PERGAMON

Vision Research 42 (2002) 181–189

Vision Research

www.elsevier.com/locate/visres

Effects of stimulus material on the Fröhlich illusion

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Received 20 March 2001; received in revised form 7 July 2001

Abstract

In the Fröhlich illusion, judgements of the first position of a moving object are typically displaced in the direction of motion. The illusion has been obtained with linear motion of a small target, and with rotary motion of a spatially extended line. We compared judgements of the initial orientation of a small dot and a line that rotated around the point of fixation. The illusion was absent with the dot, whereas it was reliably obtained with the line. When the density of the line was reduced to two dots, the illusion persisted. However, the illusion was absent when a half-line extending to only one side from fixation was presented. We discuss the results with respect to two attentional accounts of the Fröhlich illusion and an account based on spatiotemporal integration. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Motion; Localization; Space perception; Attention; Illusion

1. Introduction

When observers are asked to report the first position of a moving stimulus, they typically mislocalize the first position in the direction of motion. The localization error was discovered in the first half of the last century and is referred to as Fröhlich illusion (Fröhlich, 1923). In the last decade, interest in the effect has resurged, and a number of studies have been conducted to explore the phenomenon. In the present paper, we show that the choice of stimulus influences the size of the Fröhlich illusion.

Examination of the stimulus material shows large differences between previous studies on the Fröhlich illusions. In a study by Müsseler and Aschersleben (1998), fast linear motion (14.3 and $44° s^{-1}$) of a small target ($0.5° \times 1°$) was used. The target either moved away from central fixation (fugal), or towards central fixation (petal). Target motion was horizontal along a line passing through the point of fixation. In polar coordinates with the point of fixation as origin, the stimulus in the study showed variation of target radius, but not azimuth.

Another study using slow linear motion produced conflicting results. Thornton (in press) reported displacement opposite the direction of motion when observers judged the onset of a slowly moving target (3–$15° s^{-1}$). The target moved vertically or horizontally, and the reverse Fröhlich illusion was larger with upward and leftward motion.

Kirschfeld and Kammer (1999) replicated the Fröhlich illusion with a line (18.6°) that rotated about its center. Observers perceived the line not when it became physically visible ($\alpha = 0°$), but after a rotation of $\alpha = 60°$. At a velocity of rotation of 1.5 r.p.s., this corresponds to a temporal delay of about 110 ms. In polar coordinates with the point of fixation as origin, the stimulus in the study showed variation of azimuth, but not of target radius. Further, as observers fixated the center of the rotating line, the stimulus extended along two opposing sides with respect to the fovea. In contrast, the stimuli used in the other two studies were presented on either side of the point of fixation, but never on both sides at the same time, and moved toward or away from the point of fixation.

In the first experiment, we asked observers to judge the initial orientation of a line or a single dot that rotated about the point of fixation. Thereby, we combined stimuli used in previous studies. In addition to a rotating line used by Kirschfeld and Kammer (1999), we presented an isolated target as used by Müsseler and

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PII: S0042-6989(01)00271-1

Aschersleben (1998) and Thornton (in press) that moved on a circular trajectory. Note that studies using isolated targets produced conflicting results: In Müsseler and Aschersleben (1998), a Fröhlich illusion was observed, whereas in Thornton (in press) the opposite effect was reported. So far, the results of the different studies have not been related to the choice of stimulus material. However, we find pronounced differences between different types of stimulus material. With a single rotating dot, we found the Fröhlich illusion to be much smaller than with a spatially extended line. This difference was explored in six experiments. Experiments 1a and 1b established a reduction of the Fröhlich illusion with a single rotating dot compared to a rotating line and confirmed that the reduction of the Fröhlich illusion with the single dot was not due to eye movements. Experiment 2 varied target radius and target size in the single dot condition to make the tangential velocity comparable to previous studies. In Experiments 3 and 4, the appearance of the line was varied. In Experiment 3, the number of dots constituting the line and their eccentricity was changed, and in Experiment 4, a half-line was compared to a single dot. Finally, Experiments 5 and 6 showed that there were cueing benefits with the single dot compared to the single line. Both reaction times and orientation judgements showed an effect of cueing. The results are then discussed with reference to two current theories of the Fröhlich illusion. An attentional explanation appears to handle the data better than an explanation based on postdiction.

