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MISLOCALIZATIONS AT THE ONSET POSITION OF MOVING STIMULI

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Abstract

It is known for some time that observers have difficulties to perceive correctly the onset position of a moving stimulus. In studies from the beginning of the last century an illusion was reported, in which the error was in the direction of motion (Fröhlich effect; Fröhlich, 1923), while later studies from the present century also described an illusion, in which the opposite error was observed (onset-repulsion effect; Thornton, 2002). The basic findings and the various interpretations of these errors are reviewed and weighted against each other (among them the accounts of sensation time, metacontrast, lateral inhibition, attentional mechanism and mental extrapolation). We also show how the conflict between the illusions might be resolved and discuss the theoretical intersections to further illusions. It is concluded that processes of attentional disengagement were neglected in the explanations of the Fröhlich effect so far.

Keywords: localization error; Fröhlich effect; onset-repulsion effect; sensation time; metacontrast; lateral inhibition; attention; mental extrapolation; visual prediction; dynamic field model; attentional disengagement

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1. Discovering mislocalizations with moving stimuli

A note in a book of Friedrich W. Fröhlich (1929) stated that in 1894 the Norwegian astronomer O. Pihl noticed a perceptual illusion when localizing the onset position of a moving target: Typically an observer did not notice the target at its physical onset position, but at some later position on its motion trajectory. In other words, a localization error in the direction of motion occurred (Fig 1a).

It took some time before the scientific community dealt with this phenomenon. Almost 30 years later, the same author (Fröhlich, 1923) was the first to publish systematic experiments on the mislocalization and in the subsequent scientific debate, the illusion was termed *Fröhlich effect*. Nowadays, the Fröhlich effect is typically observed on a computer display, on which the moving target appears suddenly out of nowhere. At the time of Fröhlich (1923) such an experimental setup was difficult to implement. Instead he used a mechanical device with a moving bar entering a window. In this case the target is not perceived at the position adjacent to the edge of the window, but at a later position within that window.

In fact, Fröhlich (1923) reported not only the mislocalization but also other phenomena. For instance, he reported that the perceived width of the moving bar appeared larger than that of the physical stimulus and that the bar looked brighter at its leading than at its trailing edge (for details see Fröhlich, 1923, and Kerzel, 2010).The mislocalization and its first explanations were amply discussed in the 1930's (e.g., by Fröhlich, 1925, 1929, 1930, 1932; Metzger, 1932; Müller, 1931; Rubin, 1930), but were neglected after World War II.

Interest in the Fröhlich effect was revived in the 1990's together with two further mislocalizations in motion direction: First, Nijhawan (1994) presented a moving target in alignment with a stationary flash and observed that the target appears to lead the flash (flash-lag effect, Fig. 1c; for an overview see Hubbard, 2016, this volume, chap. 9???). In fact, Nijhawan re-discovered an observation made in follow-up studies of the Fröhlich effect (cf. Rubin, 1930; Metzger, 1932; for details see Kerzel, 2010). Second, when observers localize the offset point of a moving target, they also tend to judge it to be ahead of the target's motion trajectory. Unlike in the previous illusions, the target never reached the judged position. This observation was termed *representational momentum* (Fig. 1b) as it was seen as evidence for a mental analogue to the momentum of moving physical objects (Freyd & Finke, 1984; for an overview see Hubbard, 2016, this volume, chap. 8).[1]

Beside these errors in motion direction, another error was reported at the beginning of the present century that was opposite to motion direction: In several studies, the target's onset was found to be consistently mislocalized away from the physical onset position opposite to the direction of motion (onset-repulsion effect, Fig. 1d; Thornton, 2002; see also Actis-Grosso & Stucchi, 2003; Hubbard & Motes, 2002;

[1] Originally, representational momentum was observed with induced motions, i.e. with sequences of static stimuli. Another observation was that the offset position was judged as if the target were subject to gravity. In other words, the judged position was below the physical offset position (see also De Sá Teixeira, 2016; Zago, 2016, this volume, chap. 10???).

Hubbard & Ruppel, 2011; Kerzel, 2002; Kerzel & Gegenfurtner, 2004). As in representational momentum, the target was never presented at the judged position and this mislocalization has also been explained with reference to mental analogues of physical laws (Thornton, 2002).

