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RESEARCH ARTICLE

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Different localization of motion onset with pointing and relative judgements

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Abstract When observers are asked to judge the first position of a moving object, displacements of the judged onset in the direction of and in the direction opposite to the motion have been reported. These errors have been referred to as the Fröhlich illusion and the onset repulsion effect, respectively. To resolve the apparent contradiction between these results, a number of experimental parameters were investigated. Displacement in the direction opposite to motion was only observed when observers pointed to the onset of a slowly moving target. At higher velocities, no displacement with pointing was observed. In contrast, relative judgements of motion onset were accurate at slow velocities, but displaced in the direction of motion at fast velocities. Whether the target moved on a linear or circular trajectory did not alter the results. In one experiment, a dissociation between perceptual and memory-based judgements was found. Overall, the experimental task determined whether displacement in the direction of or in the direction opposite to motion occurred.

Keywords Localization · Position judgements · Pointing · Fröhlich illusion · Motion · Onset repulsion

Introduction

There are conflicting findings about localization errors occurring when observers are asked to judge the first position of a moving stimulus. The classical finding has been that observers err in the direction of motion and judge a position as first that is displaced in the direction of motion relative to the true first position (Fröhlich 1923). This finding was replicated with linear motion of a small stimulus (Müsseler and Aschersleben 1998; Whitney and Cavanagh 2000, 2002) and with rotary motion of a large stimulus (a long line, Kirschfeld and Kammer 1999). However, the illusion was absent with rotary motion of a small stimulus (Kerzel and Müsseler 2002). Most accounts of the Fröhlich illusion involve attention. It has been suggested that the first part of the trajectory is missed because the initial target positions receive less attention than later ones. One account suggests that it takes time for attention to reach the moving stimulus. Because attention is necessary for conscious processing, the initial positions do not reach awareness as the stimulus moves while the shift of attention is underway (Müsseler and Aschersleben 1998). Another account suggests that the initial positions are not cued by the stimulus itself, such that subsequent metacontrast masking from the stimulus itself reduces the visibility of the initial portion of the trajectory (Kirschfeld and Kammer 1999). In support of attentional involvement, it has been found that the Fröhlich illusion is larger with an efficient attractor of attention, such as a small dot, compared to an inefficient attractor, such as a long line (Kerzel and Müsseler 2002). However, the size of the attentional focus did not directly determine the size of the Fröhlich illusion.

In contrast to the classical finding of displacement in the direction of motion, a recent study reported displacement of the judged first position in the direction opposite to motion (Thornton 2002). When observers were asked to point to the first position of a small isolated target moving on a linear trajectory at slow velocities (3–15°/s), observers' judgements were displaced from the true first position in the direction opposite to motion. This displacement was referred to as the onset repulsion effect (ORE). The ORE increased with velocity. In another study using pointing movements, the opposite effect was observed at 14°/s (Müsseler and Aschersleben 1998). A major difference between the two studies is the range of possible starting positions. In Müsseler and Aschersleben's study, the target appeared left or right of fixation at 6°±0.5°. In Thornton's study, the target appeared

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randomly within a 4° viewing square centered on the middle of the screen. Although pointing movements were used in both studies, it may be that the restricted range of starting positions in Müsseler and Aschersleben's study turned pointing (i.e., absolute judgements) into a relative judgement task: With starting positions closely clustered around a fixed eccentricity, it is likely that observers judged the target position relative to an internal standard, that is, the 6° position.

The goal of the current study was to resolve the apparent contradiction between studies replicating the Fröhlich illusion and the study finding onset repulsion. To this end, a number of parameters were considered.

Movement speed

As already suggested by Thornton (2002), it may be that the ORE and the Fröhlich illusion are continuous phenomena that depend on movement speed. According to this idea, increasing target velocity would produce a transition from the ORE at slow velocities to the Fröhlich illusion at high velocities.

Type of motion

In Thornton's (2002) study, linear motion was used and displacement in the direction opposite to motion was found. Kerzel and Müsseler (2002) used circular motion and slow velocities and found no displacement when a small isolated dot was used. Müsseler and Aschersleben (1998) used linear motion and found displacement in the direction of motion. Kirschfeld and Kammer (1999) used circular motion and found displacement in the direction of motion. Although no clear relationship between type of motion and displacement is discernible, it may be that the type of motion affects the localization error.

Experimental task

Kerzel and Müsseler (2002) asked observers to adjust the position of the target stimulus on a predescribed trajectory. That is, the orientation of a freely turnable line or dot could be adjusted by moving the mouse cursor. A Fröhlich illusion was observed with a long line, but not with a small dot. Thornton (2002) and Müsseler and Aschersleben (1998) asked their observers to point to the first position and reported conflicting results. However, the latter study may have induced relative rather than absolute judgements (see above). Kirschfeld and Kammer (1999) and Whitney and Cavanagh (2000, 2002) used relative judgements and found displacement in the direction of motion. Thus, it appears that the Fröhlich illusion was present with relative judgements, whereas an ORE or no effect was observed with free pointing. It has been argued that pointing movements and relative judgements use different types of information (Bridgeman et al. 1981, 1997). Pointing was considered to have access to more veridical information about the position of objects (but see Franz et al. 2000; Kerzel et al. 2001). Therefore, pointing to a position in space may involve processes or spatial maps that are different from those involved in relative localization. These differences may explain the discrepant outcomes.

