; Öhman, Lundqvist, & Estevez, 2001), three-dimensional search spaces (e.g., Theeuwes, Atchley, & Kramer, 1998), and also measuring overt shifting of the eyes to understand the relationship between covert shifts of attention and saccadic behaviour (e.g., Deubel & Schneider, 1996; Hoffman & Subramanium, 1995). Studying the distribution of attention to moving stimuli is just one aspect of this broader trend towards a better understanding of the working of attention. Given an abundance of moving stimuli in the real world, the study of how observers attend to motion is certainly an important aspect of that endeavour. In fact, the high ecological significance of motion could be reflected in a relatively strong potential of motion to capture an observer's attention (Franconeri & Simons, 2003; Hillstrom & Yantis, 1994; McLeod, Driver, Dienes, & Crisp, 1991). This general truth notwithstanding, however, using motion in a more technical-applied context to deliberately guide an observer's attention, we have to take into account considerable shortcomings of attentional capture by motion as was made clear in the current study.

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