Dissociations in the Timing of Stationary and Moving Stimuli

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When participants are asked to localize the 1st position of a moving stimulus, they mislocalize it in the direction of the movement (Fröhlich effect; F. W. Fröhlich, 1923). This mislocalization points to a delay in the temporal sensation of a moving stimulus. However, the delay is in contrast to findings indicating a faster processing of moving stimuli. This potential dissociation was studied in 6 experiments. After establishing the effect spatially, different temporal tasks were examined under otherwise identical conditions. Simple as well as choice reaction times were shorter to moving than to stationary stimuli. Other tasks (choice reaction to structural features, temporal order judgment, and synchronization), however, produced opposite effects. Results support a view that the output of early stimulus processing directly feeds into the motor system, whereas the processing stages used, for example, for localization judgments are based on later integrative mechanisms.

Perceiving the initial phase of a moving stimulus is subject to several psychophysical distortions. For example, subjective estimates of velocity are larger and subjective estimates of temporal duration are smaller at the beginning of a movement with constant velocity (e.g., Mashhour, 1964; Rachlin, 1966; Runeson, 1974). As a consequence, when participants are presented with this movement they have the impression of a deceleration (i.e., a fast movement at the beginning that then slows down), whereas when they see a movement with a "natural" acceleration at the beginning they judge it as having a constant velocity. Another perceptual distortion, namely the effect that perceived velocity decreases with moving distance (e.g., Algom & Cohen-Raz, 1984, 1987; Mashhour, 1964; Müsseler & Neumann, 1992; Rachlin, 1966), might also be the result of the distortion at the initial phase of a movement. In those studies, constant velocity is used, which is perceived as being fast at the beginning. The influence of this overestimation is reduced with increasing moving distance, leading to an overall reduced perceived velocity (see Runeson, 1974).

Whereas the phenomena just described are observed over a wide range of velocities, the present research was concerned with an error that occurs mainly with rapid movements. When participants are asked to determine the first perceived position of a moving stimulus suddenly appearing on a screen, they typically do not localize it at the correct position but at some later position within the movement. Fröhlich (1923) was the first to study this effect systemati-

cally, so it is aptly termed the *Fröhlich effect*. The effect was amply discussed in the 1930s (e.g., by Fröhlich, 1923, 1925, 1929; Metzger, 1932; Müller, 1931; Piéron, 1935; Rubin, 1930) and was rediscovered in the 1990s (Kirschfeld & Kammer, 1999; Müsseler, 1987; Müsseler & Neumann, 1992; Neumann & Müsseler, 1990a; for a recent overview, see Müsseler & Aschersleben, 1998).

Fröhlich (1929) attributed the effect to the so-called "sensation time" (*Empfindungszeit*), that is, to the time needed to establish a central representation of a subjective "sensation." This sensation was considered to be a precondition for conscious perception, and because it takes time to generate such a sensation the perceived mislocalization occurs. However, Metzger (1932) already pointed out that the time to establish a sensation should not only influence the first position of the moving stimulus but also each part of the movement. Then, a moving stimulus should either not be perceived at all or each part of the movement should be perceived with a delay. In the latter case, a localization error should not occur; if an error does occur, it should be only a temporal one. Consequently, Metzger concluded that the Fröhlich effect reflects differences in processing times of the stimulus at the beginning relative to the later positions throughout the movement.

One possible reason for such processing-time differences is that they originate from a low-level process such as the motion-deblurring mechanism. When a stimulus moves across the retina, a large number of photoreceptors with their adjacent neurons are stimulated within the integration time of a neuron, but no motion blur is perceived. It has been suggested that motion-deblurring mechanisms aid the visual system in its analysis of the shape of retinally moving objects (e.g., Anderson & van Essen, 1987; Burr & Ross, 1986; Fahle, 1995; Morgan & Benton, 1989). Such a mechanism could prevent a blur by inhibiting signals adjacent to the actual object. Signals arriving later could act to inhibit signals arriving earlier. As at the beginning of a movement, the later-arriving signals inhibit the first parts of the movement, and as a consequence a mislocalization in the

direction of the movement results, thus producing the Fröhlich effect. One important implication is that the first positions of the stimulus are missed, which is indeed the case (see Müsseler & Aschersleben, 1998, Experiment 5).

Recently, we contrasted this low-level interpretation with an attentional account that is based on differences in processing times as well but extends it to more central mechanisms (Müsseler & Aschersleben, 1996, 1998; Neumann & Müsseler, 1990a). According to this account, the presentation of a visual stimulus initiates coding and attentional processes in parallel. Coding processes encompass all operations that serve to create an internal code of the stimulus including, for example, color, size, and location. Attentional processes consist of a shift of the attentional focus to the stimulus, that is, toward its approximate location. Only after this focus shift has been completed will the result of the coding processes be available for the participant's perceptual judgments. It is assumed that as a result of the coding processes the updating of an internal spatial map takes place and that this updating has a short latency compared with the time required for attentional processes. As only the state of the spatial map at the end of the focus shift is phenomenally available, changes of the stimulus that occur during the shift will go unnoticed, thus producing the Fröhlich effect. The advantage of this account is that it explains a broader range of findings observed with the Fröhlich effect paradigm (e.g., the effect that the size of the localization error is reduced if the moving stimulus is preceded by a valid cue; cf. Müsseler & Aschersleben, 1998, Experiment 4) as well as findings related to other perceptual phenomena such as the metacontrast or the tandem effect (Aschersleben, 1999; Aschersleben & Bachmann, 1999; Bachmann, 1984; Müsseler & Neumann, 1992; Neumann & Müsseler, 1990a; for an overview, see Bachmann, 1999).

According to any of these interpretations, the Fröhlich effect originates from a delay in the timing of the onset of a moving stimulus. This delay may result from early-vision mechanisms or from a more cognitive attentional shift, but in either case it is assumed that the first positions are skipped from subjective perception. Thus, the effect is not only a spatial but also a temporal error, and it represents the point in time the onset of the moving stimulus is perceived visually.