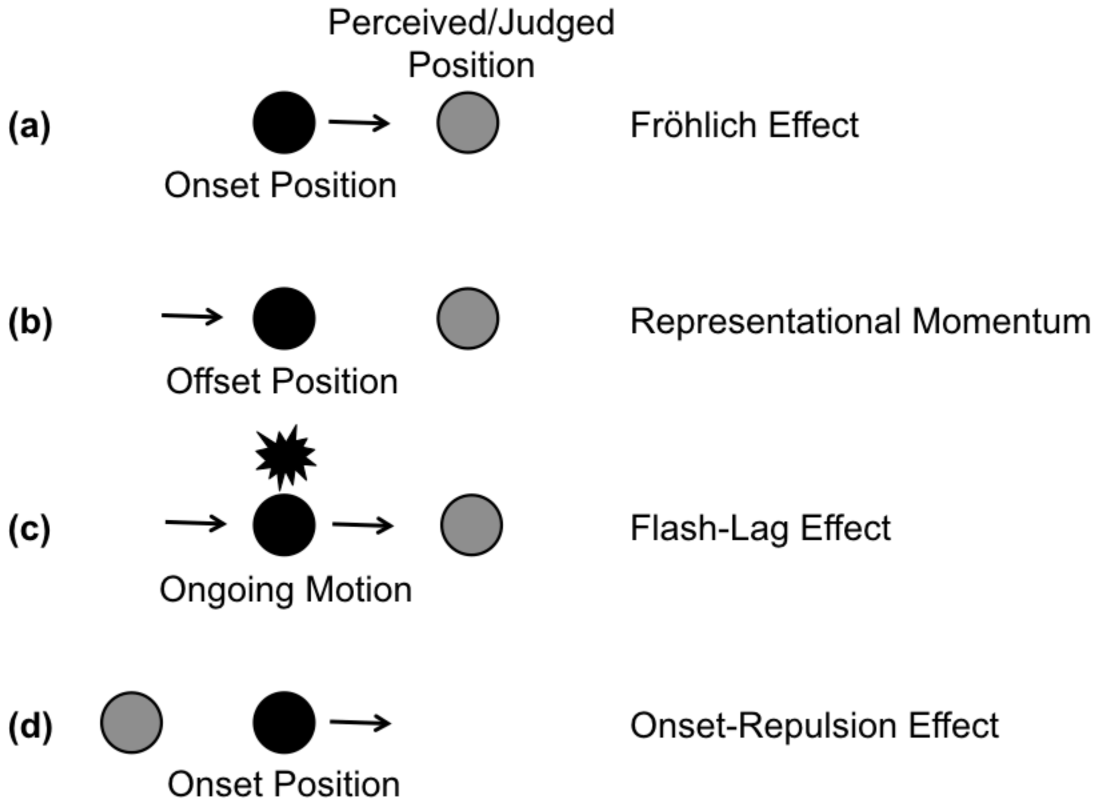

Figure 1: Four localization errors with moving stimuli: When the onset position (a) or the offset position (b) of a moving target is localized, observers typically make localization errors in the direction of movement. Similarly, when they judge a moving target that is presented in alignment with a flash, the target appears to lead the flash (c). These errors are known as the Fröhlich effect, flash-lag effect and representational momentum. In the onset repulsion effect (d), the onset position is judged opposite to the direction of motion.

The present paper deals mainly with the observation of displacements of the perceived onset position. We will first give an overview about interpretations and findings of the Fröhlich effect. Then, we take into account the conditions and findings that resulted in the error opposite to motion direction (the onset-repulsion effect), and show how the conflict between the illusions might be resolved. We end the chapter with an outlook on the possible contributions of these phenomena to our understanding of perceptual processes in general.

2. The mislocalization in motion direction: the Fröhlich effect

Explanations of the Fröhlich effect can be roughly divided into four accounts: The sensation-time account, the metacontrast or lateral-inhibition account, the attentional account, and the mental extrapolation account.

2.1 Sensation time

One main finding of Fröhlich was that the size of the mislocalization *f* increased with movement speed *v* and that the ratio *f/v* proved to be fairly constant (Fröhlich, 1923, p. 70-73). The fixed ratio *f/v* turns the spatial error into a temporal error and Fröhlich interpreted the time constancy as an expression of the sensation time ("Empfindungszeit"). The sensation time was understood as the time between the retinal impact of light and the corresponding visual sensation (see also Kreegipuu & Allik, 2003). Fröhlich saw the finding that the sensation time varied with the brightness of stimuli as plausible evidence for his explanation. It was –as expectable– on the order of 100 ms with faint stimuli and about 50 ms with bright stimuli.

At first glance, the idea of sensation time appeared attractive to explain the localization error. However, the explanation was early criticized by the contemporaries of Fröhlich, both empirically and theoretically. Rubin (1930), for instance, noted that reducing the size of the window (i.e. reducing the trajectory length) shortened the Fröhlich effect (see also Müsseler & Neumann, 1992) and thereby should also shorten the sensation time. Also, Metzger (1932) proposed that the sensation time might be longer at motion onset than at positions further along the trajectory (similar the latency differences discussed to explain other spatio-temporal phenomena; e.g. see Bachmann, 1999; Whitney, 2002; Hubbard, 2014). However, these variations are not consistent with the basic idea of sensation time and are therefore theoretically problematic. Metzger (1932) pointed out correctly that the concept of sensation time has to be applied not only to the onset of motion, but to the entire motion trajectory. In this case, an observer should perceive the moving stimulus with a corresponding temporal delay, but at all positions of the trajectory.