2. General methods

2.1. Participants

Students at the Ludwig-Maximilians University of Munich participated for pay. All reported normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

2.2. Apparatus and stimuli

The stimuli were created using a Matrox Millenium graphics card on a 21″ (diagonal) screen with a refresh rate of 96 Hz and a resolution of 1280 (H) $\times$ 1024 (V) pixels. The background was white (76 cd/m^2), and a filled black dot with a diameter of 0.1° presented in the center of the screen served as fixation point. Filled black dots (14 cd/m^2) with a diameter of 0.17° were used to form the target stimuli (cf. Fig. 1). The line consisted of 27 equally spaced dots and had a length of 19.2°. The center dot was at the same position as the fixation point. The radius of the single dot was fixed at 3.7° from the fixation point in most experiments. The line and the dot were rotated around the fixation point at velocities of

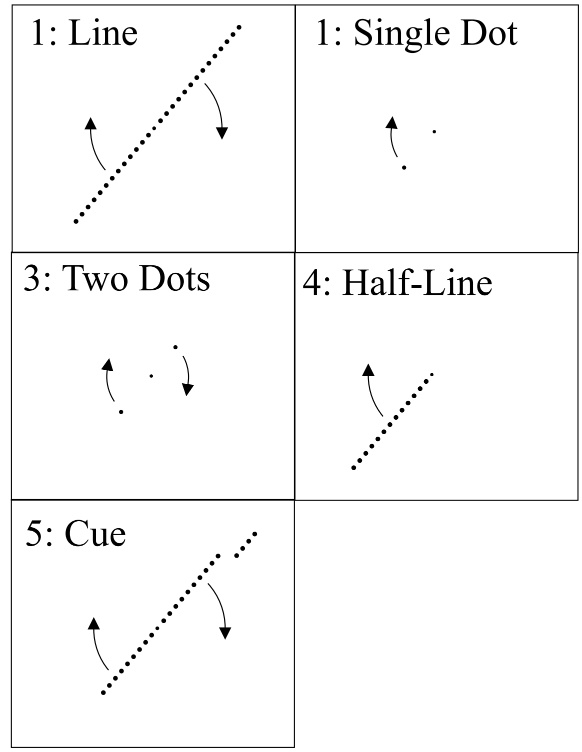

Fig. 1. Stimuli used in the experiments. The line and the single dot were used in Experiment 1. A 'line' consisting of only two dots (plus fixation point) was presented in Experiment 3. Experiment 4 made use of the half-line. A cue preceded the line in Experiment 5.

0.5 or 1 r.p.s. The target appeared at a random orientation, and moved for a randomly determined interval of 200–300 ms. The horizontal position of the left eye was monitored with a head-mounted, infrared, light-reflecting eyetracker (Skalar Medical B.V., IRIS Model 6500) in most of the experiments that involved presentation of a single dot. Fixation had to be maintained within 1° of the fixation point.

2.3. 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 rotate. Observers' task was to indicate where the target had appeared. After the target had vanished, the subject adjusted a freely turnable stimulus that was identical to the target (i.e., either a line or a dot) until it appeared to be at the initial orientation of the target. For the adjustment procedure, the mouse was used. Participants initiated and terminated a trial by pressing the left mouse button. No feedback was provided. When a fixation error occurred, an error message appeared and the trial was repeated in the remainder of the experiment. The different conditions were randomly interleaved. Data collection took place in one or two sessions. Preliminary analysis showed that session number (i.e., practice) did not change the pattern of results.

2.4. Data treatment

The angular deviation between the judged initial orientation and the actual initial orientation was calculated. Positive deviations indicate that the judged initial orientation was displaced from the actual orientation in the direction of rotation, whereas negative deviations indicated displacement opposite to the direction of rotation. Angular deviation, α, was also converted into temporal delays ($\Delta t = \alpha * 360^{-1} * \text{r.p.s.}^{-1}$). Positive deviations and delays indicate a Fröhlich illusion. Main effects and interactions of the experimental manipulations were evaluated by within-subjects ANOVAs. Means of selected experimental conditions were compared by *t*-tests. For the *t*-tests, only the level of significance was reported.

3. Experiment 1a

In this experiment localization of a spatially extended rotating line was compared with localization of a spatially confined rotating dot.

3.1. Method

Either the line, or the single dot appeared and rotated at a velocity of either 0.5 or 1 r.p.s. This corresponds to a tangential velocity of 11.6 and 23.2° s^{-1} (in degrees of visual angle). A total of 120 repetitions were collected for each of the four combinations of speed of rotation and stimulus type. Fixation was not monitored. Eight students participated.

