19

The Fröhlich effect: past and present

DIRK KERZEL

Summary

When observers are asked to localize the initial position of a moving target, they often indicate a position displaced in the direction of motion relative to the true onset position. In this review, the debate between Fröhlich, who discovered this phenomenon, and his contemporaries in the 1920s and 1930s is summarized. Striking misinterpretations of Fröhlich's findings and the anticipation of recent research on the flash-lag effect will be presented. In the second part, current accounts of the Fröhlich effect in terms of attention and metacontrast are evaluated. In the final section, reconciliation between research on the Fröhlich effect and recent reports of an error opposite the direction of motion (the onset repulsion effect) is offered.

19.1 Introduction

When asked to localize a moving target entering a window, observers often indicate a position not adjacent to the edge of the window but a position displaced in the direction of motion (see Fig. 19.1(a)). The gap between the edge of a window and the initial perception of the moving target was first discovered by the Norwegian astronomer O. Pihl in 1894, but Fröhlich (1923) was the first to study the effect systematically. Therefore, the illusion has been named the "Fröhlich effect." Fröhlich's explanation of the illusion in terms of "sensation time" was amply discussed in the 1930s (Fröhlich 1930, 1932; Rubin 1930; G. E. Müller 1931; Metzger 1932; Piéron 1935) but forgotten for the 60 years that followed. Research on the Fröhlich effect was revived at the end of the last century (Müsseler & Aschersleben 1998; Kirschfeld & Kammer 1999), and accounts of the phenomenon in terms of attention and metacontrast were forwarded. Yet more recently, an error opposite to Fröhlich's observation was reported (Thornton 2002), which is incompatible with all previous theories on the Fröhlich effect (Fig. 19.1(b)).

In the first section I will describe the methods, results, and theories of early research on the Fröhlich effect. It is surprising to see how much current work on the Fröhlich and flash-lag illusions was anticipated by past researchers and simply overlooked afterward. In the flash-lag illusion, a flash that is physically aligned with a moving object is perceived to lag behind (see Fig. 19.1(c)). I will also draw the reader's attention to the phenomenological aspects of stimulus localization described in detail in early research inspired by Gestalt

Space and Time in Perception and Action, eds Romi Nijhawan and Beena Khurana. Published by Cambridge University Press.

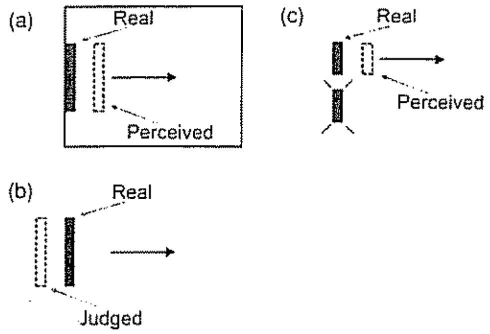

Fig. 19.1 The three illusions discussed in this chapter. In the Fröhlich illusion (a) the initial position of a bar entering a window is not perceived at the edge of the window, but some distance away from it. In the onset repulsion effect (b) the judged onset position is displaced opposite the direction of motion. In the flash-lag illusion (c) the position of a moving object that is physically aligned with a flashed object is seen ahead of the flash.

psychology. It shows that there may be more to localization then the report of a single position. In the second section, I will describe and evaluate current theories of the Fröhlich effect. In the final section, an attempt to reconcile the apparent contradiction between mislocalization of the initial position in the direction of motion (the Fröhlich effect) and recent reports of mislocalization opposite to the direction of motion (see Fig. 19.1(b)) will be presented.

19.2 Historical notes

In his seminal paper, Fröhlich (1923) reported not only one but several phenomena. In fact, Fröhlich's work did not focus on the phenomenon now considered to be the Fröhlich effect. Today, we consider the apparent displacement of the initial position of a moving target in the direction of motion the Fröhlich effect. Thereby, we refer to the displacement of the *trailing* edge of the target and denote that nothing is perceived between the physical onset position and the trailing edge, although the corresponding retinal positions were stimulated by the target. In contrast, Fröhlich was interested in the perceived position of the *leading* edge of the moving bar (see Fig. 19.2). He observed that the leading edge of the bar was not perceived right next to the border of the window and successively uncovered but appeared suddenly at a position displaced in the direction of motion relative to the edge of the frame. He considered the distance between the leading edge and the border of the frame an expression of the sensation time ("Empfindungszeit"), that is, the time between the impact of light and the corresponding visual sensation (Fröhlich 1923, 70–73). The position of the leading edge, x, divided by the velocity of the bar, equals the sensation time t, where $t = x/v$. In Fröhlich's measurements, sensation time was found to be on the order of 100 msec with faint stimuli reducing to 50 msec with bright stimuli (see Fig. 19.2(c)).

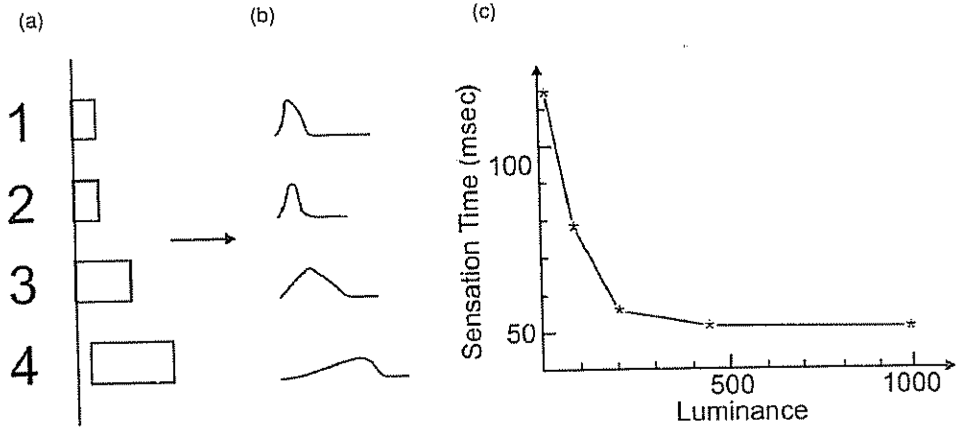

Fig. 19.2 Results of Fröhlich's (1923) experiments. (a) Appearance of a bar entering a window on the left and moving to the right according to Fröhlich (1923; adapted from p. 67). The bar appeared larger than it actually was and appeared in its enlarged width at once. The luminance of the bar decreases from (a)1 to (a)4. Only (a)4 corresponds to our current conception of the Fröhlich effect. (b) shows the perceived luminance distribution within the bars (adapted from p. 66). For the dim bar ((a)4), the luminance decreased toward its trailing edge and was highest at its leading edge. (c) Fröhlich thought that the displacement of the leading edge of the bar divided by its velocity indicated the sensation time. He measured sensation time as a function of luminance and noted that it was shorter for a bright bar (as in (a)1) than for a dim bar (as in (a)4). Luminance is given in proportional (but unknown) units (adapted from p. 74).