This perceived delay of the moving onset is reasonable from a perspective suggested by the Fröhlich effect. On the other hand, it is well-known that the visual system is sensitive to moving stimuli. Even cells at the cortical level, which respond preferably to moving stimuli, have shorter activation latencies than cells responding mainly to stationary stimuli. Neurophysiological studies differentiate between low spatial frequency channels, which are particularly sensitive to transient stimulations produced by onsets and offsets as well as by rapid motions of a stimulus, and high spatial frequency channels, which respond mainly in a sustained manner to slowly moving or stationary stimuli (Cleland, Levick, & Sanderson, 1973; Hoffmann, Stone, & Sherman, 1972; Tolhurst, 1973; for an overview, see Breitmeyer, 1992; Breitmeyer & Ganz, 1976). Differences in single-cell recordings between these two cell types amounted

to 50 ms, with the transient cells responding faster (Dow, 1974; Hoffmann et al., 1972).

There are also hints that these latency differences can be obtained in behavioral tasks; that is, simple reaction to moving stimuli seems to be faster than to stationary stimuli (Mashhour, 1964; Smeets & Brenner, 1995), and reaction time (RT) to movement onset is a decreasing function of stimulus velocity (Ball & Sekuler, 1980; Mashhour, 1964; Tynan & Sekuler, 1982). Unfortunately, these studies deviate in important aspects from the situation in which the Fröhlich effect is observed: In the study by Mashhour (1964), the RT to the sudden appearance of a stationary stimulus was compared with that to the movement onset of a stimulus already present on the screen (the same was true in the studies conducted by Sekuler and coworkers; Ball & Sekuler, 1980; Tynan & Sekuler, 1982). More critically, Mashhour observed the RT advantage for moving stimuli in only 6 of 10 participants. The study by Smeets and Brenner was concerned with relative movements; that is, the subjective velocity of the target was induced by a moving background·consisting of 40 lines on which the target (a spider) had to be detected. Furthermore, in most of these studies mean simple reaction times (SRTs) were high (between 300 and 400 ms).

In summary, neurophysiological and (at least some) behavioral evidence points to a faster processing of moving stimuli as compared with stationary stimuli, whereas the Fröhlich effect suggests a delay in perceiving the onset of moving stimuli. One possible cause for this discrepancy to occur is that different tasks require different amounts of processing of the visual stimulus. Therefore, the aim of the present research was to tap these processing stages and to establish a possible dissociation between different behavioral tasks in the timing of stationary and moving stimuli. More specifically, the findings mentioned earlier allowed us to expect dissociations in the performances in perceptual judgment tasks and in simple motor tasks between stationary and moving stimuli. Such dissociations are interesting because they help to specify the stage on which a specific task is based. For example, an assumption predicting such a dissociation is that the output of early stimulus processing feeds directly into the motor system, whereas later integrative processes are used for the perceptual judgment (Neumann & Müsseler, 1990b; Neumann, Ansorge, & Klotz, 1998; Neumann, Koch, Niepel, & Tappe, 1992; Tappe, Niepel, & Neumann, 1994).

To accomplish this, we conducted six experiments. In Experiment 1, we determined the conditions under which the localization error would appear. In Experiments 2–6, we used the (almost) identical experimental setup but different tasks to determine whether there would be a difference in the timing of stationary and moving stimuli. In Experiments 2 and 3, simple motor responses to stationary and moving stimuli were examined to test whether an RT advantage for moving stimuli could be demonstrated within the Fröhlich effect design. In the other experiments, tasks were studied that required a more detailed perceptual analysis (like the choice RT task and the synchronization task) to come closer to the processing stage used in a perceptual judgment task.

Experiment 1

This experiment was designed to determine the conditions under which the Fröhlich effect occurs. We measured the mislocalization at the beginning of a movement; that is, we asked participants to indicate the position where they had perceived the stimulus for the first time. The results of this experimental condition were compared with the localization performance in three control conditions. In the first control condition, we measured the precision of the localization judgment if a stationary stimulus is presented; therefore, we presented a short flash at the starting position. It was presented as long as the moving stimulus remained at its exact starting position (i.e., for one vertical retrace of the presentation screen). As a second control, we introduced a long-flash condition to test the influence of the overall stimulus duration. Therefore, presentation time of the long flash was identical to the duration of the whole movement. In the third control condition, we tested the influence of movement by introducing a movement-offset condition: We asked participants to judge the end of the movement, that is, to indicate the position where they had perceived the stimulus when it disappeared. In this control condition, the duration of stimulus presentation at the position that had to be judged was again identical to the movement-onset condition (one vertical retrace). For the movement-onset condition we expected a localization error in the direction of the movement (Fröhlich effect), whereas in the control conditions we expected precise judgments.

Method

Apparatus and stimuli. The experiments were carried out on a laboratory computer (Rhothron Rho-Prof 200) and a high-speed 20-in. (50.8-cm) monitor with black-on-white projection (Philips C2082DAS/II). The monitor's vertical retrace rate was 160 Hz, and its luminance was approximately 41 cd/m^2 with the rest of the room dimly lit. As moving stimuli we used horizontally striped rectangles of 0.5° × 1.0° that consisted of 16 equally sized black and white lines. Thus, their luminance was reduced to 19 cd/m^2. In the movement-onset condition, stimuli were presented randomly at two different starting positions of about 6° (center of the stimulus) to the left or right of a central fixation cross. The same was true for the presentation of the flashes, whereas in the movement-offset condition the end of the movement was at about 6°. This was done to keep eccentricity constant under each condition. The exact starting, end, and stationary positions varied between 6° ± 0.5° to prevent participants from always estimating the same position (see Figure 1).