Memory vs perception

Another distinction that is often neglected in studies on localization concerns perception vs visual short-term memory (see also Sheth and Shimojo 2000; Thornton 2002). When observers are asked to point toward the first position of a moving object, they have to rely on a representation of the object's position in visual short-term memory because the stimulus is no longer present when they initiate the movement. In contrast, relative judgements do not rely on a representation of the target position in visual short-term memory when a reference stimulus is presented simultaneously with the target stimulus. As visual short-term memory has been found to be the source of some localization errors (e.g., Freyd and Finke 1984; Kerzel 2000), it may be that the pattern of displacement is affected by whether visual short-term memory is involved or not.

Goal of study

In the present series of experiments, these factors were systematically varied. In Experiment 1, linear and circular motion was compared at slow and fast velocities. Pointing judgements were used. To make the present study as comparable as possible to previous studies, the slow and fast velocities were run in different experiments and were not randomly interleaved. The slow velocities resembled those used by Thornton (2002), whereas the fast velocities were in the range of those used in most of the other studies on the Fröhlich illusion. In Experiment 2, relative judgements were employed. Observers were asked to compare the orientation of a reference stimulus to the orientation of the first position of a target moving on a circular trajectory at slow or high velocities. The reference stimulus was either present when the target appeared (perceptual condition) or after the target had disappeared (memory condition). In Experiment 3, the results from Experiment 2 were confirmed using different methods.

Experiment 1A

In Experiment 1a, slow velocities were presented. When comparing linear and circular motion, one is faced with the problem that a fixed rotational velocity results in different tangential velocities depending on the eccentricity of the target. I chose to equate the velocity of linear motion to the tangential velocity of circular motion. That

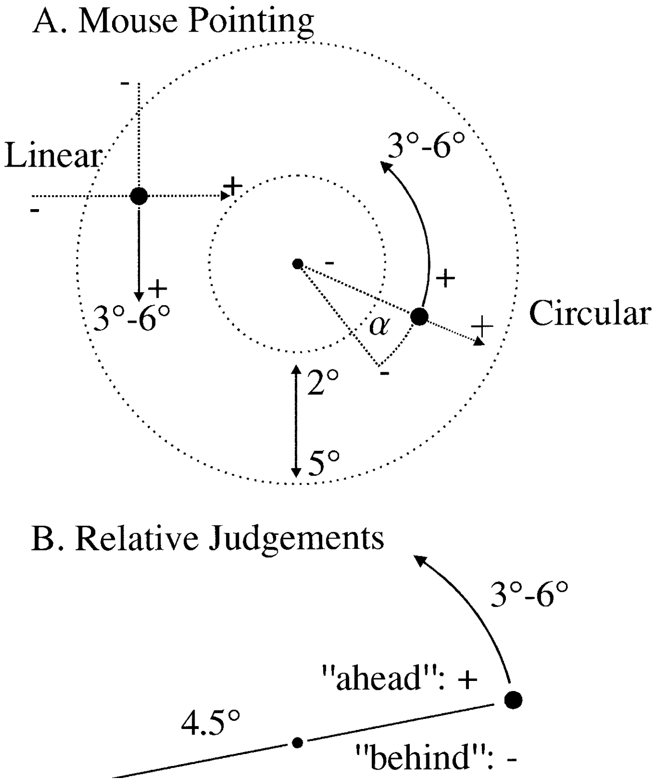

Fig. 1A, B Schematic drawing of stimulus arrangement and sign convention. **A** With linear motion, the target moved left, right, up, or down. Displacement in the direction of motion (M-displacement) received a positive sign, displacement in the direction opposite to motion a negative sign. For vertical motion, displacement in the direction opposite to motion (O-displacement) received a positive sign when it was to the right. For horizontal motion, displacement in the direction opposite to motion (O-displacement) received a positive sign when it was upwards. With circular motion, the target moved clockwise or counterclockwise. Deviations of the judged orientation (α) received a positive sign when they were in the direction of motion. Deviations of the judged radius received a positive sign when it was longer than the actual radius. With both types of motion, the length of the trajectory varied randomly between 3° and 6°. The target appeared at an eccentricity of 2°–5°. **B** When relative judgements were used, the reference line appeared either "ahead" or "behind" the initial target orientation. When it appeared "ahead," the target would cross the virtual extension of the reference line after a certain rotation (2°–20° of rotation). When it appeared "behind," it would never cross this virtual extension. For illustration, the neutral condition with no difference between target and reference orientation is depicted. This condition was not shown in Experiment 2

is, the velocity of targets on linear trajectories would correspond to the tangential velocity of targets on circular trajectories appearing at an equal eccentricity (see Figs. 1A, 2). Therefore, linear and tangential velocities increased as the initial target position became more eccentric. Observers were asked to move a cross-hair cursor to the first position of the moving stimulus.