Thus, the concept of sensation time could not provide a satisfactory answer to the question of why only the first positions were excluded from perception. Furthermore, at the time of Fröhlich it was not clear at all whether the first positions were perceptually missed or whether the first positions were simply displaced in the direction of motion.[2] Only later studies revealed that observers have indeed no access to the first positions: In experiments of Müsseler and co-workers (Müsseler & Aschersleben, 1998, Ex. 5; Müsseler & Tiggelbeck, 2013, Ex. 1) observers failed to detect brief pattern changes at motion onset but were better in detecting the change at positions further along the trajectory (see also Ansorge, Carbone, Becker & Turatto, 2010 for evidence from reaction-time studies). Thus, a mechanism is called for that prevents the very first positions from being perceived.

2.2. Metacontrast masking and lateral inhibition

At first sight, accounts of the Fröhlich effect based on metacontrast masking and lateral inhibition seemed to explain the low visibility of the initial part of the trajectory (cf. Carbone & Ansorge, 2008; Geer & Schmidt, 2006; Kirschfeld & Kammer, 1999; Piéron, 1935). Metacontrast masking was first described by Stigler (1910) and refers to

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[2] A study of Rubin (1930) already addressed this question, but his findings remained inconclusive.

the observation that the visibility of a stationary, flashed target is reduced when it is followed by a mask in its spatial vicinity (visual backward masking). Backward masking is optimal when target and mask share common stimulus boundaries, for instance, when the target is a disk and the mask is a surrounding ring. Optimal stimulus onset asynchronies (SOAs) between target and mask are between 40 to 100 ms and are thus within the range of the temporal error in the Fröhlich effect. Piéron (1935) was the first to hypothesize the Fröhlich effect to be caused by masking mechanisms.

Lateral inhibition has been used to interpret metacontrast masking (e.g. Bridgeman, 2006). The basic assumption is that the presentation of a stimulus elicits excitatory and inhibitory neuronal activity in a retinotopic (cortical) map, for instance in form of a simplified Mexican-hat function (Fig. 2a). The inhibitory parts could be crucial for the Fröhlich effect, and Geer and Schmidt (2006) proposed that multiple inhibitory connections from neighboring space have a cumulative masking effect on early parts of the target trajectory (Fig. 2b). The authors interpreted the effect of trajectory length accordingly by assuming that inhibition from adjacent stimulus positions accumulates across the trajectory. Therefore, the Fröhlich effect increases with trajectory length.

However, if the area of lateral inhibition or any other masking mechanism just moves across a retinotopic map (cf. Fig. 2b), there is no way to explain why only the first positions are excluded from the perception. This explanatory gap was already encountered by the sensation time account. As a matter of fact, the masking account predicts that most of the trajectory (except for the last position) should become invisible, because each stimulus presentation is masked by the subsequent stimulus presentations. Clearly, that is not the case. Therefore, an additional component is needed, which explains why the target becomes visible at all. In the subsequent accounts, this function was assigned to visual attention.