Only foveofugal movements were presented (i.e., movements were always directed away from the central fixation cross). The stimulus movement was induced by shifting the rectangle 0.275° to the left or right with every vertical retrace of the monitor. The movement distance made 5.5° in each direction; that is, absolute movement time was 125 ms.[1] In addition, two stimulus flashes were studied: a short flash and a long flash (presentation times were 6.25 and 125 ms, respectively).

For localization judgments, an adjustment cursor was used that was identical to the stimulus and whose home position was the fixation cross. Participants could move this cursor horizontally with the computer mouse. The participant's head was placed on a chin-and-forehead rest 50 cm from the monitor.
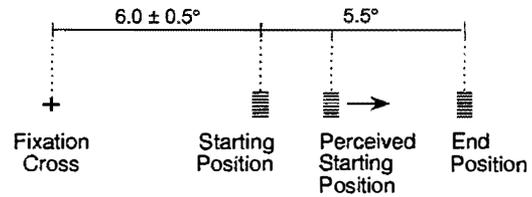

Figure 1. Stimulus presentation and the perception of the stimulus. Participants fixated a cross at screen center, and a moving stimulus appeared to the left or right of the fixation (here to the right). They moved the cursor to the position where they had seen the stimulus first.

Design. There were one experimental condition (movement onset) and three control conditions (short flash, long flash, and movement offset). These four conditions were presented blockwise in a Latin square balanced order of presentation. Twenty-four repetitions per participant were gathered within each cell of the design. In total, the participants underwent 96 trials.

Procedure. The central fixation cross with the home position of the cursor was visible throughout the experiment. Each trial began with an auditory warning signal (1,000 Hz for 50 ms), and after 1 s the stimulus appeared to the left or right of fixation. The instruction stressed concentration on the fixation cross throughout stimulus presentation. After stimulus presentation, participants placed the cursor at the position where they had perceived the beginning or the end of the movement or to where they had seen the stationary stimulus. After this localization, a mouse buttonpress confirmed the adjustment, and the cursor was moved back to the home position. The experimental procedure was self-paced; that is, only after another mouse click was the next trial initiated with a programmed 1-s delay. To familiarize participants with the task, we first presented a training block consisting of 15 trials.

Participants. Twelve students of the University of Munich (9 women and 3 men) were paid to participate. Their average age was 27.4 years. They reported normal or corrected-to-normal vision.

Results

The dependent variable was the perceived mislocalization, computed as the difference between the adjusted and the real first and last position of the stimulus with respect to movement direction. Positive values stood for errors in the direction of the movement. In the flash conditions positive values indicated more peripheral adjustments. Mean values were computed separately for every participant and each condition.

A one-way analysis of variance (ANOVA) with four levels (short flash, long flash, movement onset, and movement offset) revealed a highly significant difference between conditions, $F(3, 33) = 62.74$, $MSE = 23.17$, $p < .001$.[2] A

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[1] Note that presentation times were too short to complete eye movements. Additionally, the Fröhlich effect is not modified under conditions in which participants are even instructed to produce eye movements (Müsseler & Aschersleben, 1998, Experiment 2).

[2] To avoid the risk of violating statistical assumptions that are present in repeated measures designs due to the inhomogeneity of the variance–covariance matrix, we corrected the F probabilities in the present and the following design according to Huynh and Feldt's (1980) recommendations.

subsequent Scheffé test exhibited no difference between the three control conditions (short flash, −1.29 mm; long flash, 2.15 mm; and movement offset, 0.27 mm), but all were significant when compared with the movement-onset condition (movement onset, 22.21 mm; critical difference, 7.17 mm; $p = .01$; see Figure 2).

Discussion

The results are clear-cut. Asked to judge the starting position of a fast-moving stimulus, participants tended to mislocalize that position in the direction of the movement (Fröhlich effect). Conversely, the judgments obtained in the control conditions revealed that participants were good at localizing nonmoving stimuli and the end of the movement.

These results not only replicated the Fröhlich effect, but they also allowed us to control for other factors that possibly had an influence on our experimental setup. For example, one could argue that participants' judgments were based on spatial and temporal averaging. They might have treated the moving stimulus as a singular event and localization judgments were simply biased to the middle of the movement, thus producing the Fröhlich effect.

A related idea has been formulated in the "perceptual center" (P-center) hypothesis assuming that the perceived onset of a presented stimulus deviates from its physical onset. These P-center deviations were found to exist for temporally extended acoustic stimuli as well as for spatially extended visual stimuli (e.g., Scott, 1998; Vos, Bocheva, Yakimoff, & Helsper, 1993). At least in vision research the term *P-center* has occasionally been replaced by the term *center of gravity* (e.g., Müsseler, Van der Heijden, Mahmud, Deubel, & Ertsey, in press; Vos et al., 1993). If a P-center–like tendency works in our experimental setup, a different outcome would have to be expected. Because this idea is based on spatial and temporal averaging, a tendency toward the middle of the stimulus path would also be predicted in the movement-offset condition. This was clearly not the case, indicating that, despite the short stimulus durations, participants were able to distinguish movement onset and movement offset.

The present finding that participants were precise in judging the movement offset is somehow unexpected from a representational momentum point of view (e.g., Freyd, 1987; Freyd & Finke, 1984; for a recent overview, see Hubbard, 1995). There, it was found that an observer shifted the remembered final orientation of a previously perceived rotating target slightly forward in the direction of target rotation. However, if we take a closer look at the experimental conditions under which this phenomenon was studied, we find fundamental differences from our experimental setup. First, the velocity of the moving stimulus was different. Although the Fröhlich effect as such is not limited to the fast movements studied here (see, e.g., Müsseler & Aschersleben, 1998), the velocity used in the representational momentum literature was much smaller (usually less than 6°/s, compared to 44°/s in the present study; see, e.g., Hubbard, 1996). In addition, and partly as a consequence, the duration of stimulus presentation was much longer. While we presented the moving stimuli only for 125 ms, Hubbard (1996), for example, presented the stimuli for several seconds before participants were asked to indicate its last position. This might explain why the effect is usually interpreted as a memory rather than a perceptual phenomenon.