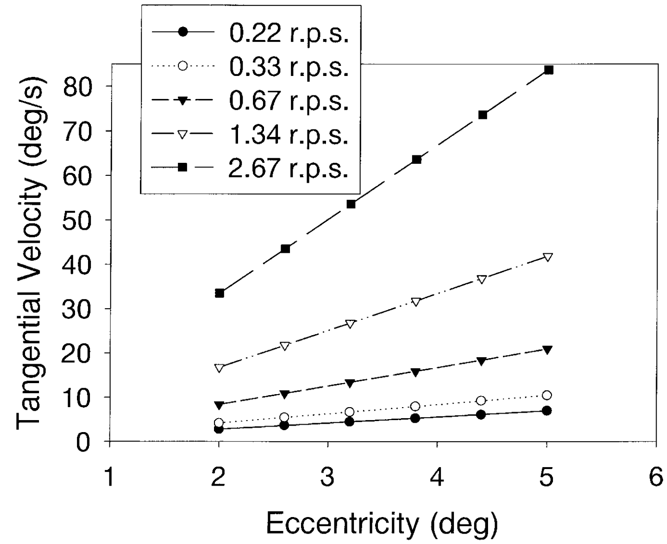

Fig. 2 Tangential velocities as a function of rotational velocity (in rotations per second, rps) and eccentricity. The larger the radius, the larger the tangential velocity for a given rotational velocity. The velocity of targets on linear trajectories was matched to the tangential velocity of targets on circular trajectories. Rotational velocities of 0.22–0.67 rps were used in Experiments 1a, 2, and 3. Rotational velocities of 0.67–2.67 rps were used in Experiments 1b and 2

Materials and methods

Participants

Students at the Ludwig-Maximilians University of Munich participated for pay. Prior to the inclusion in the study, all subjects gave their informed consent. All reported normal or corrected-to-normal vision and were naive as to the purpose of the experiment. Eight students participated in Experiment 1a and Experiment 1b, respectively. One observer participated in both experiments.

Apparatus and stimuli

The stimuli were presented on a 21" (diagonal) screen with a refresh rate of 120 Hz (Experiment 1a) and 101 Hz (Experiments 1b, 2, 3) and a resolution of 1024 (H)×768 (V) pixels. The background was medium gray, and a filled black dot with a diameter of 0.1° presented in the center of the screen served as fixation point. A filled black dot with a diameter of 0.5° was used as target stimulus. The target appeared at a random orientation and an eccentricity ranging between 2° and 5°. Similar to Thornton's (2002) study, it moved for a randomly determined trajectory length of 3–6°. With circular motion, the target moved on an orbit of fixed radius at one of three rotational velocities (see Fig. 1A). As the radius of the orbit was variable, the tangential velocity of the target changed correspondingly. With linear motion, the target moved either horizontally or vertically (left, right, up, or down). The target's path of motion was not constrained; however, it never covered the fixation point because within a 1° region around the fixation point, the background did not change its color. The velocity of the target on a linear trajectory was constant and matched the tangential velocity of circular motion starting at the same eccentricity (see Fig. 2). The horizontal position of the left eye was monitored with a head-mounted, infrared, light-reflecting eyetracker (Skalar Medical BV, IRIS model 6500). Fixation had to be maintained within 1° of the fixation point during stimulus presentation.

Table 1 M-Displacement in degrees of visual angle (°) for linear motion as a function of eccentricity and direction of motion in Experiments 1a and 1b. With upward motion, M-displacement tended to increase with increasing eccentricity, which was not the case for the other directions

Ecc. (°)	Experiment 1a				Experiment 1b			
	Left	Right	Up	Down	Left	Right	Up	Down
2.0	–0.743	–0.393	–0.064	–0.118	–0.217	0.029	0.097	0.072
2.6	–0.797	-0.488	0.130	–0.041	–0.149	0.003	0.190	–0.013
3.2	–0.829	–0.554	0.278	–0.346	–0.177	0.036	0.332	0.011
3.8	–0.967	–0.586	0.473	–0.251	–0.186	–0.150	0.475	0.085
4.4	–0.973	–0.790	0.518	–0.220	–0.300	–0.043	0.588	0.108
5.0	–1.194	–0.386	0.734	–0.184	–0.250	0.009	0.820	0.143

Positive values indicate displacement of the judged onset in the direction of motion, and negative values indicate displacement opposite the direction of motion

Design

Six different eccentricities ranging from 2° to 5° in steps of 0.6° were presented. Target motion was either linear or circular. With circular motion, the direction of motion was either clockwise or counterclockwise. With linear motion, the direction of motion was either up, down, left, or right. Rotational velocities of 0.22, 0.33, and 0.67 rotations per second (rps) were used. The corresponding linear and tangential velocities are graphed in Fig. 2. The different conditions were randomly interleaved. Each observer worked through 288 trials.

Task and procedure

Participants sat in a dimly lit room 50 cm from the screen. Head movements were restricted by a chin and cheek rest, and viewing was binocular. Each trial started with a brief (300-ms) broadening of the fixation dot as a warning signal. After 500 ms, the target appeared and started to move. Some 500 ms after disappearance of the target, a cross-hair mouse cursor appeared at the center of the screen. The observer's task was to move the cursor to the initial position of the target and to confirm their judgements by clicking the left mouse button. They were told to focus on the initial position of the target. No feedback was provided. When a fixation error occurred, an error message appeared and the trial was repeated in the remainder of the experiment.

Results

Linear and circular motion were analyzed separately. Fixation errors occurred on 0.6% of the trials. To avoid confusion, degrees of rotation are referred to as "DegRot" whereas degrees of visual angle are abbreviated with the standard symbol ("°").

Linear motion

The deviation between the judged and the actual initial position was calculated along two axes. First, deviations along the direction of motion were determined (M-displacement). Deviations in the direction of motion received a positive sign (i.e., the Fröhlich illusion), and deviations in the direction opposite to motion received a negative sign (i.e., the ORE). Second, deviations along the axis orthogonal to the direction of motion were determined (O-displacement). For vertical motion, deviations to the left received a negative sign, and deviations to the right a positive sign. For horizontal motion, upward deviations received a positive sign, and downward deviations received a negative sign.

