

Comparing mislocalizations with moving stimuli: The Fröhlich effect, the flash-lag, and representational momentum

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When observers are asked to localize the onset or the offset position of a moving target, they typically make localization errors in the direction of movement. Similarly, when observers judge a moving target that is presented in alignment with a flash, the target appears to lead the flash. These errors are known as the Fröhlich effect, representational momentum, and flash-lag effect, respectively. This study compared the size of the three mislocalization errors. In Experiment 1, a flash appeared either simultaneously with the onset, the mid-position, or the offset of the moving target. Observers then judged the position where the moving target was located when the flash appeared. Experiments 2 and 3 are exclusively concerned with localizing the onset and the offset of the moving target. When observers localized the position with respect to the point in time when the flash was presented, a clear mislocalization in the direction of movement was observed at the initial position and the mid-position. In contrast, a mislocalization opposite to movement direction occurred at the final position. When observers were asked to ignore the flash (or when no flash was presented at all), a reduced error (or no error) was observed at the initial position and only a minor error in the direction of the movement occurred at the final position. An integrative model is proposed, which suggests a common underlying mechanism, but emphasizes the specific processing components of the Fröhlich effect, flash-lag effect, and representational momentum.

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In the present paper three localization errors are compared which have been observed with moving stimuli. First, when observers are asked to localize the initial position of a moving target, they do not localize it at the onset position, but rather at a position ahead of the target's movement (the *Fröhlich effect*; e.g., Fröhlich, 1923; Kirschfeld & Kammer, 1999; Müsseler & Neumann, 1992; for an overview see Müsseler & Aschersleben, 1998). Second, when observers localize a moving target that is presented in alignment with a flash, the target appears to lead the flash (the *flash-lag effect*; e.g., Hazelhoff & Wiersma, 1924; Krekelberg & Lappe, 2001; Metzger, 1932; Nijhawan, 1994; Whitney, Murakami, & Cavanagh, 2000). Third, when observers localize the vanishing point of a moving target, they also localize it ahead of the target's movement (*representational momentum*; e.g., Freyd & Finke, 1984; Hubbard & Bharucha, 1988; for an overview see Hubbard, 1995). To date, these mislocalizations have been mainly examined independently and different accounts were formulated for each of the three localization errors.

For example, the Fröhlich effect can be explained by assuming that localizing and pointing to a target requires focal attention being directed to it. Then, the effect emerges from three well-known properties of visual attention that have been revealed by studies with stationary stimuli (Müsseler & Neumann, 1992; Neumann & Müsseler, 1990). (1) A shift of attention is elicited by a target appearing in the retinal periphery (e.g., Theeuwes, Kramer, Hahn, & Irwin, 1998). (2) An attention shift takes time (e.g., Müller & Findlay, 1988). (3) After directing attention to the target position, reaction time *and/or* recognition acuity is improved (e.g., Van der Heijden, Schreuder, & Wolters, 1985) and a phenomenal representation of the target becomes available. The target in the Fröhlich effect display is moving, implying that after eliciting the attention shift, it will have traversed a certain distance before it is reached by the attentional focus. If the first perceived position of the target is determined after completion of the focus shift, this target location necessarily deviates from the position of its physical appearance. This is what is observed in the Fröhlich effect (for empirical evidence supporting this idea see Müsseler & Aschersleben, 1998).

It is obvious that the preceding explanation of the Fröhlich effect cannot be easily applied to either the flash-lag effect or to representational momentum. The attention-shifting explanation requires both the focus shift elicited by an abrupt onset of the moving target, and also a target that exists after the focus shift has been completed. The offset situation present with representational momentum does not meet those requirements (but for an effect of attentional allocation on representational momentum, see Hayes & Freyd, this issue). Consequently, explanations of representational momentum differ fundamentally from the attentional explanation of the Fröhlich effect. Basically, accounts of representational momentum assume that—analogueous to the physical momentum of real-world objects—the mental representation of a moving target cannot

be halted instantaneously. Instead, it continues for some time in memory in a way that the remembered final position is ahead of the actual position (e.g., Hubbard, 1990; Hubbard & Bharucha, 1988; for an alternative perceptual explanation, see Jordan, Stork, Knuf, Kerzel, & Müsseler, in press; Kerzel, this issue; Kerzel, Jordan, & Müsseler, 2001).

Further, the flash-lag situation does not meet the requirements of the attention-shifting explanation in that it lacks the abrupt onset of the moving target. Some authors had suggested that the onset of the flash elicits an attentional shift from the moving target to the flashed location, and that this shift of attention produces the flash-lag effect (e.g., Baldo & Klein, 1995). However, in a recent empirical study, Khurana, Watanabe, and Nijhawan (2000), failed to find support for this explanation. Instead, these authors propose that the flash-lag effect arises due to a spatial extrapolation mechanism which is applied to the moving stimuli in order to compensate for neural latencies (Nijhawan, 1994). Without compensation, a permanent dissociation between perceived and actual physical location would occur. Other accounts assume that the flash-lag effect originates from an increased persistence of the stationary flash (Krekelberg & Lappe, 2000) or from a latency difference in processing stationary and moving stimuli (Whitney et al., 2000).

Empirical studies and corresponding explanations are often concerned exclusively with either the Fröhlich effect, the flash-lag effect, or representational momentum. Yet, the fact that the three effects represent localization errors in the direction of the movement could suggest a common underlying mechanism (see also Whitney & Cavanagh, this issue). So far, no experimental set-up has been introduced to provide for comparative analyses of localization errors in movement direction. The present paper presents a first step to address this comparison of the three effects.

In general, if patterns of localization are similar or the same at different points in the trajectory, this would suggest a common underlying mechanism for the three effects. If the patterns are quite different, this would favour distinct mechanisms. However, in this latter case it is also conceivable that differences in patterns of localization arise because each effect adds a unique feature to the presentation that requires some specific processing component in addition to the common mechanism. In the case of the Fröhlich effect, it may be that this component is the abrupt onset of the moving stimulus, a factor that is not present either in the flash-lag effect or in representational momentum. In the case of representational momentum, this component could be the abrupt offset of an already ongoing movement and in the case of the flash-lag effect it may be the localization relative to a (stationary) flash.

