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# Spatial distortions and processing latencies in the onset repulsion and Fröhlich effects

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**Abstract**

In the Fröhlich illusion, the first position of a moving target is mislocalized in the direction of motion. In the onset repulsion effect, the opposite error occurs. To reconcile these conflicting error patterns, we improved previous methods by using natural pointing movements and a large range of target velocities. Displacement was found to increase in the direction of motion, but the linear function relating velocity and displacement was shifted opposite to the direction of target motion. The results suggest that onset localization may be determined by two independent factors: first, an (attentional) delay that accounts for the increase of displacement in the direction of motion with increasing velocity. This delay is visible in motor and probe judgments and explains the Fröhlich illusion. Second, motor judgments are offset opposite to the direction of target motion. This bias is unique to motor judgments (pointing) and may be partially explained by attentional repulsion.


*Keywords:* Representational momentum; Fröhlich illusion; Position judgments; Motion; Flash lag; Pointing

## 1. Introduction

Under some circumstances, both the initial and the final position are judged to be further in the direction of motion than they really are. These errors have been referred to as *Fröhlich effect* (Fröhlich, 1923) and *representational momentum* (Freyd & Finke, 1984), respectively. Similarly, the position of a moving object is seen to spatially lead a stationary flash (flash-lag effect; Nijhawan, 1994). In general, deviations of the judged from the true target position in and opposite the direction of target motion are referred to as positive and negative *displacement*, respectively.

The initial position of a moving target is special because there are no preceding target presentations. This has some important implications. Metacontrast masking from subsequent target presentations may explain why the visibility of the initial target position is reduced (Kirschfeld & Kammer, 1999). Metacontrast masking refers to the fact that nearby objects that are presented either slightly before or after the target object may virtually eliminate conscious perception of the target object (e.g., Ansorge, Klotz, & Neumann, 1998; Breitmeyer & Ogmen, 2000). At the same time, the initial position of a moving object may receive less attention than the following position because it will take some time before the focus of attention has reached or "zoomed in" the current target position (Kirschfeld & Kammer, 1999; Müsseler & Aschersleben, 1998). Because the initial positions are attended to a lesser degree, the reduction in latency, resolution, and intensity (Hikosaka, Miyauchi, & Shimojo, 1993; Kirschfeld & Kammer, 1999, 2000; Yeshurun & Carrasco, 1998) associated with focused attention is absent, whereas metacontrast is present right from the start. Therefore, the initial part of the target's trajectory may be less visible than the rest of the trajectory.

In sum, lack focal attention and metacontrast masking are companion factors that may prevent accurate perception of the initial part of the trajectory. Importantly, the Fröhlich effect should depend on the time it takes attention to reach (or zoom in) the target and the velocity of the target. If the temporal delay was

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constant, the distance the target would traverse during the delay would increase with target velocity. A linear function relating velocity and displacement would result

$$d = t * V + s$$

where $d$ is displacement, $t$ is the attentional delay, $V$ is velocity, and $s$ is a constant spatial offset. A reanalysis of data from Kerzel (2002, Experiment 2) shows that this linear model fits the data well (see Fig. 1). The delay factor, $t$, was 7 ms which is rather small. Previous studies reported delays in the range of 20–120 ms (e.g., Kerzel & Müsseler, 2002; Kirschfeld & Kammer, 1999; Müsseler & Aschersleben, 1998). The constant spatial offset was close to zero ($s = -0.06$ deg).

Some previous reports provide further support the linear model. First, displacement was generally found to increase in magnitude in the direction of motion with increasing velocity (Fröhlich, 1923; Kerzel & Müsseler, 2002; Kirschfeld & Kammer, 1999; Müsseler & Aschersleben, 1998). However, none of the previous studies examined this relation in a quantitative manner and one of the few studies (see Table 1) that looked at a wider range of velocities (Kirschfeld & Kammer, 1999) reported a nonlinear relation suggesting that the attentional delay decreased with velocity (but see Fig. 1 and Kerzel & Müsseler, 2002). Second, shortening the time it takes attention to reach the stimulus reduces the Fröhlich illusion. When the target location was cued, the Fröhlich effect was reduced (Kerzel & Müsseler, 2002; Müsseler & Aschersleben, 1998; Whitney & Cavanagh, 2000).

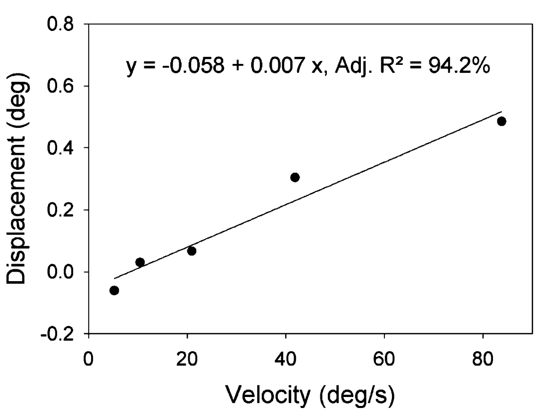


Fig. 1. Reanalysis of data from Kerzel (2002, Experiment 2). In the original study, observers compared the onset of a target moving on a circular trajectory (radius of 5 deg) to the position of a line. The line was presented either 1 s before target onset, or 0.5 s after target offset. Mean points of subjective equality (PSEs) between target and line position are plotted. Positive and negative displacement indicates that the PSEs were shifted in and opposite the direction of motion, respectively. As no difference between the perceptual and memory condition was observed, the data are collapsed across these conditions. A linear regression of velocity on displacement was run. The coefficient estimates the attentional delay (7 ms) and the offset estimates potential distortions of space (−0.06 deg).

However, more recent experiments have also questioned the linear model. Thornton (2002) found that judgments of the initial target position was not displaced in, but opposite the direction of motion (replicated by Hubbard & Motes, 2002; Kerzel, 2002). This *onset repulsion effect* could be accommodated by assuming that the constant spatial distortion was negative. However, Thornton (2002) and Kerzel (2002) reported that displacement increased in magnitude opposite to the direction of target motion when target velocity was increased. This finding cannot be accommodated by the model because a negative attentional delay is implausible. The increase of displacement should always be in the direction of motion as in Fig. 1.

More generally, one is left to wonder why observers would judge the onset of target motion at a position the target never occupied. To arrive at a solution, previous studies tried to identify the boundary conditions for onset repulsion and Fröhlich effects. Kerzel (2002) argued that target velocity and psychophysical method determine the sign of the deviation (Kerzel, 2002). With probe judgments (e.g., ahead/behind judgments about the relation between onset position and probe position), displacement was either zero or positive. Significant deviations from zero were only observed with relatively high velocities ($\geqslant 40$ deg/s). With motor judgments (i.e., mouse pointing), however, displacement was negative with slow velocities ($\leqslant 20$ deg/s) and not significantly different from zero with fast velocities ($\geqslant 20$ deg/s). Thus, the Fröhlich effect may only be observed with probe judgments and fast velocities, whereas onset repulsion may only be observed with motor judgments and slow velocities. Inspection of Table 1 largely confirms this idea.

Thus, a tentative hypothesis would be that motor judgments introduce a spatial offset opposite to the direction of motion that is not present with probe judgments. A problem for such an account is that the relation between velocity and displacement was opposite to the predicted relation. However, this may be an artifact produced by the rather restricted range of velocities. Studies reporting onset repulsion presented slow velocities from of 3 to 20 deg/s (Hubbard & Motes, 2002; Kerzel, 2002; Thornton, 2002). There is reason to believe that motor judgments are affected by the range of velocities: In Kerzel (2002), onset repulsion was reliable with 20 deg/s and mouse pointing, when this velocity was shown in a block of trials with slower target velocities, but not when it was shown in a block of trials with faster target velocities. With probe judgments, this effect of trial context was not observed (Kerzel, 2002; Experiment 2).