Fröhlich also noted that the perceived width of the bar was larger than that of the physical stimulus, which he interpreted as the perceived width capturing the duration of the primary sensation of the stimulus. On this view, the trajectory positions covered during this duration would be sensed at the same time. Because the perceived width of the bar decreased with increasing luminance, he concluded that luminance was negatively related to the duration of the primary sensation. From today's perspective, Fröhlich's ideas about the duration of the primary sensation seem untenable and have been supplanted with variable degrees of motion smear (Burr 1980) or visible persistence (Coltheart 1980).

Further, Fröhlich investigated the luminance distribution within the bar. He found that the bar looked brighter at its leading than at its trailing edge (see Fig. 19.2(b)). This effect was particularly pronounced with dim stimuli that appeared wider than bright stimuli. With dim stimuli, he also observed that the initial portion of the trajectory was not only darker than the leading edge but disappeared altogether. Fröhlich thought that the suppression of the initial part of the trajectory was due to the contrast arising between the leading edge of the bar and the previously covered positions. Thus, the phenomenon we consider to be the Fröhlich effect is only a limiting case of the larger class of phenomena observed by Fröhlich. The phenomenological observation of the luminance distribution within the target or the luminance distribution along the smeared out initial appearance of the target have been ignored in more recent research. This may be an error, because if observers are forced to report only a single point ("the onset") from a percept that shows graded levels of visibility or contrast, their judgments may be a matter of criterion. Observers have to decide what they should report and what is too weak to be worth reporting (Geer & Schmidt 2006). However, even if some of Fröhlich's phenomenological observations may be correct, his account of the illusion in terms of the "sensation time" is implausible, as contributions by his contemporaries show.

In a critique of Fröhlich's work, Rubin (1930) noted that reducing the size of the window and thereby shortening the visible trajectory of the moving bar reduced the Fröhlich effect (replicated in Müsseler & Neumann 1992). He concluded that a necessary condition for the occurrence of the Fröhlich effect was that the target continued to move after it entered the window. Fröhlich's account could only explain effects of trajectory length by assuming that the time at which a stimulus is sensed depends on processes occurring after the stimulus has been sensed. This is hard to maintain. As an alternative to Fröhlich's calculation of the sensation time, Rubin suggested that the distance between the position where the target appeared and the minimal trajectory length that resulted in a reduction of the Fröhlich illusion would be a better estimate of the sensation time. This distance indicated when perceptual processes influencing the appearance of the moving bar ended. Further, he noted that the magnitude of the Fröhlich effect was not determined by the absolute luminance as suggested by Fröhlich, but rather by the contrast between the moving element and the background.

To corroborate the hypothesis of continuing motion producing the Fröhlich effect, Rubin (1930) compared the perception of a stationary flash to the perception of the onset of a moving bar. To this end, he placed a narrow slit exactly above the edge of the elongated window where the target entered (see Fig. 19.3(b)). When the target line entered the narrow slit and the elongated window at the same time, the line in the window appeared displaced in the direction of motion relative to the slit. This, of course, is an early version of the flash-initiated cycle (Khurana & Nijhawan 1995) that was rediscovered in the debate on the flash-lag effect. Rubin also asked which of the two lines (the flashed or the continuously visible) was perceived first. Similar to more recent replications of this temporal order judgment (Nijhawan et al. 2004), he reported a lack of convergence between his own perceptions and those of his assistant. He concluded that the flash and the moving object appeared at about the same time).[1] Ironically, Fröhlich (1923) had run exactly the same experiment in his earlier publication but considered the displacement of the moving object relative to the flash and the perceived simultaneity of the two objects as support for his account.

Rubin (1930) further wondered whether the perception of the initial portion of the target was suppressed (as suggested by Fröhlich) or whether the sensations corresponding to the initial portion of the trajectory were displaced in the direction of motion. To test these conflicting possibilities, he presented a target that moved initially behind a red transparency

---

[1] In contrast to the perceived simultaneity of a flash and the onset of a moving stimulus, the temporal onset of a line moving at high speed precedes the onset of a stationary stimulus that stays on the screen (Kreegipuu & Allik 2003).