The experiments reported here were designed to directly compare the mislocalization in movement direction at the initial position, a position during an ongoing movement (i.e., the mid-position), and the final position. Experiment 1 examined the flash-lag effect at these three positions. Experiment 2 was

exclusively concerned with absolute localization judgements at the onset and offset positions. Thus, it was designed to measure both the original Fröhlich effect and representational momentum. Experiment 3 was similar to Experiment 2, but the flash was re-introduced to the procedure and its task relevance was varied. The objective was to compare the mislocalizations under those different conditions. In the General Discussion, an attempt is made to integrate the three localization errors and their possible specific processing components into one model.

EXPERIMENT 1

In Experiment 1, the flash-lag effect was examined at the onset position, the mid-position and the offset position of the moving target. More precisely, the flash appeared either simultaneously with the onset, the mid-position, or the offset. Observers were asked to judge the position where they had perceived the moving target when the flash was presented. In order to control for retinal eccentricity, circular movements with a central fixation cross were used.

Eagleman and Sejnowski (2000) already examined the flash-lag effect at the onset position and the mid-position and found no substantial differences between conditions (see also Khurana & Nijhawan, 1995). However, Eagleman and Sejnowski presented a flashed white disc in the centre of a moving ring, which might evoke masking effects. To avoid masking in the current experiments, the flash was always presented spatially separated from the moving target.

If no difference in localization performance as a function of flash position occurs, this would provide initial evidence that a common underlying mechanism is involved. Differences in localizations may indicate distinct mechanisms. It is also plausible, and more parsimonious, however, to assume that specific components may modify a basic processing mechanism. For example, a flash presented at the initial position might emphasize the abrupt onset of the moving target, which characterizes the original Fröhlich effect. Consequently, additional processing activities may be required due to the abrupt onset, which is not the case at the mid-position or the final position. Of course, flash presentations at the mid-position or at the final position might evoke other specific processing components that might also lead to different patterns of localizations.

Method

Apparatus and stimuli. Experiments were carried out on a laboratory computer (Rhothon rho-prof 200) and a 20" monitor with black-on-white projection (Philips C2082DAS/II, adjusted to 160 Hz refresh rate). The monitor's luminance was approximately 41 cd/m²; the rest of the room was dimly lit. A

dot of 2.6 mm (0.3°) with a luminance of 19 cd/m^2 was used as the moving target, which circles around a fixation cross in the center of a circle of 48 mm radius (5.5° , cf., Figure 1). The target movement was induced by rotating the dot 2° clockwise¹ with every vertical retrace of the monitor. The movement started at a random position on the circle and covered a distance of 86° , that is about a quarter of the circle with the absolute movement time of 270 ms.

The flash was a black dot of 2.6 mm (0.3°), which was presented for one refresh cycle on a virtual circle of 64 mm radius (7.3°). It appeared either simultaneously with the onset of the moving target, or when the target reached the mid-position of its movement trajectory, or it appeared with the offset of the moving target. The positions of the flash at these points in time were either in alignment with the target ($0 \text{ mm} = 0^\circ$ deviation from alignment), or the flash appeared on its virtual circle spatially before ($-8.7 \text{ mm}, -1^\circ$) or behind the point of alignment ($+8.7 \text{ mm}, +1^\circ$; cf., Figure 1). These minor deviations of flash positions were introduced to prevent observers from taking the flash position as a valid indicator of the target position.

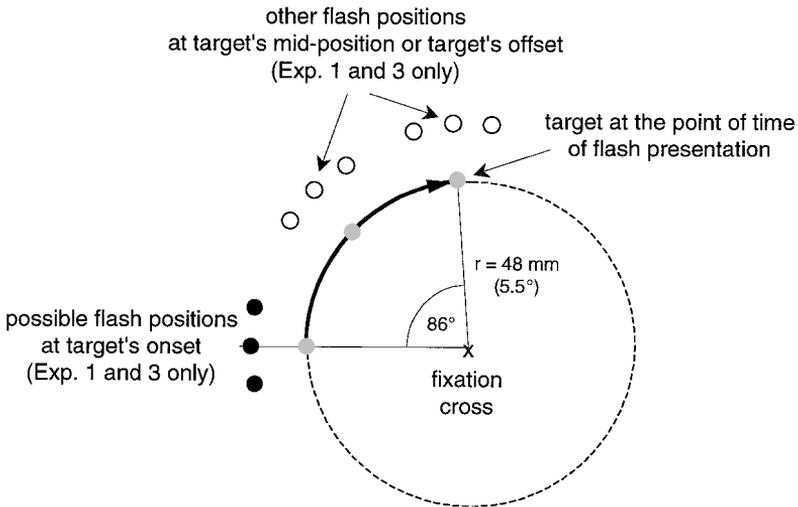


Figure 1. Stimuli presentations in the experiments. Observers fixated a cross in the middle of the screen and a moving target appeared at a random position on a circle moving in a clockwise direction. Simultaneously with target's onset, with its mid-position, or with its offset, a flash was presented for one frame. The task of the participants was to move a cursor to the position where they had seen the target at the point of time when the flash was presented (Experiments 1 and 3) or where they had seen the target for the first or the last time (Experiments 2 and 3).

¹If the description contains the degree scale only, the unit refers to the corresponding angle of rotation! If scales giving both degree and millimetre are used, the units refer to the corresponding visual angle.

An adjustment cursor, which was identical to the target, appeared 1 s after the end of target movement at a random position on the circle. It could be adjusted in a clockwise and counterclockwise direction of the circle by pressing a right or a left button, respectively. These buttons were mounted on a flat board in front of the observers.

Control of eye-movement instructions. In the experiments the participant's head was placed on a chin and forehead rest 500 mm in front of the monitor. The horizontal position of the left eye was monitored with a head mounted, infrared light reflecting eye-tracking device (Skalar Medical B.V., IRIS Model 6500). The eye movement modulated signal was band-pass, demodulated, and low-pass filtered (DC –100 Hz, –3dB) and then digitized at a rate of 250 Hz with a PC (via a DataTranslation card, DT 2821). Calibration of the monitor was accomplished by having the participant fixate at seven evenly spaced digits across the screen.