In summary, the results obtained here were in accordance with the hypothesis based on a delay in the perception of the onset of moving stimuli. This hypothesis predicted a localization error at the beginning of the movement but no such error at movement offset or under conditions with stationary stimuli. In the following experiments, we pursued this idea further and applied different temporal measurements to the Fröhlich paradigm.

Experiment 2

In the second experiment, we used an SRT task to test whether an RT advantage for moving stimuli could be demonstrated within the Fröhlich effect design. On the basis of the aforementioned neurophysiological as well as behavioral evidence, we expected participants to react faster to the onset of the moving stimulus than to the onset of a stationary stimulus. On the other hand, under the assumption that the localization error (Experiment 1) indicated a delayed timing of the moving stimulus, we had to expect slower RTs for the moving stimulus.

Method

Stimuli. Stimulus presentation was based on Experiment 1, with the following modifications: To keep stimulus duration constant, we presented only moving stimuli and long stationary stimuli (presentation time: 125 ms) at 6° eccentricity. We also abandoned the minor variations in the starting positions. Furthermore, a microswitch mounted on a flat board in front of the participants served as the response key.
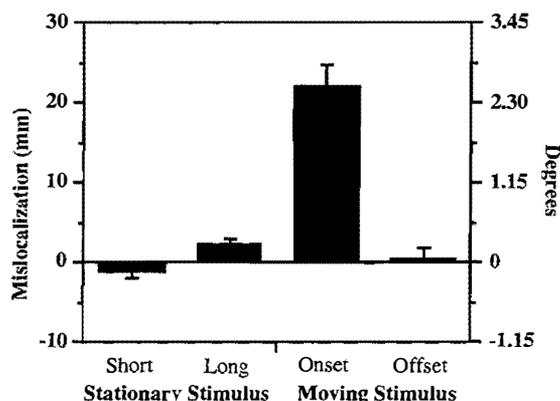

Figure 2. Mean mislocalizations and standard errors of the means (between subjects) for the first and the last position of a moving stimulus in the direction of the movement (the mislocalization of the first position indicates the size of the Fröhlich effect). In the stationary stimulus conditions, negative values indicate more foveal adjustments (Experiment 1, $n = 12$).

Design and procedure. The fixation cross was visible throughout the experiment. Each trial began with an auditory warning signal (1,000 Hz for 50 ms), and after an interval (varying randomly between 300 and 1,300 ms) a stimulus appeared to the left or right of fixation. The participant's task was to press a key as fast as possible after the appearance of the stimulus. The two conditions (moving stimulus vs. stationary stimulus) were presented blockwise with the order of conditions balanced between participants. Under each condition 112 repetitions per participant were gathered. After each block of 8 trials, feedback was given containing the mean RT and the number of errors. Errors were either early reactions (preceding the stimulus onset) or late reactions (RTs > 1 s).

The experimental procedure between blocks was self-paced (i.e., only after another mouse click was the next block initiated). Within blocks the next trial was initiated 1 s after the last reaction of the participant. To familiarize participants with the task, a training block of 15 trials was presented first.

Participants. Twelve students (8 women and 4 men) were paid to participate. Their average age was 25.9 years.

Results and Discussion

The SRT between the stimulus onset and the onset of the keypress was calculated as the dependent variable. Times shorter than 125 ms and longer than 1,000 ms were discarded from the analysis (4.4% of the trials). Mean values were computed for every participant and each condition separately. The RT was 13 ms shorter in the moving stimulus condition as compared with RT in the stationary condition (236.3 vs. 249.2 ms), $t(11) = 2.37, p = .036$, two-tailed.

Contrary to the interpretation given for the results obtained in the localization judgments (Experiment 1), there was a small but significant advantage in the SRT to a moving stimulus. If the Fröhlich effect was based on a temporal delay in the timing of the moving stimulus, then we would have to expect that the SRT to a moving stimulus was longer than to a stationary stimulus. The result revealed the opposite, which, on the other hand, was indicated by the results obtained in neurophysiological (Cleland et al., 1973; Dow, 1974; Hoffmann et al., 1972; Tolhurst, 1973) as well as response-oriented studies (Mashhour, 1964; Smeets & Brenner, 1995).

The observed dissociation between localization judgment and RT is interesting because it points to different processing stages on which perceptual judgments or motor responses are based (Neumann & Müsseler, 1990b). Similar dissociations between judgments and responses have been reported with metacontrast masked stimuli (e.g., Fehrer & Raab, 1962), with stimuli from two different modalities (auditory and visual stimuli; Neumann et al., 1992; Rutschmann & Link, 1964; Tappe et al., 1994) and in patients with visual agnosia (e.g., Goodale, Milner, Jakobson, & Carey, 1991; Farah, 1990; Milner et al., 1991). This evidence suggests that the output of early stimulus processing might feed directly into the motor system, whereas the representation used for the localization judgments is based on later integrative processes. We elaborate on this idea in the General Discussion section.

In the following four experiments we tested the idea that perceptual judgments require more processing of the stimulus than motor responses; that is, we applied different measures to determine the subjective timing of the Fröhlich effect stimuli. First, we searched for a task in which a more detailed analysis of the stimulus would be necessary. In a task in which the motor response depends on structural features of the stimulus that should be available with some delay for moving stimuli, we expected the same pattern of results as for the localization judgments. Therefore, in Experiment 3 participants had to discriminate structural features of moving and stationary stimuli in a two-alternative forced-choice (2AFC) task.

Experiment 3

In this experiment, the choice RT task was studied as a second temporal measure. Participants were asked to give a 2AFC reaction to slight changes in the structural features in the surface of both the moving and the stationary stimuli ($2AFC_S$). Because this task requires not only the detection but also the identification of a stimulus, a more detailed stimulus processing is required. If our interpretation of the Fröhlich effect as a temporal error is correct, this should be reflected in the results of the $2AFC_S$ task (i.e., longer RTs should show up for the moving stimulus as compared with the stationary stimulus condition). Because we had to change the stimuli slightly to study a choice RT task, we asked participants to give simple reactions as well. This allowed us to compare the results of both RT tasks directly.