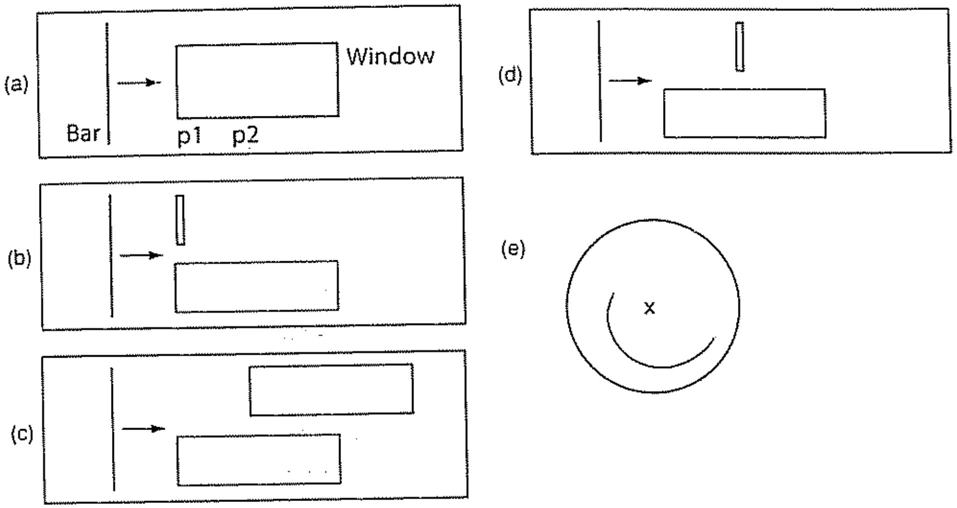

Fig. 19.3 Overview of experiments run in the 1920s and 1930s on the Fröhlich effect. (a) In Fröhlich's (1923) experiments, a bar moving behind a screen entered a window at position p1. The perceived initial position was read off a ruler below the window. Judgments of the leading edge of the bar were displaced in the direction of motion (position p2) (adapted from p. 101 in Rubin 1930). (b) Rubin (1930) and Fröhlich (1923) presented a second narrow window above the elongated window. They observed that the moving bar appeared ahead of the briefly flashed slit (adapted from p. 104 in Rubin 1930). Rubin asked observers to adjust a point below the window to the perceived initial position. (c) Metzger presented a bar moving through two elongated windows offset by a certain distance. The bar entering the window later (top window) appeared to lag behind the bar that was already visible (bottom window, adapted from p. 189 in Metzger 1932). (d) Metzger presented a bar moving through an elongated window and midway along the trajectory, the bar passed through a narrow slit above the elongated window. The flashed bar appeared to lag behind the moving bar below (adapted from p. 190 in Metzger 1932). Unfortunately, Metzger did not quantify his observations but only noted the direction of the displacement of the moving bar. About 90% of the observations that he collected from nine observers were consistent with the flash-lag effect. (e) Piéron presented part of a spiral on a rotating disk. If the disk were rotating clockwise, the spiral appeared further from the center than when it was rotating counterclockwise (adapted from Piéron 1935, p. 24).

and then behind a green transparency. If the initial stimulus characteristics were carried over to the positions further in the direction of motion, one would expect to see a red target on an otherwise green background. Rubin reported that observers' judgments were variable, but at least one subject reported seeing a red, stationary stimulus at the right place and then a green, moving object. This result suggests that the initial positions in the regular Fröhlich effect were suppressed rather than displaced into the direction of motion. In contrast to Rubin's suggestion, Cai (2003) reported that a red flash at the onset of motion was shifted in the direction of motion.

Metzger (1932) agreed with Rubin on the implausibility of Fröhlich's theory and suggested yet another one. His considerations focused on three types of appearance of the moving bar that showed overlap with the results of Fröhlich but were not quite the same.

The first type of appearance was observed at slow velocities. Metzger noted that even if the entrance point of the slit into the window were correctly perceived, the velocity of the bar seemed to change. It appeared slow at first and then accelerated after a while; a phenomenon later rediscovered by Runeson (1974). Second, Metzger observed (in agreement with Fröhlich) that the bar, at low contrasts, appeared suddenly in its entire length between the slit and the background. The perceived width of the bar exceeded its physical width when the bar first appeared, but as the bar started to move, the perceived width decreased. The third appearance type was a bar that appeared at a position offset from the edge of the screen, stood still for a moment, and then continued to move at a constant velocity. This type of appearance was more likely with high velocities and strong contrasts.

To explain these phenomena, Metzger (1932) suggested that sensation time was longest at the start of the motion and decreased as the motion progressed to a point where it became constant. He thought that the postulation of differential sensation times across the trajectory was almost trivial because "... every new process needs some time to 'shake down' and to 'push away' the process taking place at the same place..." (p. 185, translation by the author). According to Metzger, the assumption of differential sensation time could explain the three phenomena under investigation. For the sake of clarity, I will refer to the initial sensation time at the starting position p1 of the moving object as t1, and the final, constant sensation time at a position p2 further along the trajectory as t2 (see Fig. 19.3(a)). If the velocity of the target is slow such that the time needed to cover the distance between p1 and p2 is larger than the difference between t1 and t2, a moving target will be perceived with a velocity distortion (appearance type one). If the velocity of the target is intermediate, the time needed to move from p1 to p2 may equal the difference in sensation time (t1–t2) such that the complete trajectory between p1 and p2 reaches consciousness at the same time and a suddenly appearing, widened bar will be perceived (appearance type two). At high target velocities, the time needed to move from p1 to p2 may be far smaller than the difference in sensation time such that the position p2 may reach consciousness before position p1. In this case, both forward motion from p2 onward and backward motion from p2 to p1 would be perceived. Metzger noted that backward motion was mostly not perceived but that observers sometimes perceived a flicker. He argued that the conditions for the perception of the backward motion were unfavorable because it was dominated or masked by the much stronger forward motion.

To support his claims, Metzger (1932) conducted two experiments. First he placed two windows of unequal width above each other (Fig. 19.3(c)). A vertical bar moving behind the two windows was initially visible in only one of the windows. When the bar reached the edge of the other window, it became visible in the two windows. Although one and the same bar was viewed, the portion of the bar entering later appeared to lag behind and moved more slowly than the bar already visible. Second, he placed a small slit above the center of the window such that the moving bar would illuminate the vertical slit and the window at the same time and at the same horizontal position (Fig. 19.3(d)). The briefly illuminated slit appeared to lag behind the moving object. Metzger suggested that both phenomena were due to the longer sensation time at the beginning of a perceptual process. The initially longer sensation times explained why both the onset of a moving and a flashed stationary object appeared to lag behind a continuously visible moving object. Thus, Metzger not only discovered the flash-lag effect (that was rediscovered twice: MacKay 1958; Nijhawan 1994), but he also proposed differential latency (latency being a term comprising "sensation time") as an account of the phenomenon (for recent renditions see Purushothaman et al. 1998; Whitney & Murakami 1998). Although the differential latency account may justify the occurrence of the Fröhlich phenomenon and the flash-lag effect, it has difficulty accounting for the importance of the length of the trajectory (Rubin's first experiment). Accounts based on metacontrast overcome this limitation.