Saccadic eye movements were detected by analysing the eye-movement signal, so that we were able to discover the occurrence of saccades larger than at least 1° of visual angle. If a saccade was detected during a trial, the corresponding data were excluded from further analyses.

Design and procedure. Participants were confronted with all combinations of the factors target position (flash at the onset, mid-position, offset) and flash alignment (–8, 7, 0, +8.7 mm) yielding a 3 × 3 within participants design. Ten repetitions per participant were gathered within each cell of the design. In total, the participants completed 90 trials.

The central fixation cross was visible throughout the experiment. Each trial began with an auditory warning signal (1000 Hz for 50 ms). After 1 s the moving target appeared. The flash appeared either at target's onset, at the mid-position of target's trajectory, or with target's offset. The instruction stressed that participants should concentrate on the fixation cross during the entire movement. After each presentation, participants had to adjust the cursor to the position where they had perceived the moving target to be located when the flash was presented.

During the adjustment phase of the cursor, eye movements were allowed. After having localized the perceived position, a double button press confirmed the adjustment. The next trial was initiated with a programmed 1 s delay. To familiarize participants with the task, a training block consisting of 18 trials was presented at the beginning. The experiment lasted about three-quarters of an hour including the eye-movement adjustment procedure and a short break.

Participants. Six female and four male students of the University of Munich, who ranged in age from 18 to 37 years (mean age of 27.8 years), were

paid to participate in the experiment. They reported normal or corrected-to-normal vision.

Results and discussion

Exclusions of data because of saccadic eye movements were necessary in 72 of 900 trials. As the dependent variable, perceived mislocalization represents the measured difference between adjusted and real position of the target when the flash was presented. Positive values indicate errors in the direction of the movement.

Mean localization errors were computed for every participant and each condition separately. These errors were entered into a 3×3 repeated measurement analysis of variance (ANOVA) with the factors target position (onset, mid-position, offset) and flash alignment (-8.7 , 0 , $+8.7$ mm). The only significant effect was the target position, $F(2, 18) = 101.99$, $MSe = 91.61$, $p < .001$. Flash alignment, $F(2, 18) = 1.93$, $MSe = 71.38$, $p > .15$, and the interaction, ($F < 1$) were not significant.

When the flash appeared with target onset, a clear mislocalization in movement direction was observed (cf., Figure 2, means collapsed across conditions of flash alignment). This mislocalization was somewhat reduced, when the flash appeared at the mid-position and—most surprisingly—a mislocalization contrary to movement direction was observed, when the flash appeared with target's offset. All observed mislocalizations were different from zero: onset: $t = 6.80$, $p < .001$; mid-position: $t = 2.28$, $p < .05$; offset: $t = -5.05$, $p < .001$; always two-tailed.

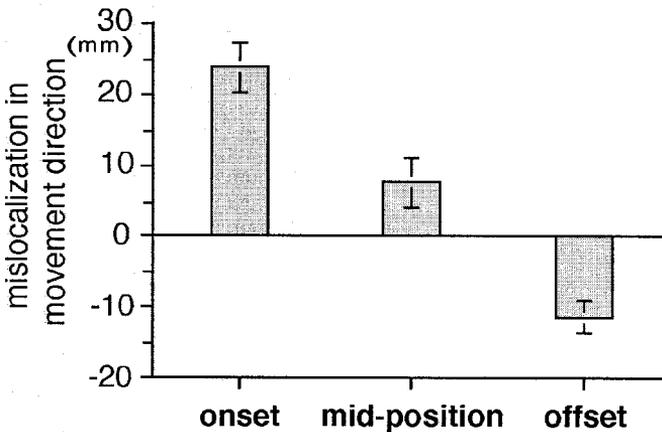


Figure 2. Mean mislocalizations and standard errors (between participants) of the target's position at the point of time of flash presentations. Positive values stand for errors in the direction of the movement, negative values for errors opposite to the direction of the movement (Experiment 1, $N = 10$, each data point about 300 observations).

The present results clearly indicate that—when observers judged the position of a moving target as the flash was presented—observers localized differentially the initial, middle and final position of a movement. This could mean that the localization errors are based on completely different mechanisms. Alternatively, this could mean that specific features of the presentations require specific processing components in addition to a common mechanism. In detail, the mislocalization at the mid-positions is less pronounced than at the initial position. We can attribute larger mislocalizations at the start of the movement to the abrupt onset of the moving target. Such abrupt onsets characterize the Fröhlich effect. Contrary to both the localization error at the onset and at the mid-position, the localization error at the offset position is reversed. Two reasons may account for this striking finding. First, the mere presentation of the flash may elicit processes, which eliminate localization errors and even reverse them. Second, the flash serves as a task-relevant comparison stimulus, which is typical for the flash-lag task but non-typical for the representational momentum task. In other words, the localizations may depend on whether the task is “to judge the target’s position when the flash is presented” or “to judge the target’s final position”. The subsequent experiments were designed to test these ideas.

EXPERIMENT 2

In this experiment, we examined whether the flash could have caused the backward displacement observed at the offset of motion. The flash was omitted and observers were asked to judge the perceived onset and offset position of the moving target. Under these conditions the original representational momentum effect and the original Fröhlich effect are expected outcomes.

Method

Stimuli, design, and procedure. Stimuli were the same as in Experiment 1, with the exception that the flashes were removed from the procedure. In the first block, half of the participants had to judge the perceived target position at the onset of the movement. In a second block, they judged the perceived target position at the offset of the movement. Blocks were separated by a short break. The block sequence was reversed for the other half of the participants. Eighteen repetitions per participant were gathered within each cell of the design.

Participants. Ten observers were paid to participate. Their mean age was 29.0 years, with a range of 21–37 years.