3.2. Results

3.2.1. Angular deviation

A two-way ANOVA (two velocities × two stimulus types) revealed a significant effect of velocity, indicating that the angular deviation was larger with fast rotation compared to slow rotation (6° vs. 12°), $F(1,7) = 17.53$, $p < 0.005$. Also, the localization error was larger when a line was presented compared to the single dot (−2.5° vs. 20.5°), $F(1,7) = 47.31$, $p < 0.0005$. The interaction of velocity and stimulus type reached significance, $F(1, 7) = 39.65$, $p < 0.0005$, showing that the increase with velocity was present with the line (15° vs. 26°, $p < 0.0001$), but not with the single dot (−2.6° vs. −2.5°, $p > 0.9$). *T*-tests showed that the angular deviation was

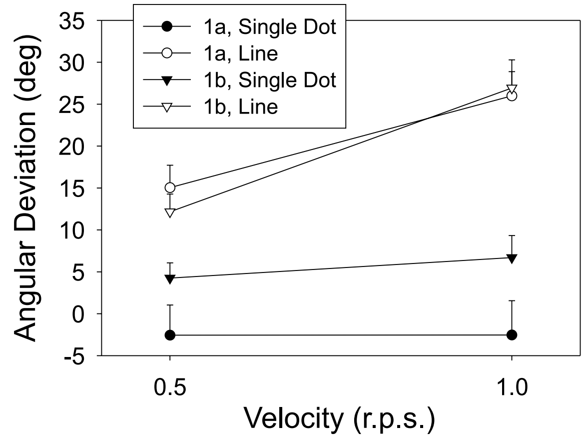

Fig. 2. Angular deviation between actual and judged initial orientation as a function of velocity of rotation and stimulus type (line or single dot) in Experiments 1a and 1b. Error bars indicate the standard error of the mean (between subjects).

significantly different from zero only in conditions with the line (*p*s < 0.001; cf. Fig. 2).

3.2.2. Temporal delay

A two-way ANOVA revealed a significant effect of stimulus type, $F(1,7) = 40.29$, $p < 0.0005$, indicating that the temporal delay was smaller with the dot than with the line (−5 vs. 39 ms). No other effects reached significance (*p*s > 0.1). *T*-tests showed that the delay was significantly different from zero with the line ($p < 0.0005$), but not with the single dot ($p > 0.5$).

3.3. Discussion

A Fröhlich illusion was obtained when observers were asked to judge the first orientation of a rotating line. Consistent with previous reports (Müsseler & Aschersleben, 1998), the deviation of the judged orientation from the actual initial orientation increased with velocity. Unlike in Kirschfeld and Kammer (1999), the temporal delay was the same for both velocities. Compared to the 110 ms delay observed by Kirschfeld and Kammer, the effect size here is relatively small (39 ms), but this difference may be explained by the different contrast and luminance of their stimuli (line: 50–100 cd/m^2, background: 2–4 cd/m^2), and by the different presentation mode (analog display). The size of the Fröhlich illusion in the present experiment is well within the range of temporal delays (24–134 ms) reported by Müsseler and Aschersleben (1998, Experiment 1) who also used black (19 cd/m^2) on white (41 cd/m^2) displays. With the rotating dot, no indication of the Fröhlich illusion was obtained, and no effect of velocity on the judged orientation of the stimulus was noted. It may be possible that stimulus velocity was too slow to obtain the illusion with a single dot (tangential velocities of only 11.6 and 23.2° s^{-1}). However, there was no displacement opposite the direction of motion as with slow linear motion (Thornton, in press).

4. Experiment 1b

In Experiment 1a, localization of a spatially extended rotating stimulus was compared with localization of a spatially confined stimulus. It may have been the case that involuntary saccades to the single dot occurred that eliminated the illusion. In contrast, the rotating line may have elicited fewer saccades because it did not provide the oculomotor system with a clear saccade target. To rule out this hypothesis, we reran some of the observers from Experiment 1a and monitored eye fixation.

4.1. Method

The experiment was as Experiment 1a with the following exceptions. Fixation was monitored. Fixation errors occurred in 1.6% of the trials. The diameter of the filled black dots was increased to 0.3°. Four observers from Experiment 1a and three fresh observers participated. 60 repetitions of each of the four combinations of velocity and stimulus type were collected.

4.2. Results

4.2.1. Angular deviation

A two-way ANOVA (two velocities × two stimulus types) revealed that angular deviation increased with velocity (8.2° vs. 16.8°), $F(1,6) = 80.72$, $p < 0.0001$, and was larger with the line than with the single dot (5.5° vs. 19.5°), $F(1,6) = 33.98$, $p < 0.005$. Also, the interaction between velocity and stimulus type reached significance, $F(1,6) = 41.12$, $p < 0.001$, showing that the effect of velocity was stronger with the line (12.2° vs. 26.9°, $p < 0.0001$) than with the single dot (4.3° vs. 6.7°, $p = 0.12$). T-tests showed that the angular deviations in the two velocity conditions were marginally different from zero with the single dot ($0.04 < ps < 0.06$), and significantly different from zero with the line ($ps < 0.005$; cf. Fig. 2).