Method

Stimuli. Stimulus presentation was based on that used in Experiment 2. To study 2AFC, we added minor changes to the stimuli. Each stimulus now contained a dark bar either at the top or at the bottom (i.e., the bottom or the top five lines were black and the rest of the stimulus remained striped).

Design and procedure. The two tasks (SRT and $2AFC_S$) and the two conditions (stationary vs. moving stimulus) were presented blockwise with the order of the four blocks balanced across participants. Under each condition and task, 96 repetitions per participant were gathered. In the SRT task, participants were instructed to react as fast as possible to the presentation of the stimulus and to ignore the kind of stimulus presented. In the $2AFC_S$ task, participants were instructed to react to the stimulus with the dark bar at the top by pressing an upper key and to the bar at the bottom by a lower key. After each block of 24 trials, feedback was given containing the mean RT and the number of errors. In addition, in the $2AFC_S$ task feedback on errors was given immediately by presenting an auditory warning signal.

The experimental procedure between blocks was self-paced; that is, only after another mouse click was the next block initiated. Within blocks the next trial was initiated 1 s after the last reaction of the participant. To familiarize participants with the task, we presented a training block of 24 trials first.

Participants. Twelve students (8 women and 4 men) were paid to participate. Their average age was 23.8 years.

Results and Discussion

The RT between the stimulus onset and the onset of the keypress was calculated as the dependent variable. Times

shorter than 125 ms and longer than 1,000 ms as well as error trials in the 2AFC$_S$ task were discarded from the analysis (2.7% of the trials). Mean values were computed for every participant and each condition separately. The SRT was 14 ms shorter in the moving stimulus condition than RT in the stationary condition (235.8 vs. 249.4 ms), $t(11) = 2.8$, $p = .008$, one-tailed. This finding replicated the results of Experiment 2. On the contrary, 2AFC$_S$ was 11 ms longer in the moving stimulus condition than RT in the stationary condition (402.0 vs. 413.4 ms), $t(11) = 3.4$, $p = .003$, one-tailed.

A 2×2 repeated measures ANOVA with the factors task (SRT vs. 2AFC$_S$) and stimulus (stationary vs. moving stimulus) revealed a significant main effect of task, $F(1, 11) = 183.51$, $MSE = 1,783.21$, $p < .001$, indicating faster RTs in the SRT task than in the 2AFC$_S$ task (SRT, 243 ms; 2AFC$_S$, 408 ms). There was no significant main effect of stimulus ($F < 1$) but a significant task $\times$ stimulus interaction, $F(1, 11) = 17.01$, $MSE = 110.75$, $p = .002$. The error rates in the 2AFC$_S$ task revealed no significant difference between conditions (stationary stimulus, 0.8%; moving stimulus, 1.1%), $t(11) = 1.1$, $p > .10$.

As expected from our interpretation for the results obtained in Experiment 2, we observed an interaction between SRT and 2AFC$_S$ and between moving and stationary stimulus. In the moving stimulus condition, participants produced shorter RTs if they just had to detect the stimulus but longer ones when asked to identify a structural feature of the stimulus. Therefore, a more detailed stimulus processing as needed for the 2AFC$_S$ task led to a delayed timing of the moving stimulus and thus revealed results that were in accordance with the temporal interpretation given for the localization error (see Experiment 1).

Experiment 4

In Experiment 3, we found an RT advantage for moving stimuli in the SRT task and a disadvantage in the 2AFC$_S$ task. This result suggested that a more detailed stimulus processing was necessary for the identification of the structural stimulus features in the 2AFC$_S$ task. If, on the contrary, a task is used that requires no such detail analysis, the additional time-consuming stimulus processing is no longer a precondition to deliver the response (e.g., in the SRT task). To test the assumption that this implication should be valid independent of the task to be performed, we asked participants to perform another 2AFC task. Different from in the previous experiment, they were instructed to discriminate whether a moving stimulus was presented or an identical stationary one. This task (2AFC$_D$) requires an analysis of only the dynamic stimulus features, whereas there is no need for a structural identification. If our processing system is more sensitive to movements, as indicated by the SRT task, we expect the 2AFC$_D$ RTs on the moving stimuli to be faster than the ones to the stationary stimuli.

Method

Stimuli.   Stimulus presentation was identical to Experiment 2.
Design and procedure.   The fixation cross was visible throughout the experiment. Each trial began with an auditory warning

signal (1,000 Hz for 50 ms), and after an interval (varying randomly between 300 and 1,300 ms) a stimulus appeared to the left or right of fixation. Participants were instructed to react to the moving stimulus by pressing an upper key and to the stationary by a lower key (or vice versa). The assignment to the keys was balanced across participants. The two conditions (moving stimulus vs. stationary stimulus) were presented at random. Under each condition, 96 repetitions per participant were gathered.

After each block of 8 trials, feedback was given containing the mean RT and the number of errors. In addition, feedback on errors was given immediately by presenting an auditory warning signal. Otherwise, the procedure remained unchanged from Experiment 2.

Participants.   Nineteen students (10 women and 9 men) were paid to participate. Their average age was 29.6 years.

Results and Discussion

Again, RTs shorter than 125 ms and longer than 1,000 ms as well as error trials were discarded from the analysis (6.8% of the trials). Mean values were computed for every participant and each condition separately. The 2AFC$_D$ RTs were 12 ms shorter in the moving stimulus condition than RTs in the stationary condition (399.0 vs. 411.3 ms), $t(18) = 2.01$, $p = .030$, one-tailed. The error rates revealed no significant difference between conditions (stationary stimulus, 6.9%; moving stimulus, 6.6%), $t(18) = 0.2$, $p > .20$).