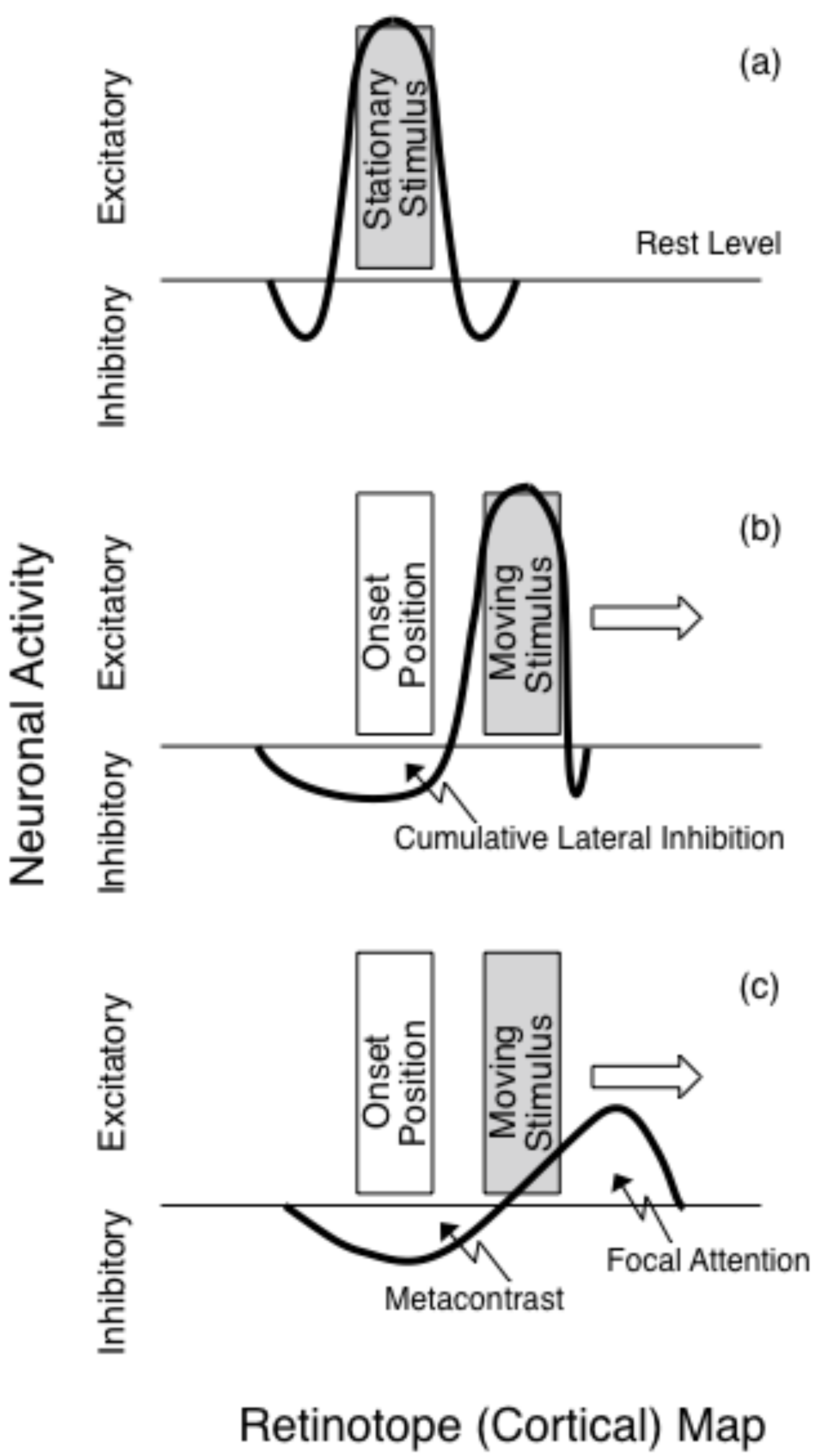

Figure 2: Simplified assumptions (a) of lateral inhibition with stationary stimuli, (b) of cumulative lateral inhibition with moving stimuli with regard to Geer and Schmidt (2006) and (c) of metacontrast and visual focal attention with regard to Kirschfeld and Kammer (1999, Fig. 6). The latter figure illustrates only the additional excitatory and inhibitory neuronal activity, which is elicited by the motion of the stimulus.

2.3 Visual attention and its neuronal implementation

At the end of the 1990s two independently developed accounts refer to attentional mechanisms to explain the Fröhlich effect. Kirschfeld and Kammer's (1999) masking-plus-focal-attention account assumed that positions on the trajectory behind the target are masked (cf. Fig. 2c), similar to Piéron's (1935) ideas and nowadays postulated by Geer and Schmidt (2006). The new assumption was that positions on the trajectory before the target are pre-activated by the target itself (cf. Fig. 2c). The authors associated this pre-activation with mechanisms similar to cue-induced visual focal attention. Thus, the approach combines mechanisms of metacontrast masking and visual focal attention.

With regard to Kirschfeld and Kammer (1999), focal attention ensures that masking does not occur along the entire trajectory. However, focal attention must first be shifted to the moving stimulus and that is why the first positions of the trajectory are excluded from perception (Fröhlich effect). Once attention has reached the moving stimulus, it becomes visible because masking is counteracted and overcome.

To support their view, Kirschfeld and Kammer (1999) presented a rotating rod that was continuously illuminated and was additionally flashed with far higher energy when it first appeared. The resulting percept was actually of two bars; a flashed bar at the correct initial position, and a moving bar that was displaced in the direction of motion (the Fröhlich effect). The interpretation was that the transient, flashed illumination of the initial orientation was strong enough to overcome masking, while the initial portion of the moving bar's trajectory was suppressed until the pre-activation (focal attention) was established. Further, Kirschfeld and Kammer concluded that perception of the moving bar had a shorter latency than perception of the stationary flashed bar, because the moving bar appeared ahead of the flashed bar and both bars appeared simultaneously (cf. the flash-lag effect, Rubin, 1930; Nijhawan, 1994; Metzger, 1932). The conclusion that moving stimuli have shorter latencies than flashed stimuli has also been confirmed in reaction-time experiments (Aschersleben & Müsseler, 1999).

The other attentional account was originally developed without reference to masking mechanisms.[3] Müsseler and co-workers (Müsseler & Aschersleben, 1998; Müsseler & Neumann, 1992, Ex. 6) simply started from three well-accepted attentional mechanisms used to explain effects with stationary stimuli (e.g. spatial cuing effects), but which should be equally applicable to situations in which stimuli are in motion (see also Ansorge, Carbone, Becker & Turatto, 2010; Carbone & Pomplun, 2007; Kerzel & Gegenfurtner, 2004; Müsseler, Stork & Kerzel, 2002): (1) The presentation of a stimulus in the visual field elicits an attentional shift toward that stimulus. (2) An attention shift takes time. (3) A phenomenal representation of a stimulus is not available before the

[3] In fact, the attentional model we started with emerged from assumptions to address metacontrast masking (Neumann & Scharlau, 2006 [English translation of Neumann, 1987], Neumann & Müsseler, 1990). The basic idea was that the target in the metacontrast situation elicits an attention shift, but before this is completed the mask appears. What the observer then perceives is the mask with shorter latencies (for similar ideas see Bachmann, 1984, 2010;Di Lollo, Enns & Rensink, 2000).

end of the attention shift. Applied to the Fröhlich-effect situation, this means that with the presentation of a moving stimulus a visual focus shift is initiated and while this shift is under way, the stimulus continues to move. The first phenomenal representation of the stimulus is available at the end of the focus shift and this is what is observed in the Fröhlich effect.