Results and discussion

Eye movements were observed in only 6 of 360 trials. These trials were excluded from further analysis. Mean localizations are depicted in Figure 3. A

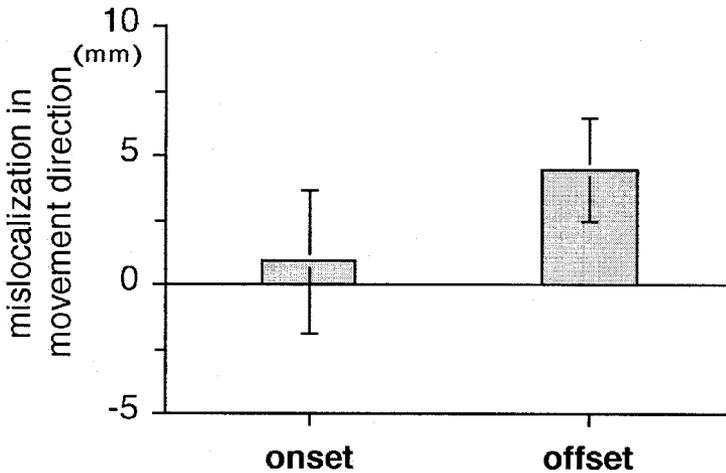


Figure 3. Mean mislocalizations and standard errors (between participants) at the onset and offset of the target (Experiment 2, $N = 10$, each data point about 180 observations).

reliable mislocalization (i.e., a deviation from zero) was only observed when participants judged the offset position, $t = 2.27$, $p < .05$, but not the onset position of the moving stimulus, $t < 1$. The judged positions of the onset and offset differed only marginally, $t = 1.46$, $p < .20$.

To conclude, representational momentum was observed with the omission of the flash from the procedure. It is not clear, however, whether this finding was due to the fact that the flash did not appear at all or that the task was changed from a comparison task (“Judge the target position when the flash is presented!”) to an absolute judgement task (“Judge the offset position!”). In any case, the observed representational momentum effect in the present study is somewhat contrary to previous findings in our laboratory according to which representational momentum occurred only with pursuit eye movements. With eye fixation, as was the case in the present study, representational momentum was not observed (Kerzel et al., 2001). One plausible reason for that could be that target movement was faster in the present study compared to the previous study.

The most striking finding of Experiment 2 is that the Fröhlich effect disappeared. Before this observations is discussed in detail, Experiment 3 will examine whether findings of Experiments 1 and 2 can be replicated when varying the task relevance of the flash.

EXPERIMENT 3

In the final experiment, the flash was re-introduced to the procedure of Experiment 2. Observers were now confronted with two tasks in two separate blocks.

They were either asked to ignore the flash and to localize the target at its onset or offset position; or they were asked to localize the target's position when the flash was presented, that is with target onset or offset. If it was the mere presentation of the flash that had eliminated representational momentum in Experiment 1, the effect should be independent from the task relevance of the flash. If the localization judgements at the final position are influenced by the task, the results of Experiment 2 are predicted for the flash-irrelevant task and the same pattern of results as in Experiment 1 is predicted for the flash-relevant task. Correspondingly, task relevance could be also responsible for the differences observed at the initial position in Experiments 1 and 2. In addition to task relevance, we also varied the length of the target's trajectory in the present experiment. This was done to introduce spatial and temporal stimulus uncertainties and also to examine the possible influence of trajectory length on perceived location.

Method

Stimuli. Moving targets were the same as in the previous experiments, but we introduced variability in the length of the target's trajectory. Movements covered now a variable distance of 74, 86, or 98° with the absolute movement times of 232, 270, to 307 ms. Additionally, the flash appeared with the onset or offset of the target. As in Experiment 1, flash positions varied spatially by -8.7, 0, +8.7 mm relative to the onset or offset of the target to prevent observers from evaluating the flash position as a valid indicator of the target position. Data were collapsed across these positions.

Design and procedure. Flash relevance (relevant, irrelevant), target positions (onset, offset), and trajectory length (74, 86, 98°) were crossed in a $2 \times 2 \times 3$ design with repeated measurements. The factors flash relevance and target positions were varied blockwise and block sequence was randomly chosen for each participant. Blocks were separated by short breaks.

When the flash was task relevant, observers were instructed to adjust the cursor to the position where they had perceived the moving target when the flash was presented. When the flash was task irrelevant, observers were instructed to ignore the flash and to judge the perceived target position either at the onset or at the offset of the movement, respectively.

Twelve repetitions per participant were gathered within each cell of the design. Altogether, each participant was presented with 144 trials.

Participants. Ten observers were paid to participate. Their mean age was 30.9 years, with a range of 24–37 years.

Results and discussion

Exclusions of data because of unwanted eye movements were necessary in 45 of 1440 trials. Mean adjusted localizations entered in a 2 (flash relevance) \times 2

(target position) \times 3 (trajectory length) ANOVA with repeated measurements. The trajectory length of the target did not exert an influence on the perceived localizations; hence, in Figure 4 means were collapsed across this factor.

The ANOVA further revealed a significant main effect of target position, $F(1, 9) = 26.30$, $MSe = 265.65$, $p < .001$, and—more importantly—a significant interaction of target position and task relevance, $F(1, 9) = 7.83$, $MSe = 430.17$, $p < .05$. When observers localized the onset and offset position with respect to the point in time when the flash was presented, a clear positive mislocalization at the initial position and a negative mislocalization at the final position were observed. This pattern of results with a task relevant flash replicates the findings of Experiment 1. When observers were asked to ignore the flash, a reduced error at the initial position and only a minor, but positive error at the final position were observed. However, this latter effect did not deviate from zero, $t = 1.14$, $p > .20$, while all other mislocalizations did deviate: for the initial position with a task-relevant flash: $t = 4.77$, $p < .001$, and with a task-irrelevant flash: $t = 2.37$, $p < .05$; for the end position with a task-relevant flash: $t = 2.35$, $p < .05$. This pattern qualitatively replicated the findings of Experiment 2. However, a significant error at the initial position was observed in the present experiment, but not in Experiment 2. Further, a significant representational momentum effect was observed in Experiment 2, but not in the present experiment. This finding indicates that ignoring the flash might be less effective than omitting its presentation. Altogether, the present findings demonstrate that the task relevance had an effect on where the target is localized.