As expected, if a stimulus' dynamic was the relevant feature, 2AFC$_D$ RTs indicated a faster processing of the moving stimulus than of the stationary one. Conversely, Experiment 3 showed that, if features of the stimulus structure had to be identified, the pattern of results was reversed with 2AFC$_S$ RTs, indicating a slower processing of moving than of stationary stimuli. Thus, not the task as such determined RTs but its inherent demands. To confirm this interpretation, we calculated an additional analysis comparing the 2AFC results of the Experiments 3 and 4. The two-way ANOVA with the within-subjects factor *stimulus* (moving vs. stationary) and the between-subjects factor *experiment* revealed a significant interaction, $F(1, 29) = 8.32$, $MSE = 2,076.40$, $p = .007$, indicating different effects of the choice RT task in the two experiments. This result is consistent with studies showing that there are separate thresholds for the perception of motion and the perception of pattern, with the first threshold being lower (Kulikowski & Tolhurst, 1973; Sekuler & Levinston, 1977).

Experiment 5

To further test the idea that perceptual judgments require more processing of the stimulus than simple motor responses, we used a temporal order judgment (TOJ) task in the present experiment. There are hints from intermodal studies comparing the TOJ task and SRT task with visual and auditory stimuli that both tasks are based on different processing stages. Neumann and coworkers, for example, observed a dissociation between the two tasks and concluded that the representation that is used for perceptual judgment (like TOJ) is based on later integrative processes (Neumann et al., 1998, 1992; Tappe et al., 1994; for similar dissociations, see Breitmeyer, 1975; Lupp, Hauske, & Wolf,

1976; May, Martin, MacCana, & Lovegrove, 1988). Therefore, we asked participants about the temporal order of an auditory comparison stimulus and the onset of a moving or a stationary stimulus. A click was used as the comparison stimulus to preclude all interfering visual interactions. On the basis of the studies mentioned earlier, we expected a dissociation between the SRT (cf. Experiments 2 and 3) and TOJ.

Method

Stimuli. Stimulus presentation was based on that used in Experiment 2. An auditory comparison stimulus (2,000 Hz for 20 ms) was presented binaurally via headphones (AKG K240, 600 Ω).

Design and procedure. The fixation cross was visible throughout the experiment. Each trial began with an auditory warning signal (1,000 Hz for 50 ms), and after a variable interval (varying randomly between 500 and 1,500 ms) the stimulus appeared to the left or right of fixation. To get the TOJs, we applied the method of constant stimuli. In each trial, the stimulus onset asynchrony (SOA) between the visual stimulus (stationary or moving) and comparison stimulus (click) was determined at random. The following SOA values were tested: ±350 ms, ±200 ms, ±100 ms, and ±31 ms. The participant's task was to judge whether the click was presented before or after the onset of the visual stimulus by clicking with the mouse cursor into a corresponding field on the screen. This field was presented with a variable interstimulus interval after stimulus presentation (varying randomly between 500 and 1,000 ms) to prevent participants from taking the offset of the stimulus presentation as an additional cue.

The next trial was initiated automatically 500 ms after the participant's judgment. The two conditions (stationary vs. moving stimulus) were presented blockwise with the order of the two blocks balanced across participants. Under each condition, 16 repetitions per SOA and per participant were gathered. In total, each participant performed 256 trials. There was a training block of 15 trials at the beginning.

Participants. Sixteen students (12 women and 4 men) were paid to participate. Their average age was 25 years.

Results and Discussion

Points of subjective equality (PSEs; 50% threshold) were computed for each participant and condition using a probit analysis (Finney, 1971; Liebermann, 1983). The PSE values indicated that the click had to be presented about 15 ms before the visual onset to be judged as simultaneously with the onset of the moving or the stationary stimulus. This finding is in accordance with the results reported in the literature (e.g., Rutschmann & Link, 1964; Neumann et al., 1992).

More important, the PSE values revealed no difference between the moving-stimulus condition and the stationary-stimulus condition (moving stimulus, −17 ms; stationary stimulus, −13 ms), $t(15) = 0.26$, $p = .799$, two-tailed. A null effect is always difficult to interpret; however, if one tries to cautiously take this result, one finds the expected dissociation between TOJ and SRT. Although SRT to moving stimuli was faster than to stationary stimuli (cf. Experiments 2 and 3), there was no such advantage for moving stimuli in the TOJ. Similar dissociations between SRT and TOJ can be found in the literature for stimulus intensity, spatial frequency, and stimulus modality (for an overview, see Jaśkowski, 1996). For example, an increase in spatial frequency leads to an increase in RT (Breitmeyer, 1975; Lupp et al., 1976; Tappe et al., 1994). The influence of this factor is either reduced in the TOJ or cannot be demonstrated all (May et al., 1988; Tappe et al., 1994).

By studying stimuli within one modality, we could provide further evidence for an interpretation recently suggested by Neumann and coworkers on the basis of intermodal judgments: Perceptual judgments and simple reactions use different stages of processing of a stimulus with the perceptual judgment (like TOJ) based on later integrative processes than SRT (Neumann et al., 1998, 1992; Tappe et al., 1994). However, choice reaction to structural features of a stimulus seem to be based on even later stages of processing. We return to this point in the General Discussion section. To get converging evidence for the occurrence of dissociations between simple motor responses and temporal measures based on a more detailed stimulus processing, we examined the synchronization task in Experiment 6.

Experiment 6

In the last experiment, we applied a fifth temporal task to the Fröhlich effect situation to test the idea that different tasks use different stages of processing. A task that requires a simple motor task (like in Experiment 2) as well as a perceptual judgment (like in Experiment 5) is the synchronization task. To complete this task, participants have to make a TOJ after each tap; that is, they have to decide whether the tap or the pacing signal came first to correct the timing of the next tap accordingly (e.g., Hary & Moore, 1987; Mates, 1994a, 1994b; Vorberg & Wing, 1996). We presented either the stationary or the moving stimulus as the pacing signal and asked participants to synchronize their finger taps with the onset of the visual signal. On the basis of the results of the preceding experiments, we again expected a dissociation between the synchronization performance and the SRT that might even show up in a delayed timing of the moving stimulus. This finding would provide converging evidence for the results obtained in Experiment 5.