It was Piéron (1935) who first proposed that metacontrast masking was responsible for the suppression of the initial portion of the trajectory. Metacontrast masking was initially investigated by Stigler (1910) and refers to the fact that the visibility of a briefly flashed stimulus is reduced when it is followed by another stimulus in its spatial–temporal vicinity. The optimal stimulus onset asynchrony (SOA) between target and mask depends on the stimulus and task parameters but ranges between 40–100 msec; both shorter and longer SOAs reduce the masking effect. Piéron reasoned that the initial positions of a bar entering a window were masked by later presentations of the stimulus. Therefore, the initial portion of the trajectory was not perceived. In support of this idea, he presented a line on a rotating disk. The line approached the center of the disk while following its circumference (see Fig. 19.3(e)). When rotated counterclockwise, the distance between the line and the edge of the disk was larger than when the disk was rotated clockwise. In contrast, the distance between center and line was shorter when the disk was rotated clockwise, thus revealing the initial portion of the trajectory to be masked by subsequent stimulation.

Some 20 years later, Alpern (1953) pointed out the incompleteness of Piéron's account because it does not make clear why masking previous target positions stops at some point. If every target position along the trajectory masked the previously presented target positions, only the final target position should be visible. However, most of the trajectory is visible and only a small part at the beginning is invisible. Similarly, such a simple metacontrast account has difficulty explaining why the Fröhlich effect decreases with shorter trajectories. If only immediate neighbors mask the previous position,[2] then the number of positions following the initial position should not matter.

19.3 Cumulative lateral inhibition

The effect of trajectory length may be explained by assuming that inhibition from adjacent stimulus positions accumulates across the trajectory and is therefore stronger with longer trajectories (Geer & Schmidt 2006). To confirm this idea, Geer and Schmidt asked their

[2] The temporal separation between target and mask has a nonlinear effect on the strength of masking. Masking is maximal with SOAs of about 40–100 msec and decreases with shorter or longer intervals. Furthermore, masking decreases with spatial separation. These two factors (overview in Breitmeyer & Ögmen 2006) suggest that masking from successive positions of a moving stimulus will depend on target speed. However, these intricate interactions were not taken into account in early work on the Fröhlich illusion.

subjects to rate the brightness of selected positions along the target's trajectory. They found that the perceived contrast of the trajectory was weakest at the beginning and increased gradually. The increase of the perceived luminance along the trajectory was steeper when the trajectory was short, that is, the target reached maximal perceived contrast faster. Furthermore, the gradual increase in contrast permits observers to make a decision as to which part of the trajectory they report. When they adopt a more conservative criterion (report of only the high-contrast part of the trajectory) the Fröhlich effect was found to be larger than with a more liberal criterion. These recent experiments emphasize the importance of phenomenal aspects in the study of localization performance. In a situation with high uncertainty, the criteria adopted by the observers to interpret their percepts are key to understanding the nature of localization.

Nevertheless, the cumulative lateral inhibition account has the same difficulty as the simple metacontrast account in explaining why only the first positions of a moving object are invisible. What is lacking in all manner of metacontrast accounts is a component that determines when the target becomes visible again. In some accounts, this role is assigned to visual focal attention either with (Kirschfeld & Kammer 1999) or without (Müsseler & Aschersleben 1998) reference to metacontrast masking.

19.4 Attention shifting

Müsseler and Aschersleben (1998) proposed that the Fröhlich effect was the result of the time it takes to move focal attention to the moving stimulus to consciously perceive it. In general, the onset of a moving stimulus in the periphery elicits a shift of visual focal attention to this position. Visual focal attention greatly improves the speed and accuracy of visual information processing (Posner 1980; H. J. Müller & Rabbitt 1989) and may even be necessary for a stimulus to reach conscious awareness (Simons & Rensink 2005). During the time it takes the spot of attention to travel to the onset position of the moving target, the target moves away from its physical onset position. In a similar vein, Baldo and Klein (1995) suggested that the flash-lag effect was due to the time it takes to shift attention from the moving object to the flashed object. In the Fröhlich effect, the first position that benefits from enhanced processing through visual attention is displaced in the direction of motion. The attention-shifting account claims that the positions presented before the attention shift is executed are not perceived. The faster the target moves, the further it will move from its onset before attention reaches it. This idea predicts that the Fröhlich effect increases with increments in target velocity. This prediction has been largely confirmed (e.g., Fröhlich 1932; Kirschfeld & Kammer 1999; Kerzel & Müsseler 2002; Müsseler et al. 2002).

Further, it is expected that cueing the onset position of the moving target should reduce the Fröhlich illusion. A cue that precedes the target onset attracts visual focal attention and effectively reduces the time elapsed before the moving target is within the focus of attention. This prediction too has been confirmed: the Fröhlich effect was reduced when a cue was presented ~120 msec before target onset in the vicinity of the initial target position (Müsseler & Aschersleben 1998; Kerzel & Müsseler 2002) or when a stationary cue was presented for 2.5 sec at the onset position (Whitney & Cavanagh 2000). In contrast, a cue of 2.5 sec did not affect the size of the flash-lag effect, showing that the Fröhlich effect and the flash-lag effect are distinct phenomena (for conflicting views see Metzger 1932; Eagleman & Sejnowski 2000). Similar to cueing, stimuli that allow for the efficient allocation of attention reduce the Fröhlich effect. For instance, attention is more easily focused on a single rotating dot compared to a rotating line passing through the fixation point (corresponding to a double cue, Posner & Cohen 1984), and the Fröhlich effect is larger for the harder to focus on stimulus (Kerzel & Müsseler 2002).

Finally, the attention-shifting account explains why mislocalization of the moving stimulus (flash-lag effect) is smaller in the complete-cycle relative to the flash-initiated cycle (Müsseler et al. 2002). At the beginning of the movement, attention is far from the moving object and a large mislocalization results. As the motion progresses, attention catches up with the moving object and the mislocalization is reduced.