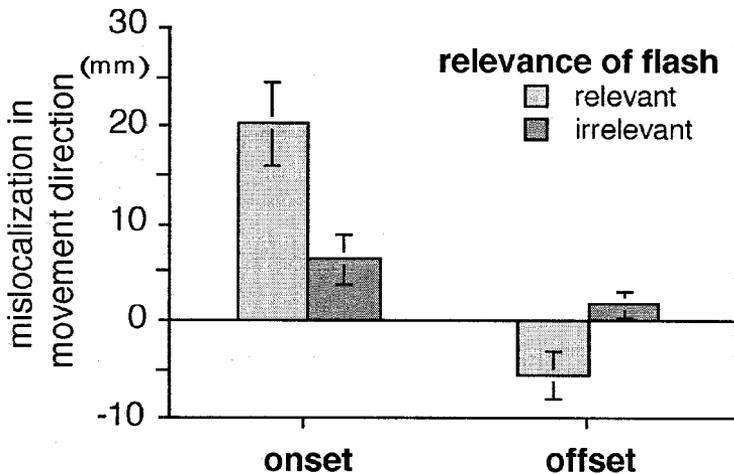


Figure 4. Mean mislocalizations and standard errors (between participants) at the onset and offset of the target (Experiment 3, $N = 10$, each data point about 360 observations).

GENERAL DISCUSSION

The present study compared localizations—with and without an accompanying flash—at the initial position, the mid-position, and the final position of a moving target. Corresponding mislocalizations are known as the Fröhlich effect, the flash-lag effect, and representational momentum. Since these phenomena describe localization errors in movement direction, a common underlying mechanism may be involved. In three experiments, we found large differences in the pattern of mislocalizations suggesting either different underlying mechanisms or a common mechanism that is modified by the specific features characterizing the conditions.

In more detail, a flash was presented in Experiment 1 in which observer's task was to localize the position of the moving target when the flash was presented. As expected, the localization error at the initial position was more pronounced than the localization error at the mid-position. We attribute larger mislocalizations at the start of the movement to the abrupt onset of the moving target. Such abrupt onsets are a defining feature of the Fröhlich effect, but are not typically associated with the flash-lag effect. Most surprisingly, in Experiment 1 the localization error at the final position was opposite to movement direction. Experiment 2 addressed this reversal by omitting the flash from the procedure. A localization error in direction of the movement occurred at the final position (i.e., the representational momentum effect), but surprisingly the localization error at the initial position disappeared (i.e., the original Fröhlich effect). In Experiment 3, the two unexpected findings, the reversed localization error in Experiment 1 and the disappearance of the localization error in Experiment 2, were qualitatively replicated by varying the task relevance of the flash. We will now address the two unexpected findings separately and then go on to develop an integrative model of mislocalizations in movement direction.

What can account for the reversed localization error at the final position in Experiment 1 and, when the flash was task relevant, in Experiment 3? The reversal was only observed when observers judged the target's position at flash presentation, that is, when the flash served as a spatiotemporal comparison stimulus. A localization opposite to movement direction could occur if the abrupt onset of the stationary flash is processed faster than the moving target. Another idea is that the last part of the target's trajectory is masked by presentation of the flash, thus evoking a negative localization error.

However, there is not much evidence to support these explanations. On the contrary, analysing the flash-lag effect suggests that the processing of the flash has a *longer* latency than the processing of the moving target (cf., Whitney et al., 2000; see also Aschersleben & Müsseler, 1999). Further, masking of the last part of target's trajectory is not very likely for three reasons. First, the quite large flash-target distances of about 2° are unlikely to produce masking effects. Second, the reversal of representational momentum effect disappeared with the

task-irrelevant flash (Experiment 3), that is, the target was still perceivable at the vanishing position of the movement. Third, even if masking mechanisms play a role, the position of the flash relative to the target's offset should have had an impact on the judgements. More specifically, the reversal should be less pronounced at a flash alignment of +8.7 mm than at a flash alignment of -8.7 mm. This was not observed (Experiment 1). Thus, it is more likely that the perceived target position at the point in time when the flash was presented does not agree with the perceived vanishing position of the target.

From that we can conclude that a spatiotemporal comparison mechanism is involved in the flash-lag effect, which—when it is introduced at the offset of a movement—leads to completely different localization judgements compared to judgements of target offset in a representational momentum task. Similarly, it is interesting to note that the comparison mechanism obviously leads to different observations when the comparison stimulus (i.e., the flash) is presented at the mid-position or the offset position. A possible explanation is that the perceived offset of the flash (cf., the persistence of the flash; Krekelberg & Lappe, 2000) determines the point in time at the target's mid-position (but not at the target's offset position), when the comparison judgement is made. Given an increased persistence of the stationary flash (as compared with the persistence of the moving target), the target continues to move before the flash visually disappears. This could have evoked the flash-lag effect at the mid-position. When the flash is presented with the offset of the target, it may still persist, but the target has already disappeared from the scene. As the target no longer moves, this persistence may not give rise to perceptual misalignment, as in the case of the mid-position. However, since the observer's task was to localize the position of the moving target when the flash was presented, this persistence could bias the selection of an earlier target position. That is, observers may be unwilling to accept that the "moving" target could have been in the same place at both the onset and offset of the flash. Such a bias could have evoked the reversal of the localization error at the offset position (but see also later).

In Experiment 2 the flash was omitted from the procedure. What accounts for the disappearance of the localization error at the initial position (i.e., the Fröhlich effect) in this experiment? Stimulus velocity could be a critical factor for the disappearance, which was quite slow in the present experiments (angular velocity of 30.6°/s with respect to the eye). In a circular arrangement, Kirschfeld and Kammer (1999) observed the Fröhlich effect with much higher velocities. At the fixation point a white line was presented rotating around its central mid-position. A clear Fröhlich effect was observed with velocities of about 45°/s and higher (estimated velocity at the circumference, cf., Kirschfeld & Kammer, 1999, Fig. 5), that is, the line was not perceived as soon as it appears but only after a certain delay. On the other hand, we were already able to demonstrate the Fröhlich effect with a velocity of 14°/s, but with a linearly-moving stimulus (Müsseler & Aschersleben, 1998, Exp. 1). Thus, it could be that the

size of the Fröhlich effect, which is well established with a linearly-moving stimulus (Aschersleben & Müsseler, 1999; Fröhlich, 1923; Metzger, 1932; Müsseler & Aschersleben, 1998; Müsseler & Neumann, 1992), is different with a circularly moving stimulus. This topic is beyond the scope of the present paper and is addressed elsewhere (Müsseler, Stork, Kerzel, & Jordan, 2002).