4.2.2. Temporal delay

A two-way ANOVA revealed an effect of stimulus type, $F(1,6) = 31.97$, $p < 0.005$, showing that the delay was larger with the line than with the single dot (36 vs. 11 ms). Stimulus type interacted with velocity, $F(1,6) = 13.71$, $p < 0.05$. With the line, the temporal delay tended to be smaller with the slow compared to the fast velocity (34 vs. 37 ms, $p = 0.07$), whereas no difference was obtained with the single dot (12 vs. 9 ms, $p = 0.36$). T-tests showed that the delay in the two velocity conditions was marginally different from zero with the single dot ($0.04 < ps < 0.6$), and significantly different from zero with the line ($ps < 0.005$).

4.3. Discussion

We were able to replicate the pattern of results obtained in Experiment 1a: The Fröhlich illusion was strongly reduced with the single dot, and the effect of velocity on the angular deviation was only present for the rotating line. Therefore, eye movements cannot explain the reduction of the illusion with the single dot.

5. Experiment 2

The relatively small Fröhlich illusion with rotation of a single dot observed in Experiments 1 is somewhat at odds with previous reports. In previous studies (Müsseler & Aschersleben, 1998), a reliable illusion was observed with small isolated targets that moved at a velocity of up to $44° s^{-1}$. Thus, it may have been that the tangential velocity of the single dot in the present study was too small (i.e., 11.6 and $23.2° s^{-1}$). To investigate effects of tangential velocity, the eccentricity of the single dot was varied. For a given rotational velocity ω, the tangential velocity v, of a stimulus at a radius r, varies as a function of $v = \omega * r$. For the rotating line, the maximal tangential velocity, $v_{max} \approx 60° s^{-1}$, occurred with elements having $r = 9.6°$ and $\omega = 1$ r.p.s. The minimal tangential, $v_{min} \approx 2.3° s^{-1}$, velocity occurred with elements having $r = 0.7°$ and $\omega = 0.5$ r.p.s. In the present experiment, the eccentricity of the dot was varied, such that tangential velocities similar to those of single elements within the line were obtained. If there was a Fröhlich illusion with a spatially confined stimulus and rotational motion, as the marginally significant effects in Experiment 1b suggest, then we expect the Fröhlich illusion to reappear in the present experiment, and we expect the size of the illusion to increase with target eccentricity (given that tangential velocity increases).

5.1. Method

Only the single dot was presented. Its diameter varied randomly between 0.17°, 0.3°, and 0.6°. The target rotated around the fixation point at eccentricities of 1.9°, 3.8°, 5.8°, 7.7°, and 9.6°. Two velocities were used (0.5 and 1.0 r.p.s.). 10–20 repetitions of the 30 conditions resulting from the factorial combination of velocity, diameter, and eccentricity were collected. Fixation was monitored (2% fixation errors). Six fresh and two observers from previous experiments participated.

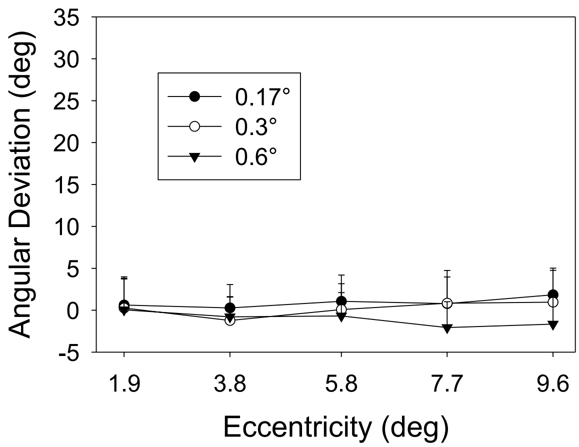

Fig. 3. Angular deviation between actual and judged initial orientation as a function of target eccentricity and target size in Experiment 2. A single dot was presented. Error bars indicate the standard error of the mean (between subjects).

5.2. Results

5.2.1. Angular deviation

A three-way ANOVA (two velocities × three diameters × five eccentricities) revealed that the angular deviation decreased with increasing diameter, $F(2,14) = 4.29$, $p < 0.05$, and was 1.5°, 0.8° and −0.5° with diameters of 0.17°, 0.3°, and 0.6°, respectively. None of the other factors reached significance (*p*s > 0.2). Overall, the angular deviation did not differ from zero ($p > 0.9$; cf. Fig. 3).

5.2.2. Temporal delay

A three-way ANOVA revealed a marginally significant effect of velocity, $F(1,7) = 5.04$, $p = 0.0595$. The delay tended to be larger with the small than with the fast velocity (5 vs. −1 ms). The effect of stimulus diameter reached significance, $F(1,7) = 3.75$, $p < 0.05$. The delay was 3, 1, and −2 ms for stimulus diameters of 0.17°, 0.3°, and 0.6°, respectively. T-tests showed that the temporal delay was not significantly different from zero (*p*s > 0.6).