Thus, on the plus side, the attention-shifting account accommodates effects of velocity, visual cues, and trajectory position. However, the relation between the magnitude of the attention shift and that of the Fröhlich effect is unclear. According to one view, attention travels with a constant velocity such that the time to complete an attention shift increases with distance (e.g., Posner et al. 1980; Posner & Cohen 1984). According to the contradictory view, attention shift is time invariant (Remington & Pierce 1984; Eriksen & Murphy 1987). If the duration of the attention shift increased with distance, one would expect the Fröhlich effect to increase with distance of the initial target position from the current focus of attention (the fovea in most cases). This view receives confirmation from the observation that the Fröhlich effect is larger for motion away from the fovea (i.e., when the distance increases after motion onset) than for motion toward it (i.e., when it decreases) (Müsseler & Aschersleben 1998). However, effects of eccentricity and in particular larger Fröhlich effects for more eccentric locations were not observed (Müsseler & Aschersleben 1998; Kerzel & Müsseler 2002). It is untenable that the Fröhlich effect depends on both distance-dependent and distance-independent attention shifts.

Further, the attention-shifting account claims that the initial positions of a moving object will only be available when the attention shift is complete. However, in conditions in which the Fröhlich effect was on the order of 2–3 deg, a slight change in the contrast of the moving stimulus made only 0.5 deg after the onset of motion was detected with 70% accuracy (Müsseler & Aschersleben 1998). If the initial portion of the trajectory never reached consciousness, how could the detection performance be so good? Additionally, the attention-shifting account predicts that regardless of the stimulus properties, the initial portion of the trajectory will be invisible. However, a colored flash at motion onset is "dragged" into the direction of motion and therefore cannot be considered invisible (Cai 2003).

19.5 Interplay between attention and metacontrast

Another model of the Fröhlich effect overcomes some of the lapses of the attention-shifting account by positing an interaction between visual focal attention and metacontrast (Kirschfeld & Kammer 1999). As already pointed out in the discussion of Piéron's (1935) work, the metacontrast account has problems explaining why we see more than the final position of a moving target. Remember that each presentation of the target leads to the suppression of previous target positions. To counteract this suppression, Kirschfeld and Kammer assumed that the onset of target motion elicited a shift of focal attention to the target and that visual attention was responsible for the visibility of the target. Similar to the attention-shifting account, it was assumed that the shift of attention takes some time, and before visual focal attention reaches the target, metacontrast has already suppressed the initial portion of the trajectory.

To test this view, Kirschfeld and Kammer (1999) investigated the localization of a rotating rod that was continuously illuminated but additionally flashed with far higher energy when it first appeared. The resulting percept was of a flashed bar at the correct initial position and a blurred bar that was displaced in the direction of motion (the Fröhlich effect). The interpretation of this striking phenomenon was that the transient, flashed illumination of the initial orientation was strong enough to overcome metacontrast masking, whereas the initial portion of the continuously lit bar was suppressed until focal attention arrived at the bar. Further, it was concluded that the moving bar had a shorter latency than the flashed bar, because the continuously visible bar appeared ahead of the flashed bar even though both bars had been presented simultaneously. Again, this condition replicates the results of Fröhlich (1923) and Rubin (1930) and repeats the idea that the spatial displacement may be used to estimate sensation time. However, Kirschfeld and Kammer hold that it only indicates the relative processing time of moving and flashed objects, not the absolute sensation time.

The approach that combines metacontrast masking and attention has the advantage that it easily accommodates the same findings as the attention-shifting approach (effects of velocity and cueing) and additionally explains why the initial portion of the trajectory is, in certain conditions, not completely invisible. If the features of the target at the beginning do not match its features during the rest of the trajectory (as in Müsseler & Aschersleben's [1998] detection experiment), masking may be reduced and the initial positions become visible again.

In this account of the Fröhlich effect, attention and metacontrast interact to produce the phenomenon. In studies unrelated to the Fröhlich effect, it was observed that attention may actually determine metacontrast masking (Di Lollo et al. 2000; but see Francis & Hermens 2002). Thus, attention and metacontrast are closely intertwined mechanisms; however, one may still question their harmony. On the one hand, the necessity of attention to travel to the target position explains why the Fröhlich effect increases with increasing velocity of the target. On the other hand, metacontrast is known to decrease with increasing distance between target and mask (Alpern 1953). As the distance between successive target presentations increases with increasing target velocity, this characteristic of metacontrast would actually predict a smaller Fröhlich effect at higher velocities. So far, such an inverted effect of velocity (i.e., a decreasing Fröhlich effect with increasing velocity) has not been observed.

One final problem with the attention-shifting and attention-shifting plus metacontrast approaches is that peripheral cueing does not completely eliminate the Fröhlich effect (Müsseler & Aschersleben 1998; Whitney & Cavanagh 2000; Kerzel & Müsseler 2002). When attention is fully allocated to a particular position, processing of the moving object should be enhanced right from the start, thereby canceling the metacontrast-induced suppression. To defend the attention-shifting account, one may argue that the Fröhlich effect with peripheral cues persists because the shifts of attention into the periphery are sometimes incomplete due to the natural coupling between fovea and focus of attention. A further point against the attention-shifting account is that there is no evidence that distracting attention by an invalid cue increases the size of the Fröhlich effect as it should (Müsseler & Aschersleben 1998). Thus, predictions derived from the involvement of attention are again difficult to substantiate. Part of this problem may be the versatile, top-down and bottom-up nature of attention affected by an enormous number of factors. Thus, it is not always clear how and whether attention was actually modulated by an experimental manipulation. Most studies have failed to check attentional deployment using independent measures such as reaction times. A notable exception is a study by Khurana et al. (2000) that measured both attentional deployment via reaction times and the flash-lag effect but failed to find any effects of attention on spatial mislocalization.