M-Displacement

A three-way ANOVA (direction of motion × velocity × eccentricity) showed that M-displacement was influenced by velocity, $F_{(2,14)}=9.00$, $P<0.005$. M-displacement was –0.22°, –0.38°, and –0.37° with velocities of 0.22, 0.33, and 0.67 rps, respectively. By *t*-test, the latter two means were significantly different from zero (*P*s<0.05). The effect of direction of motion was significant, $F_{(3,21)}=15.39$, $P<0.0001$. M-displacement was –0.53°, –0.91°, –0.19°, and 0.34° with rightward, leftward, downward, and upward motion, respectively. Further, the interaction between direction of motion and eccentricity reached significance, $F_{(15,105)}=5.05$, $P<0.0001$ (cf. Table 1).

O-Displacement

Separate analyses were run for horizontal and vertical motion. For horizontal motion, a two-way ANOVA (velocity × eccentricity) did not reveal any significant effects. Mean displacement was 0.049°, 0.061°, and 0.038° for velocities of 0.22, 0.33, and 0.67 rps, respectively. None of these means was significantly different from zero (*P*s>0.18). For vertical motion, another two-way ANOVA (velocity × eccentricity) revealed an interaction of velocity and eccentricity, $F_{(10,70)}=3.35$, $P<0.005$ (cf. Table 2). O-Displacement was 0.036°, 0.001°, and –0.012° with velocities of 0.22, 0.33, and 0.67 rps, respectively. None of these values was significantly different from zero (*P*s>0.2).

Circular motion

The angular deviation between the judged and the actual initial orientation, referred to as the azimuth, was calculated. Positive deviations indicate that the judged initial orientation was displaced from the actual orienta-

Table 2 O-Displacement in degrees of visual angle (°) as a function of velocity and eccentricity for vertical motion in Experiment 1a. Generally, O-displacement increased somewhat at the largest eccentricity of 5°. With the slow velocity, a similar increase was also present at eccentricities of 3.8° and 4.4°

Ecc. (°)	Velocity (rps)		
	0.22	0.33	0.67
2.0	–0.025	–0.110	–0.138
2.6	0.204	0.042	–0.113
3.2	0.066	–0.005	–0.163
3.8	0.393	–0.117	0.056
4.4	0.303	–0.046	0.190
5.0	0.280	0.266	0.280

Positive values indicate displacement of the judged initial position to the right, and negative values indicate displacement to the left

tion in the direction of rotation (i.e., the Fröhlich illusion), whereas negative deviations indicated displacement opposite to the direction of rotation (i.e., the ORE). Also, the deviation between the radius of the target's trajectory and the eccentricity of the judged initial position was determined. Positive numbers indicate that the judged initial position was more eccentric than the target, and negative numbers indicate that it was less eccentric.

Deviation of azimuth

A two-way ANOVA (velocity × eccentricity) did not yield any significant effects (*P*s>0.18). The angular deviation was –7.06, –8.49, and –7.33 DegRot with velocities of 0.22, 0.33, and 0.67 rps, respectively. By *t*-test, all of these means were significantly different from zero (*P*s<0.001).

Deviation of radius

A two-way ANOVA (velocity × eccentricity) showed a significant effect of eccentricity, $F_{(5,35)}=26.02$, $P<0.0001$. The deviation decreased from –0.1° at 2° eccentricity to –0.63° at 5° eccentricity. Mean deviation was –0.37°, –0.34°, –0.35° with velocities of 0.22, 0.33, and 0.67 rps, respectively. All of these means were significantly different from zero (*P*s<0.01).

Discussion

The ORE reported by Thornton (2002) was replicated with linear and circular motion. With slow linear motion, the ORE increased with velocity (i.e., M-displacement became more negative), at least from 0.22 to 0.33 rps. Although there was a similar trend in the data with circular motion, this effect did not reach significance. The ORE with linear motion was modified by the direction of motion. Consistent with Thornton's report, the ORE was larger with leftward motion than with rightward motion. Contrary to Thornton's report, the ORE was reduced with upward motion. Thornton found the ORE to be more pronounced with upward motion, and reduced with downward motion. Also, O-displacement with linear motion was not consistently displaced downward. Previous studies reported a downward bias in localization tasks (e.g. Hubbard 1995). The absence of the downward bias and the diverging effects of direction of motion may be due to the restricted field of view which resulted from using the IRIS Skalar eyetracker. While all stimuli were within the visible range, upper and lower fields were partly occluded by the eyetracker sensors. Asymmetries in the position of the top and bottom sensors may have induced up-down biases in the localization task. Further, a tendency to localize the target toward the fovea was observed with circular motion. This foveal bias increased with target eccentricity. These results are consistent with previous reports (van der Heijden et al. 1999; Sheth and Shimojo 2001; Kerzel 2002).

In sum, the ORE was replicated with pointing movements to the onset of linear and circular motion. One hypothesis put forth by Thornton was that the ORE would change into the Fröhlich illusion if the velocity of target motion was increased. Thornton investigated velocities in the range of 3–15°/s, which is comparable to the range of tangential velocities used in the present experiment (2.8°–20.4°/s, cf. Fig. 2). Thus, it may be that the transition point between ORE and Fröhlich illusion was beyond 20°/s.