Both attentional accounts were able to explain the main findings observed with the Fröhlich effect, for instance, that the Fröhlich effect increases with increasing target velocity. The effect of stimulus brightness (or stimulus contrast; Fröhlich, 1923) can be plausibly addressed by assuming that establishing focal attention or eliciting an attentional shift is more effective with bright than with faint stimuli. Further, both accounts predicted that cuing the onset position with a stationary stimulus reduced the Fröhlich effect. The observed reduction effect was small, but reliable (Adamian & Cavanagh, 2017; Kerzel & Müsseler, 2002; Müsseler & Aschersleben, 1998; Whitney & Cavanagh, 2000). Finally, they explain why mislocalizations are more pronounced in the Fröhlich effect than in the flash-lag effect: 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 (Müsseler et al., 2002).

However, the attentional accounts have also serious problems with some findings, for instance, that an increase of trajectory length led to an increase of the Fröhlich effect (Rubin, 1930; Müsseler & Neumann, 1992, Ex. 6). The authors of the masking-plus-focal-attention account (Kirschfeld & Kammer, 1999) might integrate Geer and Schmidt's (2006) assumption that inhibition from adjacent stimulus positions accumulates across the trajectory, which leads to larger Fröhlich effects with longer trajectories. The attention-shifting account of Müsseler and Aschersleben (1998) has more difficulties to accommodate this finding. The solution could be a modification of their third assumption, which claims that a phenomenal representation of a stimulus is not available before the end of the attention shift. This claim may be too strong. Note, that shifting attention towards a stimulus implies at least coarse knowledge of the stimulus location prior to the start of the shift. What happens when an attention shift cannot be successfully completed – as would be the case, when the moving target has a short trajectory and has already disappeared from the screen? Taking the third assumption literally, no stimulus should be perceived at all. It is more likely that the coarse representation of the stimulus at the beginning of the attention shift together with the incoming position information during the shift establishes what is seen. In any case, the perceived position should be closer to the starting position, i.e. the Fröhlich effect would be decreased.

Another point is that both attentional approaches use different levels of description. While Kirschfeld and Kammer (1999) selected a neuronal level of description to address masking and attentional processes, the attention-shifting account of Müsseler and co-workers (Müsseler & Aschersleben, 1998; Müsseler & Neumann, 1992) was framed in a functional formal way, which leaves the neuronal processes unspecified. Therefore, Müsseler, Stork and Kerzel (2002; see also Müsseler &

Tiggelbeck, 2013) attempted to identify the attention-shifting component in the neuronal models of Kirschfeld and Kammer (1999) and particularly in the dynamic-field account of Jancke and Erlhagen (Jancke et al., 1999; Jancke & Erlhagen, 2010). The dynamic-field account, originally developed to explain the activity of neuronal populations in the primary visual cortex of the cat (Jancke et al., 1999) and then successfully applied to perceptual mislocalizations with moving stimuli (for an overview, see Jancke & Erlhagen, 2010), assumes that the presentation of a stimulus forms an activation pattern which is not restricted to the area covered by the stimulus (see also Hubbard, 1994, 1995). Rather it spreads its activation to and integrates contextual information from the adjacent parts of the visual field. Therefore, in response to an afferent input, the activation is assumed to interact with new incoming information and, thus, modifies suprathreshold activity.

When a stimulus moves through the visual field, it can be assumed that the incoming information contributes to and modifies the activation pattern in such a way that a stimulus-driven bow wave of activity occurs, which moves continuously across the visual scene (Müsseler, Stork, & Kerzel, 2002). Depending on velocity, it peaks at or even ahead of the leading edge of the stimulus. Since the Fröhlich effect emerges in the build-up phase of the bow wave, activation is accumulated starting from the resting level. The movement resulted in a skew wave that exceeds the perceptual threshold (distance between resting level and supraliminal activation) and the Fröhlich effect is observed. It has been suggested that spreading subthreshold activation constitutes a neuronal correlate of a cue-induced attentional mechanism that alters the processing of spatial information (Bocianski, Müsseler & Erlhagen, 2008, 2010; Kirschfeld & Kammer, 1999; Müsseler & Tiggelbeck, 2013; Steinman, Steinman, & Lehmkuhle, 1995). We will come back to this point in Section 3.

2.4 Mental extrapolation (Visual prediction)

Mental extrapolations often occur in everyday life. When, for instance, a tennis ball flies through the visual scene, a spatial lag between the ball's position in the real world and its perceived position should emerge from neuronal transmission latencies. In order to hit the ball with a racket successfully, there must be some form of compensation, and this compensation might be in the motor system (e.g., Kerzel & Gegenfurtner, 2003). It overcomes the lag by predicting the position of the moving target forward.