5.3. Discussion

There was no indication of a Fröhlich illusion and little evidence for effects of rotational and tangential velocity (eccentricity). The results confirm that the Fröhlich illusion does not obtain with rotational motion of an isolated target. The only significant effect was due to target size. It may be that localization with the larger targets was easier and more accurate, resulting in angular deviations closer to zero. Thus, it may be ruled out that the low tangential velocity of the target stimulus was responsible for the reduction of the Fröhlich illusion. In fact, in the present experiment the Fröhlich illusion seems to be absent with the rotating dot.

6. Experiment 3

The purpose of Experiment 3 was to investigate whether properties of the line, in particular its density and extent, influence the Fröhlich illusion. One may hold the hypothesis that the illusion decreases with the number of elements in the display and with the spatial extent of the line. Therefore, the line was made up of only two dots (in addition to the fixation point), that were presented on opposing sides of central fixation. The dots were at an equal eccentricity from fixation, and their eccentricity was varied. Thus, the difference between the 'line' and the single dot condition in Experiment 1 was an additional element on the opposite side of fixation.

6.1. Method

The line was reduced to only three elements (including the fixation dot, cf. Fig. 1). On each side of the fixation point, a single black dot with a diameter of 0.17° was presented at five different eccentricities. Eccentricity varied between 1.9°, 3.8°, 5.8°, 7.7°, and 9.6°. Two velocities were presented. 30 repetitions of the 10 combinations of velocity and eccentricity were collected. Fixation was not monitored. Six fresh and two observers from previous experiments participated.

6.2. Results

6.2.1. Angular deviation

A two-way ANOVA (two velocities × five eccentricities) revealed that there was an effect of velocity, $F(1,7) = 34.39$, $p < 0.005$. The angular deviation increased with velocity (12.3° vs. 24.1°). No other effect reached significance (*p*s > 0.1). T-tests showed that the angular deviation was different from zero for the slow ($p < 0.02$) and the fast velocity ($p < 0.005$; cf. Fig. 4).

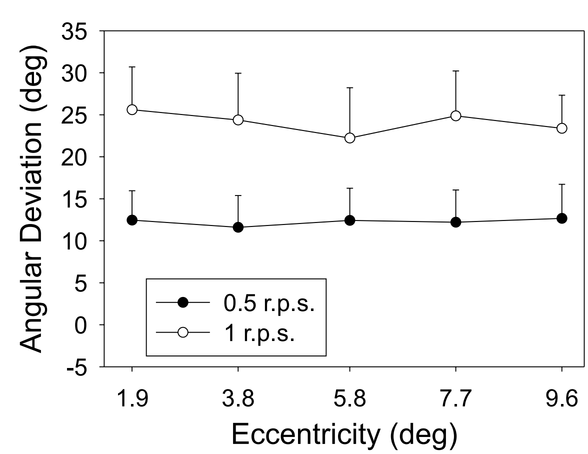

Fig. 4. Angular deviation between actual and judged initial orientation as a function of target eccentricity and velocity of rotation in Experiment 3. Two dots were presented. Error bars indicate the standard error of the mean (between subjects).

6.2.2. Temporal delay

A two-way ANOVA revealed no significant effects (ps > 0.3). A t-test showed that the temporal delay was significantly different from zero (34 ms, $p < 0.01$).

6.3. Discussion

The Fröhlich illusion was replicated with a line that consisted of only two dots (plus fixation point). Eccentricity did not have an influence on the illusion, as has been already found with linearly-moving stimuli (Müsseler & Aschersleben, 1998, Experiment 3). As the spatial extent of the line varied with the eccentricity of the two dots, one may conclude from this experiment that the spatial extent of the line is not crucial in bringing about the visual illusion. Also, the number of dots constituting the line did not affect the illusion. With only two dots, the size of the illusion was comparable to that with the full line.

7. Experiment 4

If the presentation of stimuli on opposing sides of the fixation point was crucial for the occurrence of the Fröhlich illusion with rotating stimuli, the absence of the Fröhlich illusion is predicted when a line only extends into one direction from central fixation. In this case, the extent of the stimulus is larger than the single dot, and quite comparable to the eccentricity of the two dots in Experiment 3. Further, the density of the half-line was similar to that used in Experiment 1.

7.1. Method

Either one half of the complete line, or a single dot at an eccentricity of 3.7° was presented (cf. Fig. 1). The half-line consisted of 14 dots and extended 9.6° from the fixation point. Two velocities were presented. 60 repetitions of the four combinations of velocity and stimulus type were collected. Fixation was monitored (2.8% fixation errors). Eight fresh and one observer from a previous experiment participated.