Experiment 1B

To test the hypothesis that the ORE and Fröhlich illusion are continuous phenomena that depend on target velocity, a different range of velocities was used. Rotational velocities of 0.67, 1.33, and 2.67 rps were used. This results in tangential (linear) velocities of about 8.4°–83.8°/s. On a computer monitor with a refresh rate of about 101 Hz, the nature of the displayed motion changes at very high velocities. Because the target position may only be updated every 10 ms, the target appears to jump from one location to another. With the present choice of stimulus parameters, there may be as few as three target presentations in different refresh cycles on a given trial (e.g., at 80°/s and a trajectory length of 3°). Therefore, the resulting motion is choppy.

To allow for better comparison with Thornton's (2002) study, the trajectory length was kept within the range used in Experiment 1A, that is, between 3° and 6°. Three degrees may be a relatively short length as the Fröhlich effect may reach up to 3° (Müsseler and Aschersleben 1998). Effects of trajectory length have not been investigated before; however, it may well be that using short trajectories underestimates the size of the Fröhlich illusion. If, for instance, a 1° trajectory was shown at a velocity that typically produces a Fröhlich effect of 3°, it is unlikely that the complete trajectory would be invisible to the observer. Rather, the observer will judge a position within 1° from the actual initial position as first, thereby underestimating the Fröhlich illusion.

Materials and methods

Stimuli, apparatus, design, and procedure

These were the same as in Experiment 1a with the exception that faster velocities were used. The rotational velocity was either 0.67, 1.33, or 2.67 rps. The velocity with linear motion varied with eccentricity to match the tangential velocity of circular motion.

Results

Data treatment was as in Experiment 1a. Fixation errors occurred in 1.2% of the trials.

Linear motion

M-Displacement. A three-way ANOVA (direction of motion × velocity × eccentricity) revealed a significant effect of direction of motion, $F_{(3,21)}=9.00$, $P<0.005$. Displacement was –0.02°, –0.21°, 0.06°, and 0.41° with rightward, leftward, downward, and upward motion, respectively. Only the last mean was significantly different from zero ($P<0.005$). Displacement increased with eccentricity from –0.005° at 2° eccentricity to 0.18° at 5° eccentricity, $F_{(5,35)}=2.52$, $P<0.05$. The interaction between direction of motion and eccentricity was significant, $F_{(15,105)}=2.64$, $P<0.005$ (cf. Table 1). Mean M-displacement was 0.14°, 0.06°, and –0.01° at velocities of 0.67, 1.33, and 1.67 rps, respectively. None of these values was significantly different from zero (Ps>0.4).

O-Displacement

Separate analysis were run for horizontal and vertical motion. For horizontal motion, a two-way ANOVA (velocity × eccentricity) did not reveal any significant effects. Mean displacement was 0.002°, 0.023°, and 0.069° with velocities of 0.67, 1.33, and 1.67 rps, respectively. None of these values was significantly different from zero (Ps>0.1). For vertical motion, a two-way ANOVA (velocity × eccentricity) revealed a significant effect of eccentricity, $F_{(5,35)}=2.92$, $P<0.05$. Displacement was –0.014°, 0.002°, 0.05°, 0°, –0.033°, and 0.08° with eccentricities from 2° to 5°, respectively. Mean displacement was 0.041°, 0.003°, and –0.001° with velocities of 0.67, 1.33, and 1.67 rps, respectively. By *t*-test, none of these means was significantly different from zero (Ps>0.2).

Circular motion

Deviation of azimuth. A two-way ANOVA (velocity × eccentricity) on angular deviation did not yield any significant effects (Ps>0.3). The deviation was 0.76, 1.65, and –0.38 DegRot with velocities of 0.67, 1.33, and 2.67 rps. By *t*-test, none of these means was significantly different from zero (Ps>0.3).

Deviation of radius

A two-way ANOVA (velocity × eccentricity) showed a significant effect of eccentricity, $F_{(5,35)}=17.83$, $P<0.0001$. The deviation of the judged from the actual radius decreased from –0.14° at 2° eccentricity to –0.55° at 5° eccentricity. The deviation was –0.40°, 0.37°, and –0.33° with velocities of 0.67, 1.33, and 2.67 rps. All of the latter means were significantly different from zero (Ps<0.0001).

Discussion

With high velocities, there was no ORE and no Fröhlich illusion: Pointing movements to the first position of a moving stimulus did not show a systematic deviation in or opposite to the direction of motion. Further, there was a tendency to underestimate the eccentricity of the target (foveal bias). Somewhat surprisingly, the ORE with a velocity of 0.67 rps observed in Experiment 1a was not replicated. It may be that the context of velocities affected localization. The reasons for this unexpected outcome warrant further research. For instance, it would be interesting to combine all the different velocities in a single experiment and to evaluate the effects of velocity context. In the present paper, however, the main objective was to replicate the methods of previous studies to allow for a better comparison with these studies.

Thus, increasing target velocity does not yield a smooth transition between ORE and Fröhlich illusion – at least not with blocked presentation of the two velocity ranges. Rather, ORE and Fröhlich illusion do not obtain with high target velocities and pointing. However, this conclusion is limited to motion displayed on a computer monitor. It may be that with real target motion on an analog display, instead of the choppy motion on a computer monitor, displacement may reappear at high velocities.

Experiment 2

Experiment 1 has demonstrated that there is an ORE at lower velocities, but not at higher velocities. The goal of Experiment 2 was twofold. First, the experiment examined whether the findings of Experiment 1 are specific to pointing movements. To this end, a different method was used to estimate the subjective first position of the moving stimulus. Instead of pointing toward the first position, observers were asked to compare the first position to a reference stimulus. Circular motion within two different velocity ranges (0.22–0.67 rps and 0.67–2.67 rps) was investigated. Second, the experiment examined whether the localization error observed in Experiment 1 was due to errors occurring in memory and/or perception. Pointing movements cannot answer this question as they may only be initiated after presentation of the target. That is, pointing movements are based on a representation of the first position in visual short-term memory. In contrast, reference and target stimulus may either be presented concurrently, or with a temporal offset. Whereas the former condition probes visual perception (“Where did you *see* the target relative to the reference?”), the latter condition probes visual short-term memory (“Where do you *remember* the target relative to the reference?”).