19.6 Fröhlich effect versus onset repulsion

The studies reviewed so far unanimously report a localization error in the direction of motion. However, recently the opposite error has also been reported (see Fig. 19.4). That is, the onset position of a moving target was mislocalized opposite the direction of linear motion; the onset repulsion effect (ORE, first reported by Thornton 2002). In the case of curved trajectories, the ORE is opposite the tangents to the circular trajectory (see Fig. 19.4(c), Actis-Grosso & Stucchi 2003). It is evident that explanations in terms of attention shift, metacontrast, or sensation time do not apply to this error because the target is localized at a position it never occupied and perceptual processes were never triggered for these positions. In terms of velocity, the effects depend on the range of velocities presented in an experimental session. Thus, increased velocity renders either a greater ORE (Kerzel 2002; Thornton 2002) or does not have any effect at all (Hubbard & Motes 2002; Kerzel 2002; Actis-Grosso & Stucchi 2003). When the target velocity was drawn from a relatively slow range of velocities (~5 to ~20 deg/sec), effects of velocity were absent or reversed compared to the Fröhlich effect. However, when the range of velocities was expanded from ~5 to ~40 deg/sec, increasing velocity shifted the judged position toward the direction of motion (Kerzel & Gegenfurtner 2004). This is a first indication that the ORE is susceptible to the context across trials in an experiment; that is, the judgments in a given trial can be influenced by what is presented in other trials in the same session. This is not the case for the Fröhlich phenomenon. The forward error and the increase of the error with increasing velocity persist regardless of velocity range (Kerzel 2002).

Furthermore, the ORE depends on motion type. It is largest with smooth, continuous motion and decreases with implied motion (Thornton 2002; Kerzel 2004). In a sequence of implied motion, successive target presentations were separated by large spatiotemporal

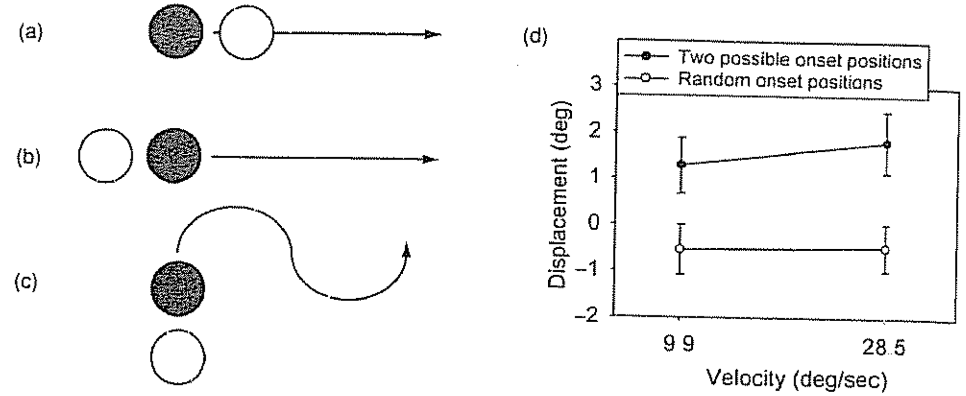

Fig. 19.4 The judged (open circle) and true onset position (filled circle) in the Fröhlich and onset repulsion effects. (a) In the Fröhlich effect, the onset position is displaced in the direction of motion. (b) In the onset repulsion effect (Thornton 2002), the onset position is mislocalized opposite the direction of motion. Most studies that reported an onset repulsion effect did not present visual references and used pointing movements. (c) In the case of circular trajectories, the initial position is displaced along the tangents of the trajectory (Actis-Grosso & Stucchi 2003). (d) By changing the uncertainty about where a target will appear, the Fröhlich effect may be turned into an onset repulsion effect. With two possible onset positions, judgments are displaced in the direction of motion and displacement increases with increasing target velocity. With random onsets, the forward error is eliminated (adapted from Müsseler & Kerzel 2004).

gaps such that each target position was more salient than with smooth motion. Because smooth target motion may elicit smooth pursuit eye movements, one may conjecture that the ORE is related to oculomotor control. This, however, was not the case as the ORE was not different in a condition with and without eye movements (Thornton 2002).

So what explains the difference between the ORE and the Fröhlich effects? The most likely reason has to be sought in the experimental procedure used to measure the error. In studies that have reported a Fröhlich effect, the onset position was judged relative to one or two environmental reference marks, such as the edge of a window (Fröhlich 1923; Piéron 1935; Kirschfeld & Kammer 1999), another moving target (Whitney & Cavanagh 2002), or two positions at a fixed eccentricity (Müsseler & Aschersleben 1998). In studies that have reported the ORE, such a fixed reference mark was missing. This was in particular the case in studies that used some form of pointing response (Hubbard & Motes 2002; Kerzel 2002; Thornton 2002; Kerzel & Gegenfurtner 2004; Müsseler & Kerzel 2004). When the target appears randomly in a relatively large area, and observers have to point to the onset position, the localization task effectively turns into an egocentric localization task. That is, observers have to localize the target with respect to their own body. In a direct comparison of pointing and relative judgments, Kerzel (2002) found that judgments of the onset position relative to a probe stimulus were displaced forward (Fröhlich effect), but mouse-pointing responses to the same stimuli were displaced backward (ORE). Thus, one may ask which attribute that distinguishes motor pointing and relative judgments accounts for the discrepant results.

A first hypothesis may be that the result of a perceptual comparison between moving target and probe stimulus is immediately available, whereas pointing movements are delayed and require memory of the initial position of the target after the trajectory has been viewed. In other words, the Fröhlich effect may be a perceptual effect while the ORE is based on memory. However, the Fröhlich effect has been observed with a probe stimulus that either appeared some time before or after target onset (Kerzel 2002). Thus, the Fröhlich effect is not only observed with immediate perceptual comparisons but persists in memory. Similarly, pointing movements render an ORE irrespective of whether responses are immediate or delayed (Kerzel & Gegenfurtner 2004). Thus, it is not the temporal aspect that is critical to the difference between relative judgments and motor pointing.

A more viable hypothesis considered by several authors (Kerzel 2002; Thornton 2002; Actis-Grosso & Stucchi 2003; Kerzel & Gegenfurtner 2004; Müsseler & Kerzel 2004) is that the uncertainty about the initial position causes observers to overcompensate for a potential error. When confronted with the task of localizing the initial position of a moving target, the most obvious error is to point to a position that is further along the trajectory. To avoid this, observers (perhaps unconsciously) compensate too much. To test this hypothesis, Müsseler and Kerzel (2004) investigated the localization of two positions at ~7 deg of eccentricity to the left and right of fixation in two different trial contexts. In the random trial context, the target appeared mostly at a random position in a large area of the screen. Only in ~17% of the trials did the target appear at the ~7 deg positions. In the constant trial context, the target always appeared in one of the two eccentric positions to the left and right of fixation (similar to Müsseler & Aschersleben 1998). In both conditions, observers localized the onset position by using a mouse cursor. The results showed an ORE in the random context condition and the Fröhlich effect in the constant trial condition (see Fig. 19.4(d)). Thus, the high uncertainty about where a target will occur induces an error opposite the direction of motion with pointing tasks.