However, in Nijhawan's view (1994, 2008; see also Hubbard, 2016, this volume, chap. 9(?)), the lag is not (only) compensated by motor predictions, but also by visual predictions. In this view, the flash-lag effect can be understood as the visualized percept of this prediction. The flash lags, because the visual system extrapolates the position of the moving target and this is what is seen. Thus, in the strong version of the extrapolation assumption, stimuli in motion are perceived at their real-time positions and do not lag behind. Alternative accounts assume different perceptual latencies for the flash and the moving target (e.g. Baldo & Klein, 1995; Whitney & Murakami, 1998).

The extrapolation assumption is controversially debated (see, e.g., the discussion in Nijhawan, 2008; Baldo & Klein, 2008; Krekelberg, 2008; Whitney, 2008). Although also seen as an explanation for the Fröhlich effect (e.g. Maus, Weigelt, Nijhawan & Muckli, 2010), it is especially difficult to see how an extrapolation mechanism works at the onset position of moving stimuli. Predicting future positions of a target requires some knowledge about the target's motion direction and velocity. As there is no preceding motion trajectory at motion onset, it is unclear how extrapolation could account for the Fröhlich effect. . Here one must probably recruit mechanisms that have been introduced in the previous sections.

As a last remark it should be noted here that a predictive component also exists in the masking-plus-focal-attention account (Kirschfeld & Kammer, 1998) and in the bow-wave account or dynamic field model, respectively (Erlhagen & Jancke, 2010; Müsseler, Stork & Kerzel, 2002). The difference is that visual prediction determines the percept while a pre-activation only prepares an area for the target to be seen.

3. Taking into account the mislocalization opposite to the direction of motion: the onset-repulsion effect

As already noted in the Introduction, some studies also found mislocalization opposite to the direction of motion. Note that this error is contrary to the Fröhlich effect: In the onset-repulsion effect (Thornton, 2002) the judged onset position of the target was found to be consistently mislocalized opposite to the direction of motion (Figure 1d; see also Actis-Grosso & Stucchi, 2003; Hubbard & Motes, 2002; Hubbard & Ruppel, 2011; Kerzel, 2002; Kerzel & Gegenfurtner, 2004).

Studies concerned with the onset-repulsion effect sometimes revealed contradictory findings. For instance, some studies found that an increment in velocity shifted the judged onset further opposite to motion direction (Kerzel, 2002; Thornton, 2002), whereas other studies did not find any effect of velocity (Actis-Grosso & Stucchi, 2003; Hubbard & Motes, 2002; Kerzel, 2002; Müsseler & Kerzel, 2004). Some authors found the onset-repulsion effect only with a relative judgment task (Kerzel, 2002), whereas others also with an absolute positioning task (Thornton, 2002; Müsseler & Kerzel, 2004). Further, the onset-repulsion effect seems to depend on motion type and motion direction. It is largest with smooth, continuous motions and decreases with implied motions (Kerzel, 2004; Thornton, 2002). Finally, upward motion or right-to-left motion resulted in stronger onset-repulsion effects than downwards or left-to-right motion (Thornton, 2002).

It is obvious that accounts in terms of sensation time, metacontrast or attention simply do not apply to these findings, most obviously because perceptual processes could never have been triggered at positions where the target was never presented (opposite to target motion). Instead, explanations of the onset-repulsion effect often refer to non-perceptual mechanisms. For instance, it is possible that the onset position is accurately perceived but is distorted during the delay before the judgment is made. In this case the onset-repulsion effect would originate from a memory failure, similar to the proposed mechanisms underlying representational momentum (Freyd & Finke, 1984; for an overview see Hubbard, 2016, this volume, chap. 8(?)). It is also possible that in this case observers have an imprecise percept of the onset position and tend to estimate the origin of the motion post hoc, which is subject to biases (see below).

However, mislocalizations of the type of representational momentum are in the direction of motion and a mechanism is needed to explain why the onset-repulsion effect is in the opposite direction. Therefore it has been discussed that estimations of the onset position run backwards along the observed trajectory as this reflects more natural, physical tendencies (Thornton, 2002). In the same vein, Runeson (1974) reported that observers perceive an illusory deceleration at the onset of a motion even when the physical velocity is constant. This may result in an opposite error if the post-hoc estimation of the onset position is calculated on the basis of constant motion along the entire trajectory.

The most critical point, however, is how to explain the contrary findings of the Fröhlich and onset-repulsion effects. It turned out that the experimental procedures used to measure the mislocalizations were quite different. In reports of the Fröhlich effect, observers were able to predict where the moving target would appear. For instance, the moving target always appeared at the fixed edge of a window (Fröhlich, 1923) or at two fixed eccentricities to the left or right of fixation (Müsseler & Aschersleben, 1998). In reports of the onset-repulsion effect, however, the moving target appeared randomly in a relatively large area (Thornton, 2002; Hubbard & Motes, 2002) and observers were unable to predict the onset positions.