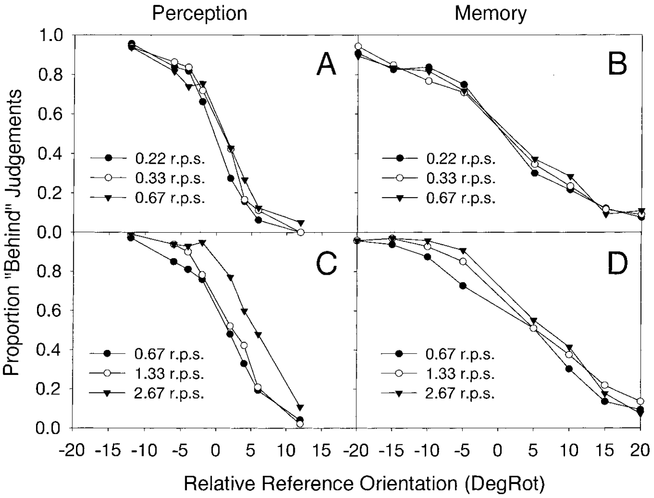

Fig. 3A–D Proportion of “behind” judgements as a function of target velocity and time of reference stimulus presentation in Experiment 2. The target moved within a slow velocity range (0.22–0.67 rps) in **A** and **B**, and within a fast velocity range (0.67–2.67 rps) in **C** and **D**. The reference stimulus was presented before target onset in **A** and **C**, and after target offset in **B** and **D**. There was a shift of the psychometric function to the right with fast velocities (**C** and **D**)

Materials and methods

Participants

Eight observers fulfilling the same criteria as in Experiment 1 participated.

Stimuli, apparatus, task and procedure

These were the same as in Experiment 1a with the following exceptions. The target always moved on a circular orbit with a radius of 5°. A line that extended 4.5° toward both sides of fixation was used as reference stimulus. Its width was 1 pixel or 0.03°. In one condition, the reference was visible for 1 s before the target appeared and remained visible until a judgement was made. In this perceptual condition, the target was offset by ±12, ±6, ±4, or ±2 DegRot from the initial position of the target. Positive numbers indicate that the orientation of the reference line was “ahead” of the initial target position, that is, the target would cross a virtual extension of the line after a rotation of 12, 6, 4, or 2 DegRot (see Fig. 1B). Negative numbers indicate that the orientation of the reference line was “behind” the initial target position, that is, the target would never cross the virtual extension of the line. In another condition, the reference was invisible while the target moved, and did not appear until 500 ms after the target had disappeared. In this memory condition, the probes were offset by ±20, ±15, ±10, or ±5 DegRot from the initial target position. The probes were farther apart than in the perceptual condition as pilot studies had shown that observers’ performance was worse in this condition, indicating some decay of position information in visual short-term memory. In both perceptual and memory conditions, the observers’ task was to indicate whether the reference line was “ahead” or “behind” of the target. Perceptual and memory conditions were run in separate sessions. The target either moved at a relatively slow velocity (0.22, 0.33, or 0.67 rps) or at a relatively fast velocity (0.67, 1.33, or 1.67 rps) The four combinations of velocity range and memory condition were run in four sessions comprising 288 trials each. Observers completed the slow velocities before the fast velocities, and for each velocity range the perceptual condition was run before the memory condition. This ordering ensured that the easiest conditions were administered first.

Results

From the “ahead-behind” judgements (see Fig. 3), the point of subjective equality (PSE) was estimated by means of a Probit analysis (Finney 1971) for each velocity, perceptual/memory condition, and observer. The PSEs indicate the relative orientation of the reference stimulus that was judged to be the same as the initial orientation of the target. Negative PSEs indicate that the reference line had to be placed behind the onset of the target stimulus in order to be judged the same. That is, the initial target position was judged to be displaced in the direction opposite to motion. Positive PSEs indicate that the reference line had to be placed ahead of the onset of the target stimulus in order to be judged the same. That is, the initial target position was displaced in the direction of motion (Fröhlich illusion). Fixation errors occurred in 1.1% of the trials.

Perceptual judgements

Slow velocities. A one-way ANOVA showed that there was no effect of velocity. PSEs were –1.16, 0.08, and 0.83 DegRot for velocities of 0.22, 0.33, and 0.67 rps, respectively. By *t*-test, none of these means was significantly different from zero (Ps>0.2).

Fast velocities. A one-way ANOVA showed that there was an effect of velocity, $F_{(2,14)}=4.55$, $P<0.05$. Displacement increased with velocity and was 1.34, 2.25, and 5.01 DegRot with velocities of 0.67, 1.33, and 2.67 rps, respectively. By *t*-test, the latter two means were significantly different from zero (Ps<0.005).

Memory judgements

Slow velocities. A one-way ANOVA did not reveal an effect of velocity. Mean displacement was –0.22, 0.61, and 1.39 DegRot with velocities of 0.22, 0.33, 0.67 rps, respectively. By *t*-test, none of these values was significantly different from zero (Ps>0.6).