Another way to manipulate uncertainty in the presence of a reference object is to vary the distance between the onset position and the reference. Hubbard and Motes (2005) found a Fröhlich effect when the initial position of the target was adjacent to a large surrounding frame (similar to Fröhlich's window) and no or backward displacement when the initial position was far from the frame. Thus, it may be the availability of salient reference marks[3] for localization of the initial position that determines whether an error in or opposite the direction of motion will occur. Hubbard and Motes suggested that the reference frame provided the observer with a limit in their attempt to retrospectively reconstruct the trajectory. The frame (or occluding plane) offered a ready explanation why the target was not visible before its appearance. Without such a delimiting stimulus, observers may attempt to retrospectively extrapolate a possible prior trajectory of the target that appeared all of a sudden. This is particularly true when the onset is unpredictable and not salient (smooth motion as opposed to implied motion).

---

[3] Note that a structured background (Thornton 2002) or the presence of a ruler (Actis-Grosso & Stucchi 2003) that can be used to read the position of the target would not qualify as salient visual references because a background or a ruler does not provide a unique point of comparison.

Thus, the two localization errors that have been presented in this review are by no means contradictory. In conditions of high uncertainty, for instance during egocentric motor localization and in the absence of visual references, an error opposite the direction of motion occurs. This error is more or less constant across target velocities and highly susceptible to effects of across-trial context, which shows that it is related to observers' strategies (of error avoidance). This backward error may combine with the Fröhlich effect when an appropriate range of velocities is selected. Overall, an error opposite the direction of motion results, but increasing the target velocity shifts the judged initial position in the direction of motion. Thus, at some high velocity, the typical Fröhlich effect is replicated (Kerzel & Gegenfurtner 2004).

In sum, Fröhlich's observation that the initial portion of a moving target was invisible is currently explained by attentional latencies or the interplay between attention and metacontrast. The present review favors the latter explanation comprised of an inhibitory component (metacontrast) that explains why the initial portion is invisible, and a facilitatory component (attention) that explains why the trajectory becomes visible again. Nonetheless, evidence for the contribution of attention is mixed and requires further clarification. Further, the mislocalization of the onset opposite the direction of motion is related to uncertainty about target appearance resulting in observers overcompensating the distance traversed by the target after its appearance. The two errors are not contradictory, but rather complementary; the forward error reflecting perceptual while the backward error reflecting cognitive processes.

Future studies are needed to disentangle cognitive and perceptual components in the mislocalization of the initial position of a moving target. One route is to manipulate participants' strategies via feedback. It seems plausible that the magnitude of the ORE will change as a function of feedback, whereas the Fröhlich effect will not. Investigations that quantify the amount of metacontrast masking by successive target presentations along an object's trajectory are missing. As laid out above, a number of researchers have speculated about the involvement of metacontrast masking in the Fröhlich illusion, but there are no data relating masking functions in "static" target-mask displays to the Fröhlich effect. These data may also clarify which aspects of the pattern of mislocalization cannot be accounted for by low-level perceptual processing, but have to be attributed to higher-level functions such as attention.

Acknowledgment

D. Kerzel was supported by the Swiss National Foundation 10011–107768/1.

References

Actis-Grosso, R., & Stucchi, N. (2003). Shifting the start: backward mislocation of the initial position of a motion. *J Exp Psychol Hum Percept Perform* **29**(3): 675–691.

Alpern, M. (1953). Metacontrast. *J Opt Soc Am* **43**(8): 648–657.

Baldo, M. V., & Klein, S. A. (1995). Extrapolation or attention shift? *Nature* **378**(6557): 565–566.

Breitmeyer, B., & Öğmen, H. (2006). *Visual Masking: Time Slices Through Conscious and Unconscious Vision*. Oxford, UK: Oxford University Press.

Burr, D. (1980). Motion smear. *Nature* **284**(5752): 164–165.

Cai, R. (2003). The Fröhlich effect is not due to a failure to perceive the beginning portion of motion trajectory. *J Vis* **3**(9): 485.

Coltheart, M. (1980). Iconic memory and visible persistence. *Perception & Psychophysics* **27**(3): 183–228.

Di Lollo, V., Enns, J. T., & Rensink, R. A. (2000). Competition for consciousness among visual events: the psychophysics of reentrant visual processes. *J Exp Psychol Gen* **129**(4): 481–507.

Eagleman, D. M., & Sejnowski, T. J. (2000). Motion integration and postdiction in visual awareness. *Science* **287**(5460): 2036–2038.

Eriksen, C. W., & Murphy, T. D. (1987). Movement of attentional focus across the visual field: a critical look at the evidence. *Perception & Psychophysics* **42**(3): 299–305.

Francis, G., & Hermens, F. (2002). Comment on "Competition for consciousness among visual events: the psychophysics of reentrant visual processes" (Di Lollo, Enns, & Rensink, 2000). *J Exp Psychol Gen* **131**(4): 590–593; discussion 594–596.

Fröhlich, F. W. (1923). Über die Messung der Empfindungszeit. [On the measurement of sensation time]. *Zeitschrift für Sinnesphysiologie* **54**: 58–78.

Fröhlich, F. W. (1930). Über die Messung der Empfindungszeit. Eine Erwiderung auf experimenteller Grundlage [On the measurement of sensation time. An answer on an experimental basis]. *Psychologische Forschung* **13**: 285–288.

Fröhlich, F. W. (1932). Bemerkungen zu G.E. Müllers Kritik der Empfindungszeitmessung [Remarks on the criticism of G. E. Müller of the measurement of sensation time]. *Zeitschrift für Psychologie und Physiologie der Sinnesorgane* **62**: 246–249.