Comparing experiments we can conclude that the perceived target position at flash presentation does not agree with the perceived onset position of the target. Thus, the size of the flash-lag effect and the Fröhlich effect are obviously different. Comparing the localizations at the initial position and the mid-position with the localizations at the final position, findings also show more divergence than convergence. These differences were also present and even more pronounced with a spatiotemporal comparison stimulus (i.e., the flash). One conclusion from this pattern of results could be that the phenomena under discussion are based on completely different processing mechanisms. However, another possible conclusion would be that specific components of the phenomena modify a basic processing mechanism, which lead to different appearances of the phenomena. In the subsequent section a simple post hoc model is proposed which may accommodate basic and specific mechanisms.

A model addressing the different mislocalizations in movement direction

Can the range of localization errors reported in these studies be integrated into a single model? With Erlhagen and Jancke (2002) we assume that the presentation of a stimulus elicits excitatory and inhibitory processes determining a spatial activation pattern, which is not restricted to the area covered by the stimulus. Rather it spreads its activation to and integrates contextual information from the adjacent parts of the visual field (Figure 5A). The build-up of an activation pattern can also be assumed to be elicited by a moving stimulus (see also Berry, Brivanlou, Jordan, & Meister, 1999; Hubbard, 1995; Kirschfeld & Kammer, 1999). However, before information build-up exceeds a perceptual threshold, the stimulus continues to move, which is assumed to contribute to and to modify the activation pattern. To be more specific, the adjacent positions in movement direction are assumed to be pre-activated by the present position. At the point in time when the stimulus approaches the positions, activation is further accumulated at these positions and—due to the direction specificity of the mechanism—a stimulus-driven bow wave of activity occurs, which moves continuously across the visual scene. Depending on velocity, it peaks at or even ahead of the leading edge of the stimulus (Figure 5B and C). Erlhagen and Jancke (1999, 2002; see also Jancke, 2000) found evidence for such a wave at the cortical level and have modelled wave-establishing mechanisms. Berry and colleagues (1999) suggested that such a wave can be also generated in the population of retinal ganglion cells.

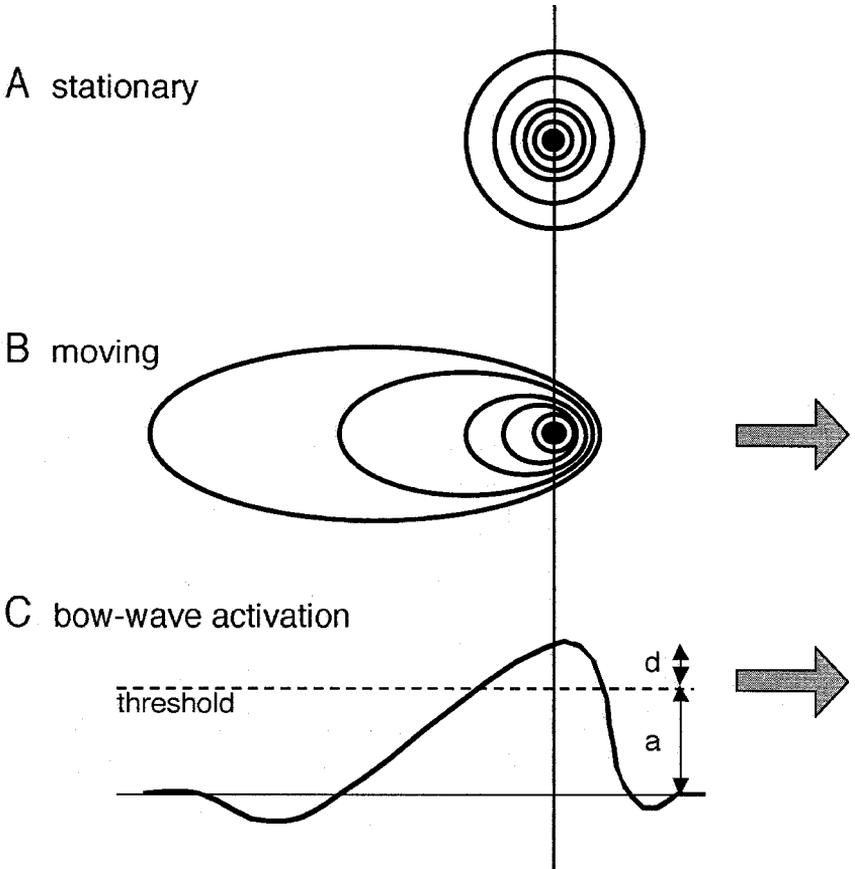


Figure 5. Schematic illustrations of the basic model assumptions. (A) The presentation of a stimulus elicits the build-up of an activation pattern which is not restricted to the area covered by the stimulus, rather spreads its activation to and integrates contextual information from the adjacent parts of the visual field (circles). (B) When a stimulus moves during the build-up phase, the previously pre-activated stimulus positions contribute to and modify the activation pattern correspondingly. (C) The consequence is a stimulus-driven bow wave of activity which is travelling across the visual field (for comparable ideas see also Berry et al., 1999; Erlhagen & Jancke, 2002; Kirschfeld & Kammer, 1999). The Fröhlich effect is determined by the time to establish the bow wave above the perceptual threshold (d); the representational momentum effect is determined by the decay time of supraliminal processing after the target's offset (d). The flash-lag effect is determined by the faster processing time of the moving target as compared to the stationary flash.