To examine the hypothesis that the error in motion direction (Fröhlich effect) and the error opposite to motion direction (onset-repulsion effect) originated from the predictability of onset positions, Müsseler and Kerzel (2004; see also Müsseler, Stork & Kerzel, 2008) conducted experiments in which two different trial contexts were used. In the random context, the target appeared mostly at a random onset position in a large area of the computer screen (similar to Thornton, 2002), but in one sixth of the trials the target appeared at about 6.6° to the left or right of fixation (Fig. 3). Only these trials of the random-context condition were compared with the trials of the constant-context condition, in which the target always appeared at the onset positions to the left or right of fixation (similar to Müsseler & Aschersleben, 1998). The judgments showed a huge difference between context conditions: The onset was localized -0.5° opposite to the direction of motion in the random-context condition (onset-repulsion effect) and 1.5° in the direction of motion in the constant-context condition (Fröhlich effect). Thus, low predictability of onset positions led to the error opposite to the direction of motion, while high predictability of onset positions led to the error in the direction of motion.[4]

[4] Note, however, that a mislocalization opposite to target motion has not always been observed in the random-context condition. In the study of Müsseler and Kerzel (2004) the error was in the direction opposite to target motion in three of four experiments. Further studies (Müsseler, Stork & Kerzel, 2008; Müsseler & Tiggelbeck, 2013) also found a clear difference between random-context and constant-context condition, but the error was always in direction of motion. The reason might be that the exploitable trials of the random-context condition were still presented above chance level at the left/right positions.