Geer, M., & Schmidt, W. C. (2006). Perception of initial moving target signals: support for a cumulative lateral inhibition theory. *J Exp Psychol Hum Percept Perform* **32**(5): 1185–1196.

Hubbard, T. L., & Motes, M. A. (2002). Does representational momentum reflect a distortion of the length or the endpoint of a trajectory? *Cognition* **82**(3): B89–99.

Hubbard, T. L., & Motes, M. A. (2005). An effect of context on whether memory for initial position exhibits a Fröhlich Effect or an Onset Repulsion Effect. *Q J Exp Psychol* **58A**(6): 961–979.

Kerzel, D. (2002). Different localization of motion onset with pointing and relative judgements. *Exp Brain Res* **145**(3): 340–350.

Kerzel, D. (2004). Attentional load modulates mislocalization of moving stimuli, but does not eliminate the error. *Psychon Bull Rev* **11**(5): 848–853.

Kerzel, D., & Gegenfurtner, K. R. (2004). Spatial distortions and processing latencies in the onset repulsion and Fröhlich effects. *Vision Res* **44**(6): 577–590.

Kerzel, D., & Müsseler, J. (2002). Effects of stimulus material on the Fröhlich illusion. *Vision Res* **42**(2): 181–189.

Khurana, B., & Nijhawan, R. (1995). Extrapolation or attention shift. *Nature* **378**(6557): 566.

Khurana, B., Watanabe, K., & Nijhawan, R. (2000). The role of attention in motion extrapolation: are moving objects "corrected" or flashed objects attentionally delayed? *Perception* **29**(6): 675–692.

Kirschfeld, K., & Kammer, T. (1999). The Fröhlich effect: a consequence of the interaction of visual focal attention and metacontrast. *Vision Res* **39**: 3702–3709.

Kreegipuu, K., & Allik, J. (2003). Perceived onset time and position of a moving stimulus. *Vision Res* **43**(15): 1625–1635.

MacKay, D. M. (1958). Perceptual stability of a stroboscopically lit visual field containing self-luminous objects. *Nature* **181**(4607): 507–508.

Metzger, W. (1932). Versuch einer gemeinsamen Theorie der Phänomene Fröhlichs und Hazelhoffs und Kritik ihrer Verfahren zur Messung der Empfindungszeit [An attempt at a common theory of Fröhlich's and Hazelhoff's phenomena and a critique of their procedure for measuring sensation time]. *Psychologische Forschung* **16**: 176–200.

Müller, G. E. (1931). Erklärung der Erscheinungen eines mit konstanter Geschwindigkeit beewegten Lichtstreifens, insbesondere auch des Pihl-Fröhlichschen Phänomens [Explanation of the appearances of a lit bar moving at constant velocity, in particular the phenomenon of Pihl-Fröhlich]. *Zeitschrift für Sinnesphysiologie* **62**: 167–202.

Müller, H. J., & Rabbitt, P. M. (1989). Reflexive and voluntary orienting of visual attention: time course of activation and resistance to interruption. *J Exp Psychol Hum Percept Perform* **15**(2): 315–330.

Müsseler, J., & Aschersleben, G. (1998). Localizing the first position of a moving stimulus: the Fröhlich effect and an attention-shifting explanation. *Perception & Psychophysics* **60**(4): 683–695.

Müsseler, J., & Kerzel, D. (2004). The trial context determines adjusted localization of stimuli: reconciling the Fröhlich and Onset Repulsion Effects. *Vision Res* **44**(19): 2201–2206.

Müsseler, J., & Neumann, O. (1992). Apparent distance reduction with moving stimuli (Tandem Effect): evidence for an attention-shifting model. *Psychol Res* **54**(4): 246–266.

Müsseler, J., Stork, S., & Kerzel, D. (2002). Comparing mislocalizations with moving stimuli. The Fröhlich effect, the flash-lag effect and representational momentum. *Vis Cogn* **9**(1/2): 120–138.

Nijhawan, R. (1994). Motion extrapolation in catching. *Nature* **370**(6487): 256–257.

Nijhawan, R., Watanabe, K., Khurana, B., & Shimojo, S. (2004). Compensation of neural delays in visual-motor behaviour: no evidence for shorter afferent delays for visual motion. *Vis Cogn* **11**(2/3): 275–298.

Piéron, H. (1935). Le processus du métacontraste. *Journal de Psychologie Normale et Pathologique* **32**: 1–24.

Posner, M. I. (1980). Orienting of attention. *Q J Exp Psychol* **32**(1): 3–25.

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. G. Bouwhuis (eds.), *Attention and Performance X*. Hillsdale, NJ: Erlbaum.

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *J Exp Psychol* **109**(2): 160–174.

Purushothaman, G., Patel, S. S., Bedell, H. E., & Öğmen, H. (1998). Moving ahead through differential visual latency. *Nature* **396**(6710): 424.

Remington, R., & Pierce, L. (1984). Moving attention: evidence for time-invariant shifts of visual selective attention. *Perception & Psychophysics* **35**(4): 393–399.

Rubin, E. (1930). Kritisches und Experimentelles zur "Empfindungszeit" Fröhlichs [Critical and experimental remarks on Fröhlich's "Sensation Time]. *Psychologische Forschung* **13**(101–112).

Runeson, S. (1974). Constant velocity: not perceived as such. *Psychol Res* **37**(1): 3–23.

Simons, D. J., & Rensink, R. A. (2005). Change blindness: past, present, and future. *Trends Cogn Sci* **9**(1): 16–20.

Stigler, R. (1910). Chronophotische Studien über den Umgebungskontrast. *Pflügers Archiv für die gesamte Physiologie* **134**: 365–435.

Thornton, I. M. (2002). The onset repulsion effect. *Spat Vis* **15**(2): 219–244.

Whitney, D., & Cavanagh, P. (2000). The position of moving objects. *Science* **289**(5482): 1107a.

Whitney, D., & Cavanagh, P. (2002). Surrounding motion affects the perceived locations of moving stimuli. *Vis Cogn* **9**(1/2): 139–152.

Whitney, D., & Murakami, I. (1998). Latency difference, not spatial extrapolation. *Nat Neurosci* **1**(8): 656–657.