7.2. Results

7.2.1. Angular deviation

A two-way ANOVA (two velocities × two stimulus types) revealed that there was an effect of stimulus type, $F(1,8) = 5.93$, $p < 0.05$. The angular deviation was larger with the half line, compared to the single dot (3.5° vs. 1.7°). No other effect reached significance (ps > 0.2). T-tests showed that the angular deviation was neither different from zero with the half-line nor with the single dot (ps > 0.3; cf. Fig. 5).

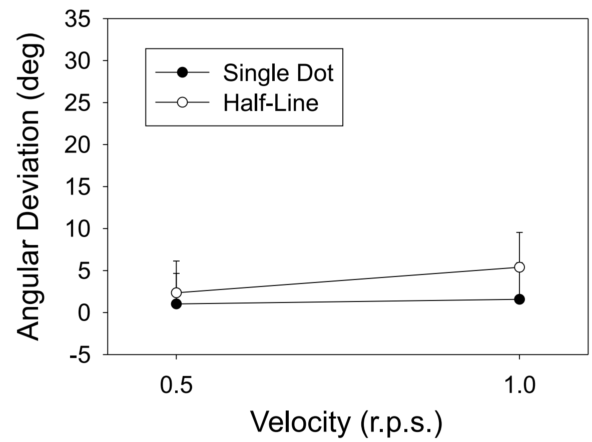

Fig. 5. Angular deviation of actual and judged initial orientation as a function of stimulus type (half-line or single dot) and velocity of rotation in Experiment 4. Error bars indicate the standard error of the mean (between subjects).

7.2.2. Temporal delay

A two-way ANOVA did not reveal any significant effects (ps > 0.1). A t-test showed that the temporal delay did not differ from zero (5 ms, $p > 0.5$).

7.3. Discussion

The Fröhlich illusion was significantly larger with the half-line than with the single dot, however, this effect was numerically small. More importantly, the displacement was not significantly different from zero with the half-line. Together with the finding that the illusion does not depend on the eccentricity of the line or the number of elements in the line, the absence of Fröhlich illusion with a half-line suggests that the Fröhlich illusion with rotating stimuli only occurs with stimuli that extend to both sides of fixation.

8. Experiment 5

So far, we have established a clear-cut difference between the localization of the initial orientation of a spatially extended stimulus (line) and a spatially confined stimulus (single dot). It may be argued that a major difference between these two stimulus types is their ability to summon focal attention. Space-based views of attentional selection hold that the size of an attentional area is inversely related to the concentration of attentional resources (Barriopedro & Botella, 1998; Handy, Kingstone, & Mangun, 1996). If the distribution of focal attention was involved in the effect, then attentional 'zooming' induced by cueing should affect the illusion. In previous studies in which the initial position of a linearly moving target was cued, the Fröhlich illusion was reduced (Müsseler & Aschersleben, 1998; Whitney & Cavanagh, 2000). The present experiment examined whether a similar effect can be observed for the rotating line.

8.1. Method

The extent of the line was reduced by showing only the inner 18 from 26 possible dots (cf. Fig. 1). This corresponds to a radius of 4.05°. 124 ms before the onset of the line, a cue was presented for 62 ms. The cue consisted of four dots presented on one side of the fixation point. Their spacing was equal to that of the line, and the closest dot was at 4.5° from fixation. They were positioned on a line passing through the fixation point. The orientation of this virtual line was random within ±10° of the initial orientation of the target line. When a cue was presented, observers were asked to adjust a half-line to the orientation of the cued side of the line. When no cue was presented, observers were asked to adjust the full line to the orientation of the target line. As in the previous experiments, two velocities were presented. 60 repetitions of the four combinations of velocity and cue presentation (present, absent) were collected. Fixation was monitored (0.4% fixation errors). Six fresh and two observers from previous experiments participated.

8.2. Results

8.2.1. Angular deviation

A two-way ANOVA (two velocities × two cue presentations) revealed that the angular deviation increased with velocity (10.9° vs. 17.6°), $F(1,7) = 17.63, p < 0.005$. Further, the angular deviation was smaller when a cue had been presented (8.5° vs. 20°), $F(1,7) = 23.41$, $p < 0.005$. Cue presentation and velocity interacted, $F(1,7) = 7.23$, $p < 0.05$, indicating that the effect of velocity was larger without a cue (15.4° vs. 24.7°, $p < 0.005$) than with a cue (6.4° vs. 10.6°, $p < 0.02$). T-tests showed that the angular deviation was different from zero for the slow and the fast velocities with and without a cue (ps < 0.05; cf. Fig. 6).