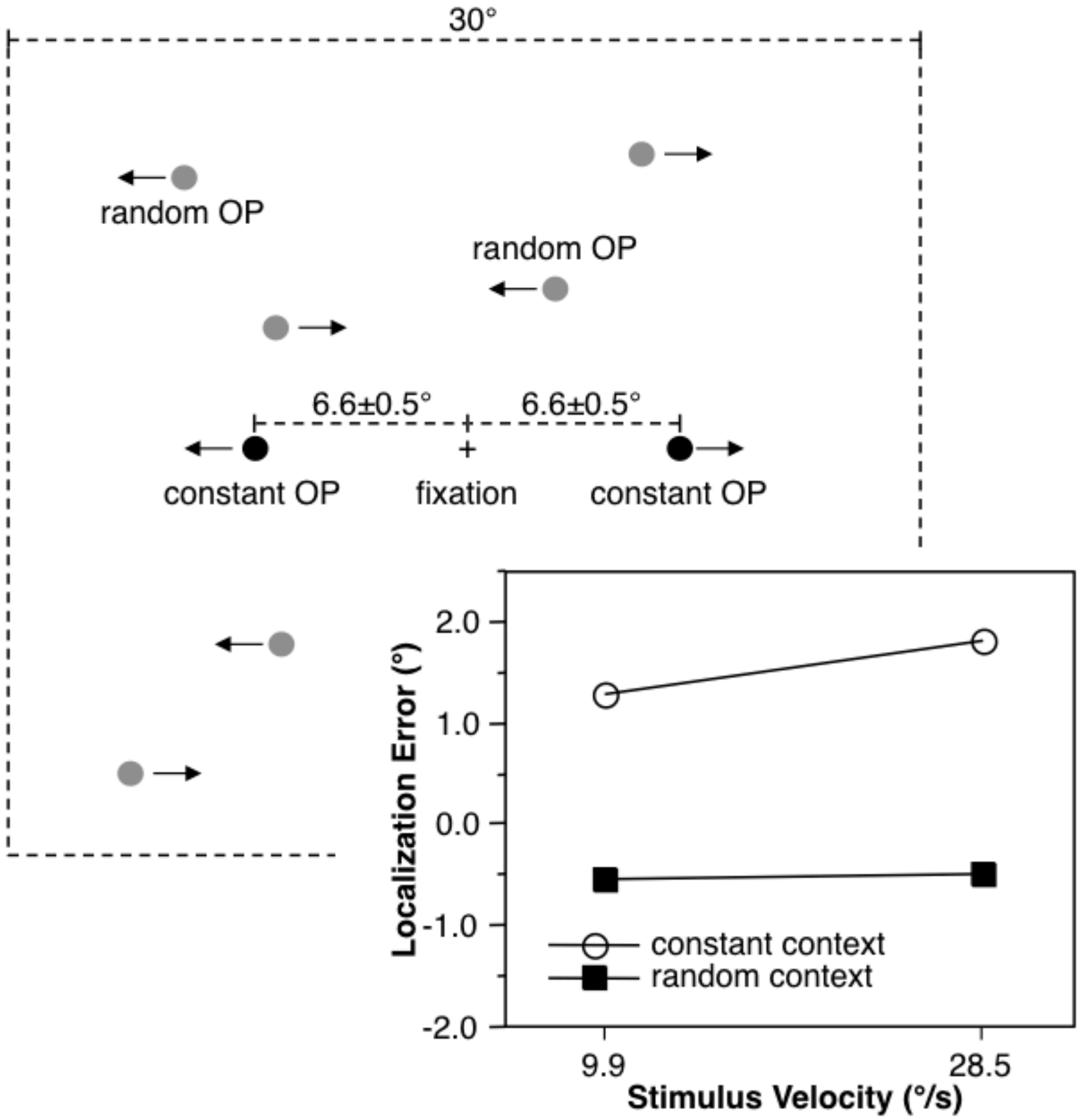

Figure 3: Trial contexts and findings of Müsseler and Kerzel (2004, Ex. 1). In the constant trial context, the target always appeared at constant onset positions (OP, black dots) to the left or right from fixation. In the random trial context, the target appeared mostly at random OPs (grey dots) in a 30x30° field of the computer screen, but in one sixth of the trials also at the constant OPs. In the data analysis, only these trials were compared with the trials of the constant context. The results showed that the onset was localized opposite to the direction of motion with the random context (negative localization error of -0.5°; onset-repulsion effect) and in the direction of motion with the constant context (positive localization error of 1.5°; Fröhlich effect).

With other authors (Actis-Grosso & Stucchi, 2003; Kerzel, 2002; Kerzel & Gegenfurtner, 2004; Thornton, 2002), we assumed that the difference between context conditions originates from an error in the judgment phase. When positional predictability is low, as is the case in the random-context condition, observers may notice a target relatively late, and with every new trial they might become aware of a possible localization error. To avoid this error, they may overcompensate and point to positions opposite to motion. Consistent with strategic adjustments, differences between the random- and constant context conditions were visible after about 15-35 trials (Müsseler & Kerzel, 2004, Ex. 4).

However, further experiments by Müsseler and Tiggelbeck (2013) casted doubts on the overcompensation explanation. With regard to the overcompensation explanation, the error opposite to motion direction is assumed not to be a perceptual one but to result from the tendency in the judgment phase to correct for the possible spatial error. Consequently, an overcompensation mechanism should mainly affect a localization task, but not a discrimination task. In an experiment of Müsseler and Tiggelbeck (2013, Ex. 1), moving targets either started out as squares and changed to circles at different positions on the trajectory, or appeared as circles and did not change (cf. also Ansorge, Carbone, Becker, & Turatto, 2010). Observers' task was to discriminate whether or not they perceived a square during the motion of the target. The overcompensation account expected equal or worse discrimination performance in the random-context condition than in the constant-context condition. This result would point out a response bias, which compensates for a possible localization error in the judgment phase. However, the contrary finding was observed: When the squares appeared in the very first positions of the motion, better discrimination performance was found in the random-context condition than in the constant-context condition. Thereafter, the difference between context conditions vanished.

This finding came with some surprise as it indicates worse perceptual performance in the constant-context condition. And this disadvantage of the constant-context condition was somewhat counterintuitive: When stimuli always appeared at predictable left/right positions, as is the case in the constant-context condition, observers can direct their attention to both positions in advance (parallel allocation of visual attention to two positions; cf. Awh & Pashler, 2000; Cave, Bush, & Taylor, 2010; Franconeri, Alvarez, & Enns, 2007; but see also Jans, Peters, & De Weerd, 2010). Directing attention to a position usually improves spatial localization in this area, as was found in several studies with stationary targets (e.g. Bocianski, Müsseler, & Erlhagen, 2008, 2010; Tsal & Bareket, 1999, 2005; Tsal, Meiran, & Lamy, 1995; Yeshurun & Carrasco, 1999). Therefore, observers in the constant-context condition of Müsseler and Tiggelbeck (2013) had not directed their attention to the left/right onset positions or alternatively, directing attention to these positions produced worse localization performance.

To examine the last possibility, Müsseler and Tiggelbeck (2013, Ex. 3) used an exogenous cue to direct attention in the random-context condition. The cue was presented at the onset positions, 280 ms before the moving target appeared. If –with moving stimuli– directing attention results in worse localization performance, presenting the cue should result in comparable mislocalizations in both context conditions. And this was what the results actually showed. When the cue preceded the motion onset, the localization error of the random-context condition increased in size relative to the localization error of the constant context[5]. Thus, Müsseler and Tiggelbeck's experiments delivered consistent results. When observers allocated their attention to the onset position, worse discrimination performance (Ex. 1) went hand in hand with worse localization precision (Ex. 3).

An issue that remains unexplained is why attention improves discrimination and localization performance with stationary stimuli while it seems to impair discrimination and localization precision at the onset position of moving stimuli. We speculated that contrary to stationary stimuli, moving stimuli require fast spatial disengagement (Petersen & Posner, 2012) from the previously attended position in order to follow the stimulus, especially at the onset position. It seems plausible that this disengagement could impair processing.

How to implement this idea in the neuronal dynamic field model discussed in the previous section? Bocianski and co-workers (2008, 2010) already applied the model to an illusion with stationary stimuli and extended it by integrating a top-down attentional mechanism. In the empirical part of their paper, observers were confronted with blockwise presentations, similar to the random and constant context used by Müsseler and Kerzel (2004). The authors assumed that the blockwise presentation of a target at constant positions modulates the