How can such a travelling wave across the visual field account for the different localizations? The Fröhlich effect emerges in the build-up phase of the bow wave. With the onset of the stimulus, activation is accumulated starting from the resting level. As already mentioned, when the stimulus continues to move, a skew wave already exceeds the perceptual threshold (distance a between resting level and supraliminal activation, Figure 5C) and the Fröhlich effect occurs. This sounds like the old sensation-time explanation proposed by Fröhlich (1923). However, if the original idea of a sensation time is developed further the delay caused by a sensation time should occur not only at the first position of the moving stimulus but at each single part of the movement as well. Then, either a moving stimulus should not be perceived at all or each part of the movement would be perceived with a temporal delay. In the latter case a location error should not occur. Metzger (1932) already pointed out this objection to the original sensation-time idea presented by Fröhlich. In the present explanation, this objection is handled by the skew shape of the bow wave that exceeds the perceptual threshold.

The representational momentum effect is characterized by the offset of a moving stimulus. In this case, an existing activation wave is assumed to decay from supraliminal to subliminal activation (distance d , Figure 5C). In a sense, the activation wave splashes over the last position of the stimulus, thus producing representational momentum. This also explains why the size of the Fröhlich effect differs from that of representational momentum. The Fröhlich effect encompasses the build-up phase (a), the representational momentum effect the decay phase (d) and both depend on at which point in time the activation pattern passes a perceptual threshold.

To explain the flash-lag effect, another implication of the bow-wave idea has to be considered. It is the implication that a moving stimulus can be assumed to be processed faster than a stationary stimulus (cf., Erlhagen & Jancke, 1999; Kirschfeld & Kammer, 1999). This is because the moving stimulus pre-activates its subsequent positions by its own movement, which is not the case for the stationary flash. As the flash-lag effect occurs because of the faster processing of the target compared to the flash, it is obvious why the size of the flash-lag effect deviates from both the size of the Fröhlich effect and representational momentum. The flash-lag effect is determined by the processing time difference between the flash and the moving target; the Fröhlich effect is determined by the time required to establish the bow wave, and the representational momentum effect is determined by the decay time of supraliminal processing after the target's offset. There is no reason to believe that these times are equal. Thus, the size of the Fröhlich effect, the flash-lag effect, and the representational momentum effect should deviate as our results demonstrated. Nevertheless, localizations are based on an identical underlying mechanism, which is only modified by the specific components of the Fröhlich effect, flash-lag effect, and representational momentum.

How to further test the model? Assume we keep the shape of the bow wave constant and vary the level of the perceptual threshold. If the perceptual threshold is increased, the activation needs more time to exceed the perceptual threshold at the onset of the movement and, as a consequence, the Fröhlich effect is expected to increase. On the other hand, with an increased perceptual threshold an existing activation wave is assumed to decay faster from supraliminal to subliminal activation at the offset of the stimulus. Thus, the representational momentum effect should decrease. The reversed predictions can be made if the level of the perceptual threshold is lowered. We have already suggested that different tasks might use different levels of the perceptual threshold (Aschersleben & Müsseler, 1999; see also Aschersleben, 1999). If that is the case, we are able to reinterpret the findings observed in Experiment 3. The assumption to add is that the threshold for a moving stimulus is higher with an accompanying task-relevant flash, probably because the stationary flash has a higher contrast than the motion-deblurred target (e.g., Burr & Ross, 1986; Fahle, 1995). In this case, the size of the mislocalization should be increased at the initial position and should be reduced at the final position. The opposite is expected with the task-irrelevant flash, that is with a relatively low perceptual threshold. This pattern of results occurred qualitatively in the interaction observed between the task relevance of the flash and the to-be-judged onset/offset position of the target. However, a quantitative problem remains. It is the reversal of the localization error with the task-relevant flash.

Other tests of the model could originate from the idea keeping the perceptual threshold constant, but varying the shape of the bow wave. For example, the velocity of the target is assumed to exert an influence on the shape of the bow wave, being skewer for a faster than for a slower velocity. The problem here is to vary skewness independently from the total height of the activation function. As it stands, the model assumes that an increase of the skewness comes along with an overall increase of the activation level. Therefore, faster velocities should increase the skewness of the bow wave, which results in an increase of the Fröhlich effect. Once established, however, it also needs longer for the activation wave of the faster velocity to decay at the target's offset from supraliminal to subliminal activation. As a consequence, an increase of representational momentum is expected. Although there is empirical evidence for both observations, a further specification of the model is needed to estimate the probably different sizes of the localization errors.

CONCLUSIONS

The aim of this paper was to explore localization errors at various points during an object's trajectory. While patterns of localization varied considerably depending on whether we probed at the initial, mid or final position, in the previous section, we took some initial steps towards to integrating these findings

into a single model. The model suggests that a moving target is represented by a skewed activation pattern, which originated from excitatory and inhibitory processes in a topographic map. The Fröhlich effect is assumed to emerge from a build-up phase, the representational momentum effect from a decay phase and both depend on at which point in time the activation pattern passes a perceptual threshold. The flash-lag effect is assumed to originate from another implication of the model according to which a moving stimulus is processed faster than a stationary stimulus. It is interesting to note that the model's basic mechanisms are not necessarily incompatible with the attentional formulations we started with to explain the Fröhlich effect. In our view and in the view of Erlhagen and Jancke (2002), it is possible that the model's formulations exemplify how attentional mechanisms could be neurophysiologically implemented in the brain. Needless to say that future research is needed to further determine this link.