8.2.2. Temporal delay

A two-way ANOVA showed that the temporal delay was reduced with the cue (16 vs. 38 ms), $F(1,7) = 20.66$, $p < 0.005$. No other effects reached significance (ps $>$ 0.1). T-tests confirmed that the angular deviation was different from zero with and without cue (ps < 0.02).

8.3. Discussion

Consistent with previous studies, the Fröhlich illusion was reduced when one part of the line was cued. In previous studies, effects of cueing have been attributed to attentional mechanisms (Müsseler & Aschersleben, 1998).

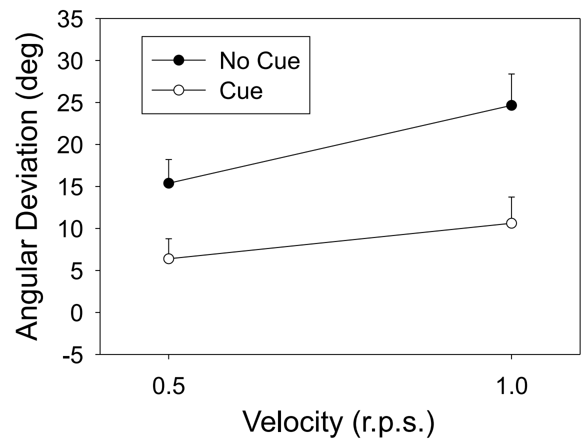

Fig. 6. Angular deviation between actual and judged initial orientation as a function of cue presentation (present, absent) and velocity of rotation in Experiment 5. Error bars indicate the standard error of the mean (between subjects).

9. Experiment 6

To measure the allocation of attention with the line and the dot, we used a speeded probe discrimination task. A cue, either a line or a single dot, preceded a probe by approximately 100 ms. The probe, an '×' or an '+' indicating a left or right keypress, appeared at a fixed radius that corresponded to the radius of the single dot, and with a variable azimuth that corresponded to the azimuth of the line or single dot. Thus, the probe position was either cued by a single dot, or by an element within the line. If the dot was a more efficient focal attractor than the line, we would expect faster responses with the dot cue than with the line cue.

9.1. Method

Either the complete line cue consisting of 27 filled dots, or a single dot cue (eccentricity of 3.7°) in addition to the fixation dot was presented at a random orientation for 52 ms. After presentation of the cue, a blank interval of 52 ms followed during which only the fixation dot was visible. Then, the probe stimulus was presented at the same orientation as the cue for another 52 ms. The eccentricity of the probe stimulus was 3.7° with the line and the dot–cue. Thus, the probe was presented at the same position as the cue in the dot–cue condition, and at a fixed position along the line in the line–cue condition. The symbols '×' and '+' were used as probe stimuli. They were identical in size and measured 1.2° × 1.2°. The black lines used to draw the symbols were 0.3° thick. Subjects had to discriminate the probe stimuli by pressing a left or right response key as fast and as accurately as possible. The stimulus-response mapping was counterbalanced across subjects.

120 repetitions of the four combinations of cue and probe types were collected. Response latencies shorter than 100 ms and longer than 1000 ms were considered anticipations and missing trials and repeated in the remainder of the experiment. Fixation was monitored. Six fresh and two observers from previous experiments participated.

9.2. Results

Anticipations, missing trials, and trials with fixation errors were excluded from the analysis (2.6%). By *t*-test, the percentage of choice errors did not differ between conditions with a dot–cue and a line–cue (2 vs. 3%), $p > 0.4$. Responses were faster by 32 ms with a dot–cue compared to a line–cue (516 vs. 548 ms), $t(7) = 26.17$, $p < 0.0001$.

9.3. Discussion

Responses were faster with the single dot as a cue compared to the line as a cue. Therefore, the single dot may be considered a more efficient attractor of focal attention. Also, the size of the reaction-time difference (about 30 ms) corresponds to the size of the perceptual delay difference between the onset of the line and the single dot derived from the perceived angular deviations in Experiment 1 which points to attentional factors as an explanation of the difference (see discussion). A possible objection to the present experiment is that metacontrast masking from surrounding dots made probe discrimination more difficult in the line–cue condition. In a control experiment, we compared reaction times when a dot–cue was presented with reaction times when two dots surrounded the probe. There was a nonsignificant 4 ms reaction time advantage for the two-dot condition (499 vs. 503), $t(7) = 1.3$, $p = 0.23$, and no effect on choice errors (2% vs. 2.2%), $p > 0.7$. Thus, masking from the surrounding dots does not explain the cueing benefit with the single dot.