Method

Stimuli. Stimulus presentation was based on that used in Experiment 2. The participant was asked to tap with the right index finger on a silent electrical contact switch.

Design and procedure. The central fixation cross was visible throughout the experiment. Each trial began with an auditory warning signal, and after 1 s, stimulus presentation was started. Each trial consisted of 36 stimulus presentations (randomly to the left or right of fixation) with an SOA of 800 ms. Instructions required participants to start tapping within the first three signals and then to tap along with the signal as precisely as possible. The instruction stressed onset synchronization, so that it was the finger's initial contact with the response key that had to be synchronized with the onset of the stimulus. The two conditions (stationary vs. moving stimulus) were presented blockwise, and the order of conditions was balanced between participants. In each

condition there were 8 trials × 36 taps, resulting in 288 data points per participant. The warmup phase consisted of 5 practice trials at the beginning of each block.

Participants. Originally, the sample consisted of 12 paid students. Two participants had to be excluded from the final analysis because they did not conform to the preset criteria for acceptable performance (see below). The remaining 10 participants (5 women and 5 men) had a mean age of 27.6 years.

Results and Discussion

First, data were corrected according to the criteria usually applied to synchronization data (see, e.g., Aschersleben & Prinz, 1995, 1997). Data analysis started with the 7th signal in each trial. The first taps were not included because participants needed a few signals to pick up the beat. Hence, the means refer to the taps matching the remaining 30 signals in each trial. Mean asynchronies between tap onsets and stimulus onsets were computed per trial. Negative values indicated that taps came first. Trials were dropped from the analysis when they contained less than 10 taps or when the standard deviation exceeded a preset criterion of 100 ms. A participant was excluded when more than 25% of his or her trials had to be rejected. After the exclusion of 2 participants, 4.4% of the trials were rejected.

The mean asynchronies per trial were entered into an ANOVA that distinguished two within-subjects variables: *condition* (stationary vs. moving stimulus) and *trial* (8 repetitions). Only one source of variance was significant, the difference between the stationary and the moving stimulus, $F(1, 9) = 11.34, MSE = 10,106.40, p = .008$. Because there was no main effect of *trial* and no interaction ($ps > .20$), in further analyses we considered only the averages of the 8 trials per condition.

As a typical result obtained in synchronization experiments, negative asynchronies were observed throughout; that is, the tap led over the pacing stimulus (see, e.g., Aschersleben & Prinz, 1995, 1997). In addition, the size of the asynchrony was significantly decreased under the moving stimulus condition as compared with the stationary stimulus condition (-21 vs. -75 ms), with the latter asynchrony lying in the usual range for visually presented stimuli (see Aschersleben & Bachmann, 1999). That is, the timing of the tap was delayed when the moving stimulus served as the pacing signal indicating that, similar to the localization judgment and the choice RT task to structural features, the synchronization task seemed to be based on later integrative processes.

General Discussion

In the present research, the Fröhlich effect—a mislocalization of the first position of a moving stimulus in the direction of its movement—was examined relative to its perceived timing. In Experiments 2–6, we tested the idea that this mislocalization, appearing as a spatial error, is caused by a temporal delay in the subjective timing of the stimulus. Before these temporal experiments, the effect was established spatially (Experiment 1). Asked to judge the starting positions of fast-moving stimuli, participants tended to make

localization errors in the direction of the movement. On the other hand, participants made no localization errors when judging the position of the stationary stimuli or the offset location of moving stimuli.

In Experiments 2–6, four different temporal tasks were examined under otherwise (almost) identical conditions: SRT, 2AFC RT, TOJ, and synchronization performances (SP). SRT (Experiments 2 and 3) and $2AFC_D$ RTs (Experiment 4) that required the detection of a moving or a stationary stimulus without the need to identify structural stimulus features were shorter to the onset of a movement than to the onset of a stationary stimulus. Conversely, other temporal measures revealed a delay in the perceived timing of the moving stimulus. $2AFC_S$ RTs that required the identification of structural features in the surface of the stimulus were longer to the moving stimulus than to the stationary stimulus, resulting in an interaction between the task (SRT vs. $2AFC_S$) and the stimulus (stationary vs. moving stimulus; Experiment 3). The SP showed that the size of the asynchrony between the pacing signal and the tap was increased with the stationary stimulus as compared with the moving stimulus; thus, the timing of the tap was delayed when the moving stimulus served as the pacing signal (Experiment 6). Finally, the TOJ revealed no difference between the two presented stimuli (Experiment 5).

In summary, the results reveal a clear dissociation between localization judgment and simple reactions. Even when we replaced the localization judgment by tasks that were more comparable to an SRT response, namely by a $2AFC_S$ or an SP task, the dissociation remained remarkable, indicating that a stimulus can affect perceptual judgments as well as motor responses in a task-dependent manner.

Dissociations emerging from different tasks can be used to specify the informational stage on which a given motor response or perceptual judgment is based (cf. Aschersleben, 1999b; Neumann & Müsseler, 1990b). A somewhat comparable dissociation was first reported by Fehrer and Raab (1962). The Fehrer–Raab effect indicates that the SRT to a target is unaffected by metacontrast masking, even if the target is completely obliterated by the mask. Thus, the simple motor response is not affected by the subsequent presentation, whereas the perceptual judgment is. Furthermore, eye-movement studies reveal that participants are unaware of target displacements if they occur during saccadic eye movements; however, pointing to targets being flashed during saccades has been found to be accurate (Bridgeman, Lewis, Heit, & Nagle, 1979; Hansen & Skavenski, 1985).