In Experiment 1, we reexamined onset localization with motor judgments and introduced some methodological improvements. First, we presented a large range of velocities (5–40 deg/s) to avoid context effects. The

Table 1
Overview of previous studies

| Study | Velocity range | N (velocity) | Method | Onset | Displacement |
|---|---|---|---|---|---|
| Hubbard and Motes (2002) | 5–15 deg/s | 2 | Mouse pointing | Random | − (n.s.) |
| Kerzel (2002) | 0.2–0.7/0.7–2.7 r.p.s. | 5 | Mouse pointing | Random | − (Decrease)/n.s. (n.s.) |
| | 0.2–0.7/0.7–2.7 r.p.s. | 5 | Probe judgments | Random | n.s. (n.s.)/+ (Increase) |
| Kerzel and Gegenfurtner (this work) | 5.4–43.0 deg/s | 4 | Natural pointing | Random | − (Increase) |
| Kerzel and Müsseler (2002) | 0.5–1.0 r.p.s. | 2 | Adjustment | Random | + (Increase) |
| Kirschfeld and Kammer (1999) | 0.5–1.5 r.p.s. | 4 | Adjustment | Restricted | + (Increase) |
| Müsseler and Aschersleben (1998) | 14.3–44 deg/s | 2 | Mouse pointing | Restricted | + (Increase) |
| Müsseler, Stork, and Kerzel (2002) | 0.9 r.p.s. | 1 | Adjustment | Random | + |
| Thornton (2002) | 3–15 deg/s | 5 | Mouse pointing | Random | − (Decrease) |
| Whitney and Cavanagh (2002) | 5.6–38.5 deg/s | 3 | Probe judgment | Random | + (Increase) |

The range of velocities is given in degrees per second (deg/s) and rotations per second (r.p.s.) for linear and circular motion, respectively. *N* (velocity) indicates the number of velocities presented in this range. Observers were asked to move a mouse cursor to the onset of the stimulus (mouse pointing), to adjust the target stimulus (e.g., a moveable bar) such that it matched the onset position (adjustment), or to compare the onset position to a probe stimulus and to indicate the relative position (probe judgment). The onset position was either highly unpredictable, or restricted to a small area of the display. The deviation of the judged from the true position (displacement) was either in the direction of motion (+), opposite to motion (−), or not significantly different from zero (n.s.). Whether displacement decreased, increased or was nonsignificant (n.s.) is indicated in brackets.

question is whether the predicted linear relation between velocity and displacement would emerge. Second, we asked observers to directly point to the target with the index finger (natural pointing) instead of pointing with a mouse-driven cursor. Mouse judgments are relative to an initial cursor position whereas direct finger pointing is "absolute" in the sense that it partially avoids such visual reference points.

Further, the contributions of cognitive and attentional factors to onset localization were investigated. In particular, we asked whether *attentional repulsion*—which is unrelated to the attentional delay—and *error avoidance* may explain the shift opposite to target motion. These accounts will be presented in detail in Experiments 2 and 4, respectively. In Experiment 2, observers were required to respond as fast as possible such that the target was still visible during the pointing movement. This manipulation was expected to increase attentional repulsion. In Experiment 3, apparent/implied target motion was presented. To test an account in terms of error avoidance, Experiment 4 varied the speed–accuracy instructions. If error avoidance was responsible for onset repulsion, it should be larger with accuracy instructions. Finally, Experiment 5 investigated possible effects of stimulus material.

## 2. Experiment 1: natural pointing to the initial position

To evaluate whether onset localization would follow a linear model, we presented observers with a wide range of velocities. The target appeared and immediately started to move at a velocity of 5.4, 10.7, 21.5, or 43.0 deg/s for a distance between 5.3 and 8.1 deg. After target offset, observers were asked to release a home key and to point to the initial target position. A touch screen was used and observers were asked to point to the initial position of the target with their index finger as accurately as possible.

### 2.1. Methods

The stimuli were generated by a Cambridge Research Systems (Rochester, England) Visual Stimulus Generator and presented on a 17″ (diagonal) CRT display (ELO Touchsystems, Fremont, California, USA) with a refresh rate of 100 Hz and a resolution of 800 (H)×600 (V) pixels. The ELO Entuitive-monitor was equipped with a touch interface that recorded the touched screen position at a resolution of 4096 (H)×4096 (V) lines. While the index finger was touching the screen, we calculated the average of the finger position, weighted by the pressure applied to the screen at each moment. The linear regression relating the monitor's touch coordinates to its pixel coordinates was determined individually for each participant prior to the experiment. For all observers, $r^2$ was larger than 0.99. The rooted mean squared error of the predicted values with respect to the target positions was on the order of 3–4 pixels, corresponding to 0.16–0.22 deg.

A black fixation square (0.21 deg) was presented in the center of the screen. The background was light gray (27.8 cd/m$^2$) and the circular target was bright white (maximal luminance 55.6 cd/m$^2$). The edges of the target were smoothed with a two-dimensional Gaussian function (SD = 0.16 deg). The target appeared at a random position within a 24.2 deg (H)×13.5 deg (V) window centered on the fixation dot and immediately moved left, right, up, or down. To avoid involuntary saccades to the target, trajectories that would come close to the fixation point were suppressed. For horizontal motion, initial target positions within a region of 2.6 deg above or below the fixation point (center-to-center) across the horizontal extent of the screen were excluded. For vertical motion, the initial target positions within a region of 2.6 deg left and right of the fixation point across the vertical extent of the screen were excluded. The target moved for a randomly determined trajectory length between 5.3 and 8.1 deg at a velocity of 5.4, 10.7, 21.5, or 43.0 deg/s.

The possible combinations of the four directions of motion and the four target velocities were randomly intermixed. Within a block of 16 trials, each condition was presented only once. Participants worked through 20 blocks (320 trials). Eight students at the Justus-Liebig-University of Giessen participated for pay. All reported normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Participants sat in a fully lit room 40 cm from the screen. To start a trial, participants pressed a key on a button box and kept it depressed until the response was emitted. The key press triggered presentation of the fixation mark which remained visible until the participant touched the screen. After trial initiation, a randomly determined interval between 250 and 750 ms elapsed before the target appeared and started to move. Observers were instructed to maintain fixation on the fixation mark while the target moved, and to keep the button depressed until the target vanished. Then, observers were asked to release the button and to touch the position on the screen where the target had appeared with the index finger of the preferred hand. When the button was released within 100 ms after target offset, the response was considered anticipatory and auditory error feedback was given. Observers were asked to stress accuracy over speed.

### 2.2. Results

The first 32 trials were considered practice and were excluded from the analysis. The difference between true and judged target onset was determined. Displacement of the judged onset in the direction of target motion was given a positive sign, and displacement opposite the direction of target motion was given a negative sign. For each observer and each combination of motion direction and velocity, trials in which displacement deviated by more than two standard deviations from the mean of the respective condition were considered outliers. Further, response latencies were calculated. The time from target offset to release of the button is referred to as reaction time and the time from release of the button to contact with the screen is referred to as movement time.