Fast velocities. A one-way ANOVA revealed that displacement increased with velocity, $F_{(2,14)}=6.22$, $P<0.05$. Mean displacement was 2.29, 4.71, 6.11 DegRot with velocities of 0.67, 1.33, and 2.67 rps, respectively. By *t*-test, the latter two values were significantly different from zero (Ps<0.05).

Discussion

There were three main results. First, there was no significant displacement in the direction opposite to motion in any of the conditions. Therefore, the ORE observed in Experiment 1a is specific to pointing movements: The ORE did not obtain with relative judgements, regardless of whether perception or memory were probed. In a further experiment not reported here, an ORE was also absent when a same-different procedure was used (e.g., Freyd and Johnson 1987). However, judgements were highly variable with the same-different procedure such that a firm conclusion was not possible. Second, there was no marked difference between perceptual and memory-based localization of the first position. Numerically, judgements were shifted further in the direction of motion when the reference stimulus appeared after target offset than when the reference stimulus was visible while the target was presented. Third, the Fröhlich effect was absent with a slowly moving isolated target and relative judgements. This finding is consistent with a prior study using constrained pointing (Kerzel and Müsseler 2002). However, when a spatially extended stimulus, such as a line, was presented, the same rotational velocities have been shown to produce a reliable Fröhlich illusion (Kirschfeld and Kammer 1999; Kerzel and Müsseler 2002).

Experiment 3

A possible objection to the interpretation of Experiment 2 is that it partially rests on a null effect. There was no displacement of the judged initial position with slow velocities. With fast velocities, however, displacement in the direction of motion – the standard Fröhlich illusion – occurred. Further, the memory condition was always run second for each set of velocities. Therefore, whatever strategy observers may have developed for performing the former task could have carried over and influenced the latter. Also, asking observers to compare a line to a relatively large dot may have fostered the development of strategies. Although they should have compared the center of the dot to the line, they may not have always done so and they may have developed varying strategies. To increase confidence in the conclusions that there is no ORE with slow velocities, the slow velocity conditions of Experiment 2 were rerun with a more sensitive method, a larger number of participants, counterbalanced ordering of perception and memory conditions, and a different target stimulus. Instead of using the method of constant stimuli as in Experiment 2, the PSE was estimated with a PEST procedure (Lieberman and Pentland 1982). Further, a small line was used as a stimulus. Even though it is a line, it may be considered spatially confined as its extent was rather small, about 1°.

Participants

The same eight observers as in Experiment 2 and six additional observers fulfilling the same criteria participated.

Materials and methods

Stimuli, apparatus, and procedure were the same as in Experiment 2 with the following exceptions. The radius of the reference line was reduced to 3.8°. A 1° line that was similar to the reference line was used as target stimulus. The radius of the target stimulus extended from 4° to 5°. Two velocities were presented (0.22 and 0.44 rps). A PEST procedure (Lieberman and Pentland 1982) adjusted the orientation of the reference line so it appeared at the PSE. Four estimates of the PSE based on 40 trials were collected for each velocity and observer. The perceptual and memory condition were blocked and run in a single session. The ordering of blocks was counterbalanced across observers. Because wearing the head-mounted eyetracker for a long time is rather uncomfortable and the number of trials was large (320 perceptual + 320 memory), eye fixation was not monitored. As most (12/14) observers had participated in experiments in which eye fixation was monitored, one may assume that observers abided by the instruction to keep fixation on the central dot.

Results

Perceptual judgements

A *t*-test showed that there was no difference between the two velocities (*P*>0.8). By *t*-test, displacement was not significantly different with the slow (0.53 DegRot, *P*>0.6) or the fast velocity (0.41 DegRot, *P*>0.7).

Memory judgements

t-Tests showed that there was no difference between the two velocities (*P*>0.9) and that displacement was significantly different from zero with the slow (5.59 DegRot, *P*<0.05) and fast (5.57 DegRot, *P*<0.05) velocity.

Discussion

There was no displacement of the initial target position when the reference stimulus was visible. In contrast, the target position was displaced in the direction of motion when the reference stimulus appeared after target presentation. Thus, localization in the perceptual condition was different from localization in the memory condition. Visual short-term memory showed a shift of the remembered initial position in the direction of motion that was not present in perception. This finding is consistent with the numerical trend in the data from Experiment 2 and confirms the suspicion that some strategic factors may have shadowed the difference between perception and memory in Experiment 2. Further, the results support the notion that memory, and not necessarily perception, is the source of localization errors (Freyd 1987; Sheth and Shimojo 2001; Thornton 2002). In particular, memory for dynamic events may be shifted in the direction of motion, for instance with memory for the final position of a moving target ("representational momentum", e.g., Freyd 1987).

Importantly, mislocalization in the memory condition was in the direction of motion, not opposite the direction of motion. Because of the temporal offset between target presentation and judgement, the memory condition in the present experiment is more similar to the pointing task in Experiment 1 than the perceptual condition. Because the displacements with relative judgements and pointing are in opposite directions, we may be more confident to conclude that there is no ORE with relative judgements. If at all, displacement in the direction of motion occurred.