Similar dissociations between perceptual judgment and motor behavior have recently been found for the "induced Roelofs effect" (i.e., a misperception of target position in the presence of a surrounding frame presented asymmetrically in the field; Bridgeman, Peery, & Anand, 1997), for the Ebbinghaus–Titchener illusion (Aglioti, Goodale, & DeSouza, 1995; Haffenden & Goodale, 1998), the Müller–Lyer figure (Post & Welch, 1996), and the Ponzo illusion (Brenner & Smeets, 1996). Additional evidence for similar dissociations can be found in neuropsychological studies:

Cortically blind patients fail to perceive visual targets even though they can point toward them (e.g., Goodale et al., 1991; Perenin & Jeannerod, 1975; Pöppel, Held, & Frost, 1973; Weiskrantz, Warrington, Sanders, & Marshall, 1974).

The dissociations just described were observed within one modality. Performance in different tasks but with identical stimulus material was studied. Dissociations also occur if stimuli are presented in two different modalities. SRTs to auditory stimuli are shorter than to visual stimuli, whereas the TOJ reveals increased latencies for auditory stimuli (e.g., Neumann et al., 1992; Rutschmann & Link, 1964; Tappe et al., 1994; for an overview, see Jaśkowski, 1999). Here, too, this finding indicates that a stimulus can affect perceptual judgments and motor responses in a different manner. Neumann explained this latter kind of dissociation by drawing on the theoretical concept called "direct parameter specification." The idea behind this concept is that sensory information can specify motor output parameters via a direct link that does not depend on a cognitive representation, whereas the different kinds of judgments do (e.g., Neumann, 1990; Neumann et al., 1998; Neumann & Klotz, 1994). That is, the output of early stimulus processing can feed directly into the motor system. The representation, however, that is used for perceptual judgment is based on later integrative processes. A similar distinction has been introduced by Paillard (1987), who labeled the two levels "sensorimotor" and "cognitive." This interpretation is in line with a distinction put forward by Goodale and Milner (1992). On the basis of neuropsychological studies, they argued that the neural substrates of visual perception are distinct from those underlying visual action control.

Obviously, such a general account can also explain the dissociations we observed with the Fröhlich effect paradigm. Localization judgments as well as $2AFC_S$ and SPs require a cognitive representation of the stimulus, whereas the SRT and $2AFC_D$ are based on early stimulus analyses with the TOJ lying in between. This interpretation can be illustrated using accumulation functions that have to reach a certain threshold to either lead directly to a motor reaction or to a central representation of the stimulus (see Figure 3). On the
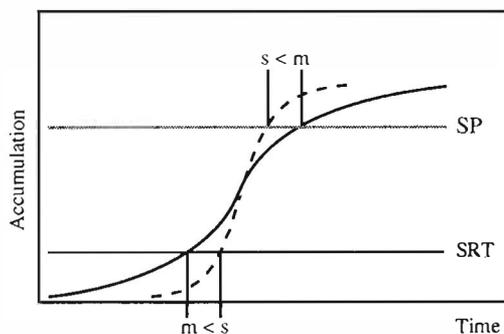

Figure 3. Illustration of the hypothetical accumulation functions. The solid line indicates the accumulation function for the moving stimulus (m) and the dashed line for the stationary stimulus (s). Horizontal lines illustrate two different thresholds for simple reaction time (SRT) and the synchronization performance (SP).

basis of our results we have to assume a steeper accumulation function for the stationary stimulus than for the moving one. Accordingly, the different tasks correspond to different thresholds the function must reach before a task can be performed (for a comparable assumption, see Hanes & Schall, 1996).

There is more we can conclude from our findings, however. The results obtained in the $2AFC_S$ and the SP experiment demonstrate that the perceived onset of the moving stimulus is delayed compared with that of the stationary stimulus. This supports the interpretation that the Fröhlich effect is caused by a temporally delayed timing of that stimulus.

A related interpretation of the performance in SP tasks can be found in an account explaining the usually observed negative asynchrony: the lead of the motor response. This account is based on two assumptions: First, synchrony is established at a central level (i.e., central representations of the pacing signal and the motor response are brought to coincidence). Second, the motor response is represented by its (sensory) effect. Thus, the negative asynchrony occurs as a result of the differences in peripheral and central processing times between the two codes (Aschersleben & Prinz, 1995, 1997; Gehrke, Aschersleben, & Prinz, 1999). The notion of code coincidence—the temporal coincidence of codes that stand for external events and codes that stand for self-generated actions—suggests a view that emphasizes the commensurability of actions and events in terms of their entry into a common representational domain and therefore the role of action effects (both perceived and expected) in action control. This idea—already put forward by Lotze (1852) and James (1890)—has been elaborated further by Prinz (1990, 1992; Hommel, Müsseler, Aschersleben, & Prinz, 1999; Müsseler, 1999; Prinz, Aschersleben, Hommel, & Vogt, 1995).

So far, the suggested interpretations of the Fröhlich effect we mentioned in the introduction have not been discussed in such a common-coding conceptualization of perception and action, but they easily can be. According to the low-level movement-deblurring mechanism, the Fröhlich effect occurs because the first parts of the movement are inhibited by the later incoming signals. As these mechanisms are not active with stationary stimuli, the representation of the moving stimulus the judgment is based on is established later than the representation of the stationary stimulus. This representational level is assumed to be the one used in synchronization tasks to time the actions by bringing two codes to coincidence: the common-coding level. According to the attentional account described earlier (Müsseler & Aschersleben, 1998), the coincidence of the attention shift and coding processes determines what is reported in the perceptual judgment. Still, the attentional account fails to explain why a moving stimulus should arrive later at the representational level than the stationary stimulus. Otherwise, the difference between moving and stationary stimuli in the $2AFC_S$ and SP tasks cannot be explained.

This problem can be solved by introducing the post hoc assumption that the completion of the attentional process is especially delayed when a correction is necessary. Such a

time-consuming correction is inevitable for the system when there is divergence between the spatial position that elicited the attentional shift (i.e., the position of the stimulus' appearance) and the spatial position at the end of the shift. This interpretation is, however, a matter for further investigation.

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