REFERENCES

- Aschersleben, G. (1999). Task-dependent timing of perceptual events. In G. Aschersleben, T. Bachmann, & J. Müsseler (Eds.), *Cognitive contributions to the perception of spatial and temporal events* (pp. 293–318). Amsterdam: Elsevier.
- Aschersleben, G., & Müsseler, J. (1999). Dissociations in the timing of stationary and moving stimuli. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 1709–1720.
- Baldo, M.V.C., & Klein, S.A. (1995). Extrapolation or attention shift. *Nature*, *378*, 565–566.
- Berry, M.J., Brivanlou, I.H., Jordan, T.A., & Meister, M. (1999). Anticipation of moving stimuli by the retina. *Nature*, *398*, 334–338.
- Burr, D.C., & Ross, J. (1986). Visual processing of motion. *Trends in Neurosciences*, *9*, 304–307.
- Eagleman, D.M., & Sejnowski, T.J. (2000). Motion integration and postdiction in visual awareness. *Nature*, *407*, 2036–2038.
- Erlhagen, W., & Jancke, D. (1999). Motion waves in primary visual cortex as a neural correlate for the perception of moving objects. *Society for Neuroscience, Abstracts*, *25*, 679.
- Erlhagen, W., & Jancke, D. (2002). Contextual influences on processing of position in visual space: A theory. *Manuscript submitted for publication*.
- Fahle, M. (1995). Perception of oppositely moving verniers and spatio-temporal interpolation. *Vision Research*, *35*, 925–937.
- Freyd, J.J., & Finke, R.A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*, 126–132.
- Fröhlich, F.W. (1923). Über die Messung der Empfindungszeit [Measuring the time of sensation]. *Zeitschrift für Sinnesphysiologie*, *54*, 58–78.
- Hayes, A.E., & Freyd, J.J. (this issue). Representational momentum when attention is divided. *Visual Cognition*, *9*, 8–27.
- Hazelhoff, F.F., & Wiersma, H. (1924). Die Wahrnehmungszeit [The sensation time]. *Zeitschrift für Psychologie*, *96*, 171–188.
- Hubbard, T.L. (1990). Cognitive representation of linear motion: Possible direction and gravity effects in judged displacement. *Memory and Cognition*, *18*, 299–309.
- Hubbard, T.L. (1995). Environmental invariants in the representation of motion: Implied dynamics and representational momentum, gravity, friction, and centripetal force. *Psychonomic Bulletin and Review*, *2*, 322–338.

- Hubbard, T.L., & Bharucha, J.J. (1988). Judged displacement in apparent vertical and horizontal motion. *Perception and Psychophysics*, *44*, 211–221.
- Jancke, D. (2000). Orientation formed by a spot's trajectory: A two-dimensional population approach in primary visual cortex. *Journal of Neuroscience*, *20*(14), U13–U18.
- Jordan, J.S., Stork, S., Knuf, L., Kerzel, D., & Müsseler, J. (in press). Action planning affects spatial localization. In W. Prinz & B. Hommel (Eds.), *Attention and performance XIX: Common mechanisms in perception and action*. Oxford, UK: Oxford University Press.
- Kerzel, D. (this issue). A matter of design: No representational momentum without predictability. *Visual Cognition*, *9*, 66–80.
- Kerzel, D., Jordan, J.S., & Müsseler, J. (2001). The role of perceptual anticipation in the mislocalization of the final position of a moving target. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 829–840.
- Khurana, B., & Nijhawan, R. (1995). Extrapolation or attention shift? *Nature*, *378*, 566.
- Khurana, B., Watanabe, K., & Nijhawan, R. (2000). The role of attention in motion extrapolation: Are moving objects “corrected” or flashed objects attentionally delayed? *Perception*, *29*, 675–692.
- Kirschfeld, K., & Kammer, T. (1999). The Fröhlich effect: A consequence of the interaction of visual focal attention and metacontrast. *Vision Research*, *39*, 3702–3709.
- Krekelberg, B., & Lappe, M. (2000). A model of the perceived relative positions of moving objects based upon a slow averaging process. *Vision Research*, *40*, 201–215.
- Krekelberg, B., & Lappe, M. (2001). Neuronal latencies and the position of moving objects. *Trends in Neuroscience*, *24*, 335–339.
- Metzger, W. (1932). Versuch einer gemeinsamen Theorie der Phänomene Fröhlichs und Hazeloffs und Kritik ihrer Verfahren zur Messung der Empfindungszeit [An attempt towards a common theory of the phenomena of Fröhlich and Hazelhoff and a criticism of their measurement of sensation time]. *Psychologische Forschung*, *16*, 176–200.
- Müller, H.J., & Findlay, J.M. (1988). The effect of visual attention on peripheral discrimination thresholds in single and multiple element displays. *Acta Psychologica*, *69*, 129–155.
- Müsseler, J., & Aschersleben, G. (1998). Localizing the first position of a moving stimulus: The Fröhlich effect and an attention-shifting explanation. *Perception and Psychophysics*, *60*, 683–695.
- Müsseler, J., & Neumann, O. (1992). Apparent distance reduction with moving stimuli (Tandem effect): Evidence for an attention-shifting model. *Psychological Research*, *54*, 246–266.
- Müsseler, J., Stork, S., Kerzel, D., & Jordan, S. (2002). Different localizations with linear and circular movements. *Manuscript submitted for publication*.
- Neumann, O., & Müsseler, J. (1990). Visuelles Fokussieren: Das Wetterwart-Modell und einige seiner Anwendungen [Visual focusing: The Weather-Station Model and some of its applications]. In C. Meinecke & L. Kehrer (Eds.), *Bielefelder Beiträge zur Kognitionspsychologie* (pp. 77–108). Göttingen, Germany: Hogrefe.
- Nijhawan, R. (1994). Motion extrapolation in catching. *Nature*, *370*, 256–257.
- Theeuwes, J., Kramer, A.F., Hahn, S., & Irwin, D.E. (1998). Our eyes do not always go where we want them to go: Capture of the eyes by new objects. *Psychological Science*, *9*, 379–385.
- Van der Heijden, A.H.C., Schreuder, R., & Wolters, G. (1985). Enhancing single-item recognition accuracy by cueing spatial locations in vision. *Quarterly Journal of Experimental Psychology*, *37A*, 427–434.
- Whitney, D., & Cavanagh, P. (this issue). Surrounding motion affects the perceived locations of moving stimuli. *Visual Cognition*, *9*, 139–152.
- Whitney, D., Murakami, I., & Cavanagh, P. (2000). Illusory spatial offset of a flash relative to a moving stimulus is caused by differential latencies for moving and flashed stimuli. *Vision Research*, *40*, 137–149.