Data from Experiments 1–5 are summarized in Tables 2–4 and Figs. 2–4. Table 2 and Fig. 2 show mean displacement as a function of velocity. Additionally, Table 2 presents the results of regressions of target velocity on displacement, and *t*-tests comparing each mean to zero. Fig. 3 shows displacement as a function of velocity and direction of motion. Fig. 4 shows mean reaction and movement times as a function of target velocity. Table 3 shows mean reaction and movement time as a function of motion direction.

#### 2.2.1. Displacement

Anticipations (1.2%; RTs smaller than 100 ms) and outliers (4.2%; beyond two standard deviations of condition mean) were excluded from the analysis. A two-

Table 2
Effect of target velocity on the difference between judged and true onset position in degrees of visual angle for Experiments 1–5

| Velocity | Experiment 1 | Experiment 2 | Experiment 3 | Experiment 4 | | Experiment 5 | |
|---|---|---|---|---|---|---|---|
| | | 700/900 ms | Apparent/ implied | Speed | Accuracy | Smooth | Sharp |
| 5.4 deg/s | −1.09 ± 0.31*** | −1.87 ± 0.23*** | −0.08 ± 0.03 | −1.04 ± 0.35** | −0.87 ± 0.26** | −0.28 ± 0.20 | −0.19 ± 0.19 |
| 10.7 deg/s | −0.95 ± 0.29** | −1.28 ± 0.25*** | −0.01 ± 0.05 | −0.92 ± 0.36** | −0.80 ± 0.27** | −0.10 ± 0.18 | −0.19 ± 0.17 |
| 21.5 deg/s | −0.73 ± 0.26** | −0.63 ± 0.24** | 0.37 ± 0.09*** | −0.48 ± 0.41 | −0.63 ± 0.26** | −0.05 ± 0.18 | 0.20 ± 0.18 |
| 43.0 deg/s | −0.19 ± 0.22 | −0.13 ± 0.25 | 0.09 ± 0.13 | 0.30 ± 0.40 | −0.28 ± 0.27 | 0.48 ± 0.20** | 0.72 ± 0.19** |
| Intercept (deg) | −1.22*** | −1.85*** | – | −1.27*** | −0.96*** | −0.35* | −0.38* |
| Coefficient (ms) | 24*** | 43*** | – | 37*** | 16** | 19*** | 26*** |
| $R^2$ (%) | 99.2 | 84.6 | – | 99.6 | 99.9 | 98.6 | 97.1 |

Mean and standard error of the mean (between-subjects) are given in the format $M \pm \mathrm{SE}$. Data are collapsed across the 900 and 700 ms response windows in Experiment 2. Linear regressions of velocity on displacement were run. Coefficients, intercepts and the adjusted $R^2$ values are shown. $R^2$ values reflect the deviation of the fitted line from the mean displacement values (averaged across observers). For Experiment 2, a logarithmic function yielded a better fit than a linear one ($y = -3.28$ deg $+846$ ms $* \ln(x)$, $R^2 = 99.6$). Data are collapsed across the 900 and 700 ms response windows in Experiment 2.

Note: Positive and negative values indicate that the judged position was displaced in and opposite the direction of motion, respectively. The mean of each condition was compared to zero by *t*-test. *T*-values with probabilities lower than 0.10, 0.05, and 0.01 are marked by, *, **, and ***, respectively.

Table 3
Mean reaction (RT) time, movement (MT) and total (TT = RT + MT) times in ms as a function of direction of motion and experimental condition

| | Direction | Experiment 1 | Experiment 2 | | Experiment 3 | Experiment4a | | Experiment 4b | Experiment 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 900 ms | 700 ms | Apparent | Speed | Accuracy | Simple | Sharp | Smooth |
| RT | Left | 342 | 359 | 338 | 440 | 301 | 439 | 281 | 340 | 340 |
| | Right | 346 | 354 | 337 | 442 | 312 | 444 | 285 | 341 | 345 |
| | Up | 340 | 349 | 335 | 438 | 302 | 442 | 281 | 335 | 340 |
| | Down | 373 | 351 | 335 | 437 | 297 | 428 | 277 | 333 | 329 |
| | *M* | 350 | 353 | 337 | 439 | 303 | 438 | 281 | 337 | 339 |
| MT | Left | 809 | 355 | 271 | 547 | 350 | 650 | – | 532 | 524 |
| | Right | 812 | 360 | 276 | 561 | 354 | 658 | – | 528 | 523 |
| | Up | 811 | 351 | 271 | 560 | 350 | 639 | – | 523 | 526 |
| | Down | 811 | 355 | 275 | 544 | 355 | 645 | – | 515 | 515 |
| | *M* | 811 | 355 | 273 | 553 | 352 | 648 | – | 525 | 522 |
| TT | *M* | 1160 | 708 | 609 | 992 | 656 | 1087 | – | 862 | 860 |

Data from Experiments 1–5 is shown.

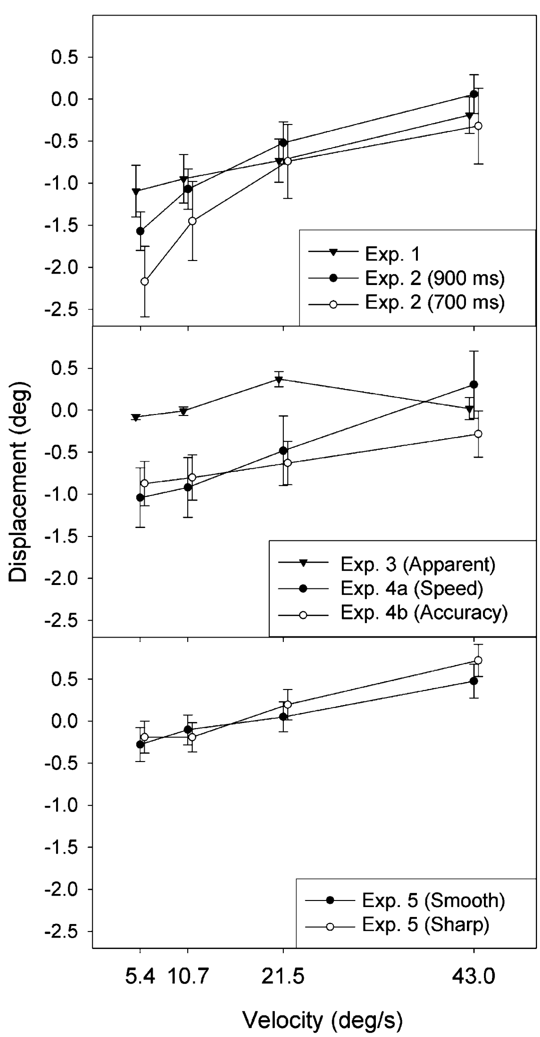


Fig. 2. Mean displacement as a function of velocity in Experiments 1–5. Error bars indicate the between-subjects standard error. Observers responded after *target offset* in Experiments 1, 3, 4, and 5, and after *target onset* in Experiment 2. Positive and negative displacement indicates mislocalization in and opposite the direction of motion.

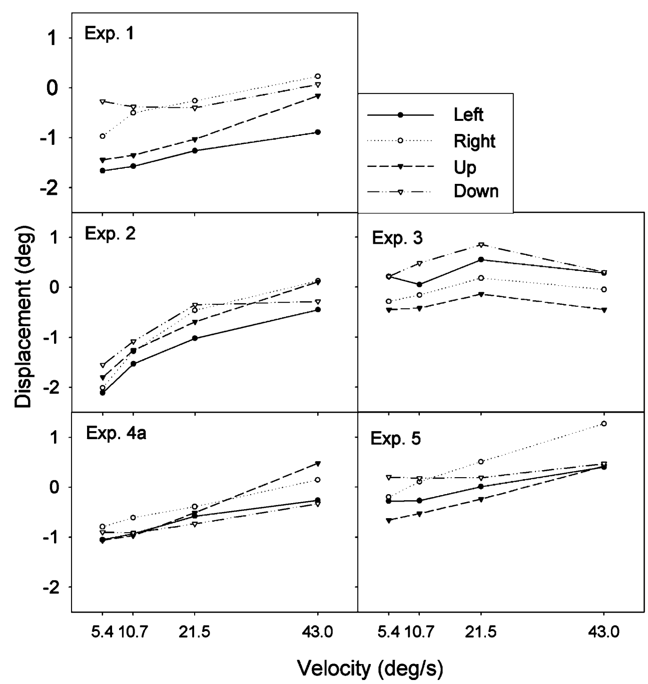


Fig. 3. Mean displacement as a function of velocity and direction in Experiments 1–5. For clarity, error bars were omitted. Positive and negative displacement indicates mislocalization in and opposite the direction of motion, respectively.

way ANOVA (Velocity × Direction) revealed that displacement increased in the direction of motion with increasing velocity of target motion, $F(3,21) = 18.42$, $MSE = 0.27$, $p < .001$. There was a main effect of motion direction, $F(3,21) = 5.23$, $MSE = 1.65$, $p < .01$, showing backward displacement was larger with leftward and upward than with rightward and downward motion. A marginally significant interaction between velocity and direction, $F(9,63) = 2.00$, $MSE = 0.18$, $p = .053$, indicated that the linear increase of displacement with velocity was reduced with downward motion.

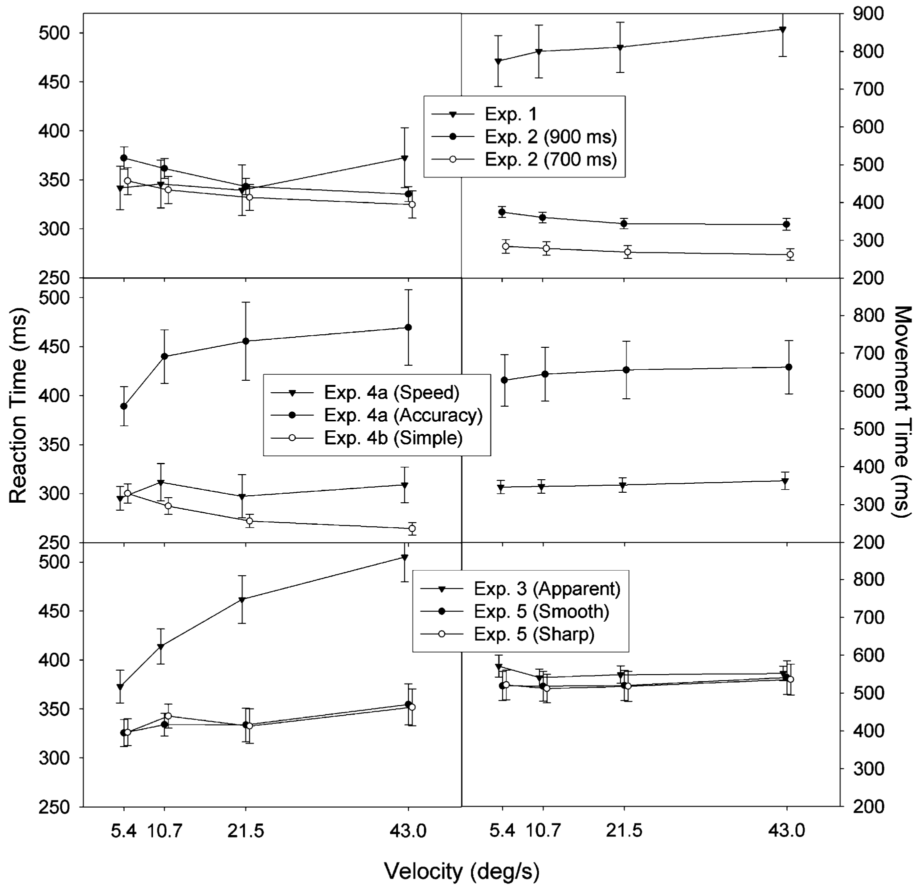


Fig. 4. Mean reaction time (left panel) and movement time (right panel) as a function of velocity in Experiments 1–5. Error bars indicate the between-subjects standard error. In Experiment 4b, simple response time, $r$, was measured. These data were fit with the Piéron equation, $r = r_0 + aV^{-b}$ where $r_0$ is a constant that reflects invariant motor and sensory components, $V$ is target speed and $a$ and $b$ are arbitrary constants. The constant $b$ has been shown to be around 0.5 and 1.0, depending on experimental paradigm. The simplest model assumption would be that the stimulus has to pass through a certain distance before it is detected. This model would predict a linear dependence of reaction time on velocity with $b = 1$. However, most studies find exponents close to 0.5. In the present experiment, the best fit was achieved with $r_0 = 215.33$, $a = 135.41$, and $b = 0.27$. The data show that velocity does influence the detection of the onset of a moving stimulus.

### 2.2.2. Reaction time

The same trials as for the analysis of displacement were excluded. A two-way ANOVA (Velocity × Direction) revealed that reaction time was slower with the fastest velocity, $F(3,21) = 4.70$, MSE = 1593.21, $p < .05$. Further, the main effect of motion direction, $F(3,21) = 4.11$, MSE = 234.25, $p < .05$, showed that reaction times to downward motion were slowest.

### 2.2.3. Movement time

The same trials as for the analysis of displacement were excluded. A two-way ANOVA (Velocity × Direction) revealed that movement times were longer with the fastest velocity, $F(3,21) = 11.15$, MSE = 3555.15, $p < .001$.

## 2.3. Discussion

When observers were asked to point to the first position of a moving target, displacement was consistently negative. This replicates the onset repulsion effect first reported by Thornton (2002). In contrast to previous studies, displacement increased linearly in the direction of motion with increasing velocity. As shown in Table 2, the fit of a linear regression to the data was very good, such that the linear model, $d = t * V + s$, is well supported by the data. That is, displacement, $d$, may be a function of a delay ($t = 24$ ms) and a constant spatial offset ($s = -1.21$ deg). Therefore, pointing to the initial position of a moving target may be determined by two factors: first, an (attentional) delay producing a linear increase of target displacement in the direction of motion. Second, a constant spatial offset displacing judgments opposite to the direction of target motion.

Across studies, one may conclude that the attentional delay affects probe and motor judgments in a similar manner, however, the constant spatial offset is unique to motor responses. As shown in Table 1, previous studies using probe judgments always reported positive displacement in the direction of motion that increased in magnitude with increasing velocity. The present experiment shows that this increase may also be observed with motor judgments, if a wide range of velocities is presented. The conflicting results reported in previous studies may result from having presented a restricted range of velocities. Thus, onset localization with motor judgments partly reflects mechanisms that also underlie the Fröhlich illusion. In a sense, there is no contradiction between Fröhlich illusion and onset repulsion. Although the sign of displacement differs, the increase with increasing velocity is the same. Motor judgments introduce a negative spatial offset that changes the sign of the displacement, but leave the dependency on velocity intact. As outlined in the introduction, plausible accounts of the dependence on velocity are available; however, a convincing account of the constant spatial offset (i.e., onset repulsion) is missing. The following experiments test potential explanations.

Two further results are worth mention. Onset localization differed as a function of direction of motion and was larger with upward than with downward motion. Typically, position judgments of moving objects are displaced downward (Hubbard, 1990) such that onset repulsion and the downward bias add up with upward motion and partly cancel each other with downward motion (see also Thornton, 2002).

Analysis of latencies revealed that reaction times and movement times were slower with the fastest velocity. This may be due to task preparation (Bertelson, 1967): the interval between trial initiation and target offset was shortest with the fastest velocity. Therefore, task preparation was worst with this velocity. The difference in reaction times also entailed a difference in the time intervals that the initial position had to be kept in short-term memory (time between target offset and response = retention interval).

## 3. Experiment 2: speeded pointing

The major result of Experiment 1 was that displacement increased in the direction of motion with increasing velocity which is consistent with the assumption of a constant attentional delay. Further, there was a constant offset opposite to motion, which remains largely unexplained. As this offset was not present with probe judgments (see Fig. 1), one may attribute the bias to motor processes. Examination of the literature on pointing movements shows that there is a bias of manual and oculomotor movements away from distractors that attract attention but have to be ignored (e.g., Fischer & Adam, 2001; Sheliga, Craighero, Riggio, & Rizzolatti, 1997; Sheliga, Riggio, & Rizzolatti, 1994; Tipper, Howard, & Jackson, 1997; Tipper, Howard, & Paul, 2001). We will refer to this finding as attentional repulsion and it should be noted that attentional repulsion is independent of the hypothesis of an attentional delay. For instance, if observers execute a pointing movement or saccade along the saggital plane while ignoring lateral distractors, the manual and saccadic trajectories are biased to the right with distractors on the left, and to the left with distractors on the right (Sheliga et al., 1997). In the present experiment, one may assume that observer's attention followed the target's trajectory. If manual responses were biased away from the focus of attention, the endpoint of the movement would be biased away from the target's trajectory. Mislocalization opposite to the direction of target motion would result.

One possible test of the attentional repulsion hypothesis would be to force observers to respond while the target was still visible on the screen. In this case, one may assume with some confidence that visual spatial attention is centered on the target: when position is the relevant response dimension, sudden onsets involuntarily attract attention (Folk, Remington, & Wright, 1994; Yantis & Egeth, 1999), such that attention would be focused on the target. After target offset, the distribution of attention should be less focal, but still along the target's trajectory. Therefore, one may expect attentional repulsion to be stronger when observers respond while the target is still on the screen compared to responses after target offset. Pilot studies have shown that the shortest total time from target onset to contact with the screen was on the order of 600 ms. Thus, if observers were asked to respond right after target offset, the target would still be on the screen with slow target motion. With a trajectory length between 5.3 and 8.1 deg, the target would be visible during most of the pointing movement with target velocities between 5.4 and 10.7 deg/s. Therefore, the negative offset is expected to increase for these velocities if observers are instructed to respond right after target offset.

### 3.1. Methods

Apparatus, stimuli, design, and procedure were the same as in Experiment 1 with the following exception. Participants were instructed to point to the initial target position as soon as the target appeared. When participants failed to touch the screen within a given temporal response window, an acoustic error message was presented. Twenty-one students fulfilling the same criteria as in Experiment 1 participated in the Experiment. They were randomly assigned to one of two groups. For 10 observers, the response window was set to 900 ms which required fast pointing movements. For 11 observers, the response window was set to 700 ms which required fast jabs at the screen. Observers were asked to respond as fast and accurate as possible.

### 3.2. Results

#### 3.2.1. Displacement

Anticipations (700 ms: 3.0%; 900 ms: 2.6%), late trials (700 ms: 9.2%; 900 ms: 3.1%), and outliers (700 ms: 3.6%; 900 ms: 3.3%) were excluded from the analysis. A three-way mixed-factors ANOVA (Response Window × Velocity × Direction) did not reveal any significant effects of response window (all $ps > .25$). There was a significant effect of velocity, $F(3,57) = 112.56$, $\mathrm{MSE} = 0.43$, $p < .001$, indicating that displacement increased with increasing velocity. The interaction between velocity and direction reached significance, $F(9,171) = 3.89$, $\mathrm{MSE} = 0.18$, $p < .001$, indicating that the linear increase of displacement with velocity was less pronounced with downward motion.

Further, a three-way mixed-factors ANOVA (Experiment × Velocity × Direction) was run to compare unspeeded (Experiment 1) and speeded (Experiment 2) responses. Significant main effects of direction, $F(3,81) = 4.34$, $\mathrm{MSE} = 2.13$, $p < .01$, and velocity, $F(3,81) = 126.55$, $\mathrm{MSE} = 0.39$, $p < .001$, were confirmed. There was a significant interaction of direction and velocity, $F(9,243) = 5.00$, $\mathrm{MSE} = 0.18$, $p < .001$. Importantly, velocity and experiment interacted, $F(3,81) = 10.13$, $\mathrm{MSE} = 0.39$, $p < .001$, indicating that the negative displacement was more pronounced with speeded responses than with unspeeded responses for the slow velocities.

#### 3.2.2. Reaction time

The same trials as for the analysis of displacement were excluded. A three-way mixed-factors ANOVA (Response Window × Velocity × Direction) did not reveal a main effect of response window ($p > .3$). Latencies depended on the direction of motion, $F(3,57) = 7.14$, $\mathrm{MSE} = 115.26$, $p < .001$, and decreased with increasing velocity, $F(3,57) = 47.25$, $\mathrm{MSE} = 334.73$, $p < .001$. The effect of velocity was stronger with the 900 ms response window, $F(3,57) = 2.87$, $\mathrm{MSE} = 334.73$, $p < .05$.

#### 3.2.3. Movement time

The same trials as for the analysis of displacement were excluded. A three-way mixed-factors ANOVA (Response Window × Velocity × Direction) revealed that mean latencies were smaller with the 700 ms response window than with the 900 ms response window, $F(1,19) = 13.77$, $\mathrm{MSE} = 40,894.19$, $p < .005$. Latencies depended on the direction of motion, $F(3,57) = 4.28$, $\mathrm{MSE} = 165.98$, $p < .01$, and decreased with increasing velocity, $F(3,57) = 37.58$, $\mathrm{MSE} = 350.26$, $p < .001$. The effect of velocity was marginally stronger with the 900 ms response window, $F(3,57) = 2.55$, $\mathrm{MSE} = 350.26$, $p = .0645$.

### 3.3. Discussion

Overall, the judged onset was displaced opposite to the direction of target motion. As in Experiment 1, displacement increased in the direction of motion with increasing velocity. However, onset repulsion for the slowest velocities was much larger than in Experiment 1. This result is consistent with the hypothesis that observers attended to the moving target and that the motor response was biased away from the focus of attention. Because the distracting stimulus (i.e., the target) was still visible with the slow velocities while the pointing response was underway, the attentional repulsion away from the target's trajectory was expected to be particularly strong in these conditions. With fast moving targets, the full trajectory had been traversed when observers initiated their response, such that the distribution of attention may have been less focused.

Further, reaction times decreased with increasing velocity. This pattern is different from that observed with unspeeded responses in Experiment 1. In Experiment 1, observers initiated their response after target offset which led to longer presentation and movement preparation times for slow target velocities. In Experiment 2, observers initiated their response after target onset such that movement preparation times were constant across velocities. Nonetheless, response initiation was quicker with fast moving than with slowly moving targets. Generally, simple response times to the onset of motion in a random dot pattern or sine-wave grating increase with decreasing velocity (e.g., Burr & Corsale, 2001; Burr, Fiorentini, & Morrone, 1998; Tynan & Sekuler, 1982). However, target onset preceded motion onset in previous studies, whereas target onset and motion onset were coupled in the present experiment. To determine whether velocity influences the detection of stimulus onset, we measured simple response times in Experiment 4b.

## 4. Experiment 3: apparent/implied motion

Experiment 3 was designed as a further test of the attentional repulsion hypothesis. If motor responses to the onset of a moving target were biased away from focus of attention, it may be sufficient to present only the initial and final target positions. The first position would attract attention initially, and the final (second) target presentation would subsequently capture attention. Consequently, responses to the initial position should be biased away from the distracting second target position. Mislocalization opposite to motion should result. To test this hypothesis, presentation of the first and final target positions was separated by a blank interval that matched the time the target would take to smoothly move this distance at one of the velocities used in the previous experiments.

It should be noted that Thornton (2002) ran a similar condition which he called "implied" motion and found that there was displacement opposite to motion that was smaller than the repulsion observed with smooth motion. As pointed out in the introduction, the present study controls for context effects such that these results may or may not be similar to the present study.

### 4.1. Methods

Apparatus, stimuli, design, and procedure were the same as in Experiment 1 with the following exception. The trajectories were determined as in Experiment 1, but the target was shown in its initial and final positions only. Target presentation time was 60 ms and the interstimulus-interval (ISI) was adjusted to match the display duration of a target traveling through the complete trajectory. If, for instance, the target would take 200 ms to travel from its initial to its final position with continuous position change, the apparent/implied motion target would be shown in its initial and final positions for 60 ms each, separated by an 80 ms blank interval. Thus each target velocity in the previous experiments would be associated with a particular range of ISIs. For a given target velocity, the exact ISI depended on the trajectory length which varied randomly between 5.37 and 8.06 deg. Thus, ISIs varied between 880–1380, 380–630, 130–250, and 0–60 ms for target velocities of 5.4, 10.7, 21.5, and 43.0 deg/s, respectively. For ease of presentation, the different ranges of ISIs are referred to by the "virtual" smooth target velocity. Previous research has shown that ISIs between 100 and 300 ms yield a good impression of apparent motion, whereas target presentations separated by shorter ISIs are perceived as quasi-simultaneous, and longer ISIs are perceived as mere succession (e.g., Neuhaus, 1930). Thus, a velocity of 21.5 deg/s would produce a good impression of apparent motion, whereas slower target velocities (5.4 and 10.7 deg/s) would not convey a good impression of motion. The mere succession of target displacements without apparent motion is referred to as implied motion.

Each combination of target velocity and direction was presented once in a block of 16 trials. Observers worked through 20 blocks (640 trials) interrupted by a short break after 10 blocks. Ten students fulfilling the same criteria as in Experiment 1 participated in the Experiment. Observers were instructed to stress accuracy over speed.

### 4.2. Results

#### 4.2.1. Displacement

Anticipations (3.4%) and outliers (4.0%) were excluded from the analysis. A two-way ANOVA (Velocity × Direction) revealed a significant effect of velocity, $F(3,27) = 7.26$, $\mathrm{MSE} = 0.22$, $p < .001$. Direction of motion affected displacement, $F(3,27) = 10.74$, $\mathrm{MSE} = 0.50$, $p < .001$. Further, motion direction and velocity interacted, $F(9,81) = 2.32$, $\mathrm{MSE} = 0.04$, $p < .05$.

#### 4.2.2. Reaction time

The same trials as for the analysis of displacement were excluded. A two-way ANOVA (Velocity × Direction) showed that reaction time increased with increasing velocity, $F(3,27) = 34.72$, $\mathrm{MSE} = 3819.19$, $p < .001$.

#### 4.2.3. Movement time

The same trials as for the analysis of displacement were excluded. A two-way ANOVA (Velocity × Direction) did not reveal any significant effects.

### 4.3. Discussion

The localization of the initial target position that was followed by a second target presentation (i.e., a distractor) was accurate in most conditions. Contrary to what is expected based on attentional repulsion, there was no displacement in or opposite the direction of distractor presentation with slow (5.3 and 10.7 deg/s) and very fast (43 deg/s) virtual velocities. When the time interval between target and distractor presentation was appropriate to give a good impression of apparent motion (virtual velocity of 21.5 deg/s), there was displacement toward the distractor (i.e., in the direction of apparent motion). It is not entirely clear what caused the reversal of the sign of the displacement. Maybe the motor system confounded the two positions. Such confusion may underlie the global effect, and the situation may be similar here (see Section 8). Therefore, the results of the present experiment do not provide strong evidence against an account in terms of attentional repulsion: the change of the motion type may have introduced difficulties for the motor system that were not present with the smoothly moving target.

Analysis of the response latencies showed that movement times, but not reaction time, increased with velocity. As in Experiments 1, the effect of velocity may be attributed to response preparation. Shortly after target onset (i.e., with fast target motion) participants' level of preparation was lower than with longer time intervals (i.e., with slow target motion). Further, inspection of Fig. 4 shows that participants may trade reaction time and movement time. Compared to Experiment 1, reaction times are much shorter, whereas movement times are much longer.

## 5. Experiment 4a: speed–accuracy tradeoff

The second account of the negative spatial offset that will be tested here is error avoidance (see also Thornton, 2002). The most obvious error that an observer may try to avoid in the present task is to point to the target itself when responses to a past position are required. Thus, efforts to compensate should be largest if the target is still visible while the response is initiated (see Experiment 2). The next obvious error is to point to a past position that is not the required position. If asked to point to the initial position, the remaining positions on the trajectory are potential errors. The subjective weight of the on-trajectory errors may be higher than the subjective weight of off-trajectory errors. If error avoidance was the reason for the negative spatial offset, then instructions to avoid errors should increase this tendency. That is, the magnitude of the negative offset should increase with instruction to be as accurate as possible.

To test the error avoidance account, participants were either encouraged to respond as fast as possible while neglecting accuracy, or they were instructed to stress accuracy over speed. As in Experiment 1, observers were asked to point to the onset of a moving target after the target disappeared.

### 5.1. Methods

Apparatus, stimuli, design, and procedure were the same as in Experiment 1 with the following exception. Eighteen students fulfilling the same criteria as in Experiment 1 participated in the Experiment. They were randomly assigned to one of two groups. Nine participants were instructed to stress speed over accuracy (speed instruction), whereas the remaining nine participants were instructed to stress accuracy over speed (accuracy instruction).

### 5.2. Results

#### 5.2.1. Displacement

Anticipations (speed: 3.6%; accuracy: 0.8%) and outliers (speed: 4.0%; accuracy: 3.5%) were excluded from the analysis. Prior to the exclusion of outliers, the variability of the responses was determined for each observer. Standard deviations were smaller with the accuracy instruction than with the speed instruction ($M = 1.6$ vs. 2.1), $t(16) = 2.78$, $p < .05$, indicating that observers were able to voluntarily trade speed and accuracy.

A three-way mixed-factor ANOVA (Instruction $\times$ Velocity $\times$ Direction) showed that displacement increased with increasing velocity, $F(3, 48) = 38.64$, $\text{MSE} = 0.35$, $p < .001$. The increase of displacement with increasing velocity was more pronounced with the speed than with the accuracy instruction, $F(3, 48) = 5.81$, $\text{MSE} = 0.35$, $p < .005$. Further, there was an interaction of direction and velocity, $F(9, 144) = 3.03$, $p < .005$, indicating that the increase with velocity was more pronounced with upward motion.

A linear regression of target velocity on displacement was run for each observer (see Table 2). Between-groups comparisons showed that the slopes were significantly larger with the speed than with the accuracy instruction, $t(11, \text{unequal variances}) = 3.12$, $p < .01$. No significant between-groups difference was observed for the intercepts.

#### 5.2.2. Reaction time

The same trials as for the analysis of displacement were excluded. A three-way mixed-factors ANOVA (Instruction $\times$ Velocity $\times$ Direction) revealed that reaction times were shorter with the speed compared to the accuracy instruction, $F(1, 16) = 15.79$, $\text{MSE} = 83,229.92$, $p < .001$. Reaction times depended on the direction of motion, $F(3, 48) = 6.66$, $\text{MSE} = 430.91$, $p < .001$ and increased with increasing velocity, $F(3, 48) = 5.45$, $\text{MSE} = 5371.59$, $p < .005$. The effect of velocity was stronger with the accuracy instruction, $F(3, 48) = 3.30$, $\text{MSE} = 5371.60$, $p < .05$.

#### 5.2.3. Movement time

The same trials as for the analysis of displacement were excluded. A three-way mixed-factors ANOVA (Instruction $\times$ Velocity $\times$ Direction) revealed that movement times were shorter with the speed compared to the accuracy instruction, $F(1, 16) = 16.20$, $\text{MSE} = 388876.96$, $p < .001$. The effect of motion direction approached significance, $F(3, 48) = 2.33$, $\text{MSE} = 785.54$, $p = .0864$. Movement times increased with increasing velocity, $F(3, 48) = 3.50$, $\text{MSE} = 2439.30$, $p < .05$.

### 5.3. Discussion

Overall, observers were well able to voluntarily control the relation between speed and accuracy. Responses were faster and the variability was larger with the speed than with the accuracy instruction. As in Experiment 1, responses were faster with slow target motion which may reflect increasing response preparation with increasing time interval between trial and response initiation. Importantly, the speed–accuracy instruction did not affect the constant offset of the localization responses. If error avoidance produced the negative spatial offset, the magnitude of this offset would be expected to increase when observers were making larger efforts to avoid errors (accuracy instruction).

However, only the slope of the function relating velocity and displacement changed. When observers were asked to stress accuracy over speed, the increase of displacement with velocity was weaker than with an instruction to stress speed over accuracy. With the speed instruction, reaction times, and therefore the retention interval was shorter than with the accuracy instruction. Therefore, the decay of the memory trace was larger with the accuracy instruction, and responses may have "regressed" to the average position. Alternatively, it may be that observers tried to compensate for effects of velocity at cognitive level if told to be as accurate as possible.

## 6. Experiment 4b: simple responses

In this experiment, observers were asked to release the home key as soon as the target appeared. The time interval between target onset and release response estimates the simple response time. Previous studies indicate that it takes longer to detect the onset of slow compared to fast motion.

### 6.1. Methods

The same participants as in Experiment 4a were tested. Experiment 4b was run right after Experiment 4a. Apparatus, stimuli, design, and procedure were the same as in Experiment 1 with the following exception. Participants were instructed to initiate each trial by depressing a key with the index finger of the preferred hand and to lift the index finger as rapidly as possible when the target appeared. After detecting stimulus onset, participants touched the fixation point at leisure.

### 6.2. Results

Simple response time was calculated as the temporal interval between onset of the target and release of the home key. Anticipations (3.8%) and trials in which the screen was touched outside a 1.13 cm (1.6 deg) region around the central fixation point (3.5%) were excluded. A three-way mixed-factors ANOVA (instruction in Experiment 3a × velocity × direction) was run. The instruction in Experiment 4a did not affect simple response times and did not interact with the remaining factors ($ps > .39$). Simple response times decreased with increasing velocity, $F(3,48) = 29.32$, $\mathrm{MSE} = 620.01$, $p < .001$. The main effect of motion direction approached significance, $F(3,51) = 2.32$, $\mathrm{MSE} = 276.97$, $p = .086$. A nonlinear function was fit to the data (see Fig. 4).

### 6.3. Discussion

The simple response times decreased with velocity. This result replicates previous studies that have investigated the detection of motion in a stimulus that was visible prior to motion onset (e.g., Burr & Corsale, 2001; Burr et al., 1998; Tynan & Sekuler, 1982). The nonlinear relation between velocity and reaction time somehow conflicts with the linear relation between velocity and displacement that was observed in Experiments 1–3. The localization data suggest that there is a constant delay between stimulus onset and the availability of a position signal. The simple response times, however, suggest that the delay between stimulus onset and motor response differs as a function of velocity (see also Kirschfeld & Kammer, 1999). Thus, it may be that the read-out of the position signal used for localization responses differs from the detection of a combined position–motion signal used for simple responses.

## 7. Experiment 5: target shape

Experiment 5 was designed as a control experiment that would allow for a better comparison with previous studies. In Experiments 1–4, a target with smoothed edges was presented (see methods in Experiment 1). All of the previous studies, however, used sharp-edged targets that contained high spatial frequencies. To examine whether stimulus material would influence localization, the smooth-edged target used in Experiments 1–4 was compared to a sharp-edged target. The targets were randomly intermixed and observers were asked to point to the initial position of the target after the target had disappeared.

### 7.1. Methods

Apparatus, stimuli, design, and procedure were the same as in Experiment 1 with the following exception. Either the smooth-edged target used in Experiments 1–4 was presented or a sharp-edged target. The sharp-edged target was a bright-white annulus with a diameter of 0.54 deg and a 0.32 deg center of background luminance. Each combination of target shape, velocity, and motion direction was presented once in a block of 32 trials. Ten students fulfilling the same criteria as in Experiment 1 participated. Participants worked through 20 blocks (640 trials) interrupted by a short break after 10 blocks. Accuracy was stressed over speed.

### 7.2. Results

#### 7.2.1. Displacement

Anticipations (1.1%) and outliers (3.3%) were excluded from the analysis. A three-way ANOVA (Target

Shape × Velocity × Direction) showed that displacement increased with increasing velocity, $F(3, 27) = 35.86$, $MSE = 0.32$, $p < .001$. The interaction of target velocity and direction, $F(9, 81) = 5.72$, $MSE = 0.20$, $p < .001$, indicated that the increase of displacement with velocity was reduced for downward motion and increased for rightward motion. The interaction of target shape and velocity, $F(9, 81) = 3.20$, $MSE = 0.14$, $p < .05$, indicated that the increase of displacement with increasing velocity was slightly more pronounced with the sharp-edged than with the smooth-edged target.

Because the ANOVA showed a significant interaction of target shape and velocity, linear regressions of target velocity on displacement were run for each observer and target shape. The mean slopes differed marginally between the two target shapes, $t(9) = 1.98$, $p = .0794$. The mean intercepts did not differ.

#### 7.2.2. Reaction time

The same trials as for the analysis of displacement were excluded. A three-way ANOVA (Target Shape × Velocity × Direction) revealed a main effect of motion direction, $F(3, 27) = 4.46$, $MSE = 499.87$, $p < .05$, but no effect of velocity. The interaction of target velocity and target shape approached significance, $F(3, 27) = 2.76$, $MSE = 194.87$, $p = .0617$.

#### 7.2.3. Movement time

The same trials as for the analysis of displacement were excluded. A three-way ANOVA (Target Shape × Velocity × Direction) revealed a main effect of motion direction, $F(3, 27) = 6.29$, $MSE = 435.72$, $p < .001$. Movement times increased with increasing velocity, $F(3, 27) = 4.72$, $MSE = 1825.60$, $p < .01$.

### 7.3. Discussion

For both target shapes, displacement increased linearly with velocity. There was a slight difference between the results obtained from the two target shapes. The function relating velocity and displacement was somewhat less steep with smooth targets, but this effect was not quite significant. Displacement was significantly positive with fast velocities, and not significantly different from zero with slow velocities. This result is surprising because the smooth target condition failed to replicate the highly consistent negative offset in Experiments 1, 2, and 4. The only difference between the present and previous experiments was that observers did not know which target would be presented on a given trial. Thus, it seems that destroying the perceptual set (i.e., expectations about what the observer is likely to see in a given trial) greatly reduces the bias to localize the motion onset opposite to the direction of target motion. This result supports the notion that cognitive factors mediate pointing movements to the initial position of a moving target.

The second important outcome of this experiment was that the linear increase of displacement with velocity persisted even though the constant negative offset was largely eliminated. Analysis of the reaction and movement times showed that movement times increased with increasing velocity. Overall, latencies in this experiment were shorter than in previous experiments with accuracy instruction (Experiments 1, 3, 4a; see Table 3).

## 8. General discussion

The present study investigated pointing responses to the onset of a moving stimulus. Previous studies have reported both mislocalization in and opposite the direction of motion. It was suggested that displacement in the direction of motion (the Fröhlich effect) resulted from the time attention takes to reach the moving target (Kirschfeld & Kammer, 1999; Müsseler & Aschersleben, 1998). If the attentional delay was constant across velocities, displacement would be expected to increase linearly with velocity. In a reanalysis of previously published data (Kerzel, 2002), velocity was regressed onto displacement and a linear dependence was confirmed (but see Kirschfeld & Kammer, 1999): When relative judgments were used to estimate the perceived onset, the coefficient of the regression was positive and the intercept was close to zero. However, studies that used mouse pointing responses (Hubbard & Motes, 2002; Kerzel, 2002; Thornton, 2002) reported mislocalizaton opposite the direction of motion and no linear increase of displacement in the direction of target motion with increasing target velocity. These studies have typically used a rather restricted range of slow velocities (e.g., 3–15 deg/s) such that context effects may have influenced observers' responses (see also Kerzel, 2002).

The present study improved previous methods by showing a larger range of velocities (5–43 deg/s) and employing natural pointing responses. The major result was that displacement of the judged onset position, $d$, mostly conformed to a linear model comprising an (attentional) delay factor, $t$, target velocity, $V$, and a constant spatial offset, $s$: $d = t * V + s$. The attentional delay factor varied between 16 and 37 ms and the spatial offset between −1.27 and −0.35 deg. Therefore, the present study partly resolves the conflict between the Fröhlich illusion and the onset repulsion effect. Importantly, the Fröhlich effect is always observed with probe judgments, whereas onset repulsion is (mostly) observed with motor judgments. The crucial hypothesis is that probe and motor judgments are susceptible to different error sources. The delay affects both probe and motor judgments, whereas (cognitive) factors add a constant spatial offset only with motor responses. There are good explanations for the delay in terms of attention and metacontrast. In contrast, the situation is less clear for the constant spatial offset.

The present study tested possible explanations of the constant spatial offset with motor judgments. Based on previous work on pointing responses, it was hypothesized that the spatial offset was caused by repulsion of motor responses away from the focus of attention. Saccadic and manual trajectories have been shown to veer away from the current focus of attention. These findings offer a plausible explanation for the constant offset: attention moves in the direction of motion because the moving target drags the focus of attention with it. Therefore, repulsion from the focus of attention would result in a bias away from the target's trajectory (i.e., opposite to motion).

The results of Experiment 2 were consistent with the attentional repulsion hypothesis. In Experiment 2, observers were asked to respond as rapidly as possible to the onset of the moving target. With slow target motion, the target was still visible on the screen while the motor response was underway. This should have maximized attentional repulsion with slow velocities. In agreement with this hypothesis, displacement opposite to motion was larger with velocities of 5.4 and 10.7 deg/s. In Experiment 3, only the first and final positions of smooth target motion were presented such that apparent or implied motion resulted. Observers were instructed to respond after target offset. It was expected that attention moved from the first to the final target position. Therefore, motor responses should be biased away from the final target position (i.e., opposite to the direction of target motion). However, localization of the onset position was accurate in most conditions. In fact, when the temporal interval between first and final target presentation was such that a good impression of motion resulted, displacement was toward the final target position.

It is not entirely clear what caused the reversal of the sign of the deviation, however, it may be that the motor system was susceptible to errors that also underlie the "global effect" (Coeffe & O'Regan, 1987; Findlay, 1982; Findlay & Gilchrist, 1997; Sailer, Eggert, Ditterich, & Straube, 2002). Fast saccades to a target that is accompanied by a distractor often land in the center of gravity between target and distractor. This effect has also been observed for combined saccadic and pointing movements: if, for instance, participants were asked to saccade and point to a target at 8 degrees of eccentricity, and a distractor was presented at 4 deg, the amplitude of the movement would be reduced by about 0.1–0.5 deg compared to a condition without a distractor (Experiment 1 in Sailer et al., 2002). In analogy to this paradigm, one may consider the positions occupied by the target in the onset localization task as distractors. Consequently, one would expect pointing movements to be displaced in the direction of motion (toward the remaining positions along the trajectory). It may be that depending on the spatio-temporal parameters, the error pattern resembles onset repulsion (with smooth motion) or the global effect (with apparent motion).

In Experiment 4, the speed–accuracy relation was varied. If the negative spatial offset was caused by error avoidance, it should increase in magnitude when observers are instructed to avoid errors (i.e., accuracy instruction). This prediction was not confirmed.

In Experiment 5, a control condition was run that compared a smooth-edged target to a sharp-edged target. Differences between the targets were slight, but the constant displacement was strongly reduced. It may be that destroying expectations about what an observer would see on a given trial eliminated onset repulsion. Maybe interactions between expectation and attention, as documented in research on endogenous shifts of attention (e.g., Müller & Rabbitt, 1989), modulate motor responses. Therefore, the results of Experiment 5 do not directly contradict the attentional repulsion hypothesis.

In sum, the present study shows that onset repulsion and Fröhlich illusion may be reconciled by assuming that an attentional delay produces a localization error that increases in the direction of motion with increasing velocity. This delay factor was found to be robust across all experiments. Additionally, there was a constant, negative offset in motor judgments that was not observed in previous studies with probe judgments (cf. Figs. 1 and 2). Two explanations of the negative offset (i.e., onset repulsion) have been examined. Attentional repulsion claims that motor responses are biased away from the position of distracting stimuli. In onset localization, the trajectory of the target may act as distractor. This hypothesis can explain some, but not all of the present data. Error avoidance claims that observers try to avoid pointing to positions the target occupied after it appeared. This idea could not be supported when the speed–accuracy relation was varied. Thus, the constant negative bias with pointing responses is a somewhat volatile phenomenon that may reflect attentional processes, but is not immune to cognitive influences.

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