10. General discussion

In the present study, we examined effects of stimulus material on the Fröhlich illusion. In Experiment 1, we found a reliable Fröhlich illusion when a spatially extended stimulus (a line of 19.2° diameter) rotated about its center. With a spatially confined stimulus (smaller than 1°), no indication of a Fröhlich illusion was obtained. Eye movements to the isolated target did not account for this difference. Experiment 2 showed that the absence of a Fröhlich illusion with the spatially confined stimulus was not caused by the specific choice of stimulus diameter or stimulus eccentricity. Also, the illusion was absent across a wide range of tangential target velocities. Experiment 3 showed that the density of the line and its spatial extent did not change the size of the Fröhlich illusion. Experiment 4 demonstrated that the important difference between the line and the single dot was that stimulation occurred on opposite sides of central fixation in the former condition, but only on one side in the latter. When a half-line was presented, the illusion was absent. Experiment 5 showed that the Fröhlich illusion was reduced when the initial orientation of the target was cued. Reaction time data in Experiment 6 established that the single dot was a more efficient cue for shifts of attention than the line. In sum, the present experiments show that the important difference between the single dot and the line stimulus is that stimulation occurs on both sides of the central fixation points with the line. Differences in velocity, eccentricity, or density may not explain the absence of the Fröhlich illusion with the single dot.

10.1. Attentional models

Attentional accounts hold that the Fröhlich illusion is due to the lack of focal attention at the onset of stimulus motion. One attentional account of the Fröhlich illusion holds that the mislocalization is due to the time it takes to shift attention towards the moving object (Müsseler & Aschersleben, 1998). While the attention shift is underway, the stimulus moves away from its initial position, and only a later portion of the trajectory reaches visual awareness. Another attentional account of the Fröhlich illusion holds that the error results from the interplay of visual focal attention and metacontrast (Kirschfeld & Kammer, 1999). Because the initial positions are masked by subsequent positions along the trajectory, and attention does not enhance processing of the first position, the first part of the trajectory is missed. A common prediction of the two models is that more efficient allocation of attention to the stimulus should reduce the illusion.

Previous studies showed that double cueing on both sides of fixation results in less efficient allocation of attention to the cued locations than cueing on only one side (Posner & Cohen, 1984). This finding was replicated in our Experiment 5 in which a line was a more efficient cue than a single dot. Also, the reduced cueing benefits with double cues are consistent with our finding that the occurrence of the Fröhlich illusion with rotating stimuli depends on the stimulus appearing on both sides of fixation. However, there does not appear to be a metric relationship between the attentional focus and localization. When the extent of the line was varied in Experiment 5, a zoom lens conception of attention (Eriksen & St. James, 1986) would hold that attention is less focussed with a larger stimulus extent, such that a metric relation between attention and localization would predict an increase of the Fröhlich illusion with stimulus diameter. This prediction was not confirmed. Rather, the present results suggest that only the direction of the shift modulates the illusion. If a shift of attention in a single direction is possible, the illusion is absent. In contrast, if attention is divided between two opposing sides, the illusion occurs. Therefore, attentional mechanisms offer a plausible, but not fully satisfactory explanation of the effect.

10.2. Postdiction

A third account of the Fröhlich illusion does not explicitly address effects of attention. Rather, the postdiction model assumes that spatiotemporal integration is responsible for the illusion (Eagleman & Sejnowski, 2000a). The model holds that the visual system has an internal model of the external world which partially results from information integrated in a recent time window. When an unpredicted event occurs, the internal model is devalued, and a new integration process is started. For instance, the onset of a moving stimulus may reset the internal model completely, such that the window of integration is temporally offset from the onset. Building the internal model from information available after the onset shifts the perceived position of moving objects beyond their onset. However, devaluation of the internal model is not all or none, but depends on at least two factors: salience of the stimuli (Eagleman & Sejnowski, 2000b; Purushothaman, Patel, Bedell, & Ogmen, 1998), and predictability of the resetting event (Eagleman & Sejnowski, 2000b; Whitney & Cavanagh, 2000). The lower the salience of the resetting stimuli and the better an event can be predicted, the more does the visual system rely on the internal model and the smaller is the temporal offset of the window of integration.

To account for the present findings the postdiction model would have to assume differences in saliency between the line and the single dot. Although a strict operational definition of saliency is missing, one may assume that a large stimulus is more salient than a small stimulus. A more salient stimulus would reset the integration process more completely than a less salient stimulus and would produce a larger Fröhlich illusion. Such an argument would account for the differences between the line and the dot in terms of their differences in size. However, Experiments 3 and 4 showed that the size of the stimulus only plays a minor role. Rather, the data suggest that the important difference between a rotating line and a rotating dot is that the line occupies opposing sides of fixation, whereas the dot does not.

Acknowledgements

We wish to thank S. Bauer, M. Mench, T. Schönenberg, and V. Schradi for helping to collect the data.

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