General discussion

The present study aimed at resolving a contradiction in the literature on the localization of the first position of a moving stimulus. Most studies reported displacement of the judged initial position of a moving target in the direction of motion (Fröhlich 1923; Müsseler and Aschersleben 1998; Kirschfeld and Kammer 1999; Whitney and Cavanagh 2000, 2002; Kerzel and Müsseler 2002). Recently, the opposite effect was noted: When observers were asked to point to the initial position of a moving target, judgements were displaced from the true initial position in the direction opposite to motion (Thornton 2002). A number of parameters were investigated that may account for this contradiction. First, the velocity of target motion was varied. With slow velocities of 2.8–20.4°/s, the ORE was replicated (Experiment 1a). With higher velocities of 8.4–83.8°/s, no displacement was found (Experiment 1b). Thus, there was no change from ORE to Fröhlich illusion with increasing velocity when pointing movements were used. Second, linear and circular trajectories were compared (Experiments 1a, b). The ORE was reliably obtained with both types of motion, but the effect of velocity was more pronounced with linear than with circular motion. Third, the experimental task was changed from absolute to relative judgements. A clear-cut difference was observed. The ORE occurred with pointing movements (Experiment 1a), but not with relative judgements (Experiments 2, 3). Conversely, the Fröhlich illusion was absent with pointing movements, even at high velocities (Experiment 1b), but it was clearly present with relative judgements at high target velocities (Experiment 2). Further, the effect of velocity with pointing and relative judgements was different: Increasing target velocity in the slow range increased displacement in the direction opposite to motion with pointing, whereas no displacement was found with high velocities. In contrast, increasing velocity in the fast range increased displacement in the direction of motion with relative judgements, whereas no displacement was found with slow velocities. Fourth, there may be some instances when tasks requiring visual short-term memory dissociate from purely perceptual tasks. In Experiment 3, displacement in the direction of motion was observed when the initial position had to be maintained in short-term memory but not when a perceptual comparison was possible. However, no such difference was noted in Experiment 2, which may be explained by the different methods used in Experiment 3.

Caveats

The present experiments showed that the choice of experimental task affects localization performance. Pointing judgements at slow velocities produce onset repulsion, whereas relative judgements at high velocities result in the Fröhlich illusion. One may object to this conclusion that the retention interval in the two tasks was not exactly matched. Although the mouse cursor appeared at the same temporal offset as the reference stimulus (500 ms after target disappearance), moving the mouse cursor may take more time than the relative judgement procedure. Two arguments may refute this objection. First, when pointing movements to the first position were initiated after a variable interval of 0–10 s, there was a slight decrease in the ORE over time (Thornton 1999), but the sign of the displacement did not change. Second, Experiment 3 showed that if there was a time course with relative judgements at all, its direction was opposite to what was found in pointing movements: In Experiment 3, a bias in the direction of motion occurred with a retention interval of 500 ms that was not observed in the perceptual condition with a zero retention interval. In Experiment 2, only a small numerical difference between perceptual and memory conditions was found.

Functional considerations

The present experiments show that during pointing movements toward the initial position of a slowly moving target, an error opposite to the direction of motion occurred. This error did not obtain with relative judgements. Rather, an error in the direction of motion was observed with relative judgements at high target velocities. Presumably, relative judgements are more pure measures of perception or memory, as they do not require motor action. A possible reason for displacement in the direction opposite to motion with pointing may be overcompensation for target motion during pointing movements: Under natural conditions, there is a high pressure on pointing or grasping movements to be accurate because misguided movements may be harmful. Therefore, it is possible that the brain compensates for potential errors in perception when pointing toward positions in space. When confronted with the task of localizing the first position of a moving stimulus, it may try to avoid the obvious error of pointing toward later positions of the target. To this end, the brain has to consider the fact that the target moved after the first position was presented. Possibly, the brain occasionally overcompensates for target motion after stimulus onset, in particular when slow velocities are involved. Overcompensation results in errors opposite the direction of motion. This hypothesis fits with the observation that the only study using free pointing (which was not entirely the case in Müsseler and Aschersleben 1998; Kerzel and Müsseler 2002) produced onset repulsion (Thornton 2002).

Further, the present results question the view that pointing movements have access to more veridical spatial information than relative judgements (Bridgeman et al. 1981, 1997). In fact, pointing movements were shown to be less accurate than relative judgements in some conditions. However, the present results support the notion of distinct processes or representations subserving motor actions and cognitive judgements (Goodale and Milner 1992).

Future research

It would be interesting to see how other forms of tasks behaved in the present experimental setup. In the present study, absolute judgements were confined to pointing by moving a mouse cursor. If the hypothesis of overcompensation was correct, other forms of manual pointing such as moving the hand towards the initial target position on the screen would be expected to show the same onset repulsion. The predictions for other forms of absolute judgements, for instance as eye movements, are less clear. If observers were asked to look at the first position of a moving target, it may be that onset repulsion was not obtained. The reason is that eye movements are not subject to the same ecological constraints as hand movements. The eye may wander about quickly and misguided eye movements are less harmful than misguided hand movements. Also, other forms of relative judgements may be employed. For instance, the initial position may be compared to an internal standard that is never shown, but has to be computed from the target positions that are shown in a training phase (e.g., McKee et al. 1986). With this method, a memory-based reference is compared to a perceptual target. As differences between memory and perception have been confirmed (see Experiment 3), the results from such a procedure would be interesting.

In sum, a localization error in the direction opposite to motion occurred when observers were asked to point toward the first position of stimulus moving at slow or medium velocity (<20°/s). A possible explanation is that when pointing toward positions in space, the brain compensates for possible errors, such as missing the first position. Overcompensation and mislocalization in the direction opposite to motion may result. No displacement in the direction opposite to motion was found when relative judgements were used. Rather, the first position was displaced in the direction of motion with fast velocities (>20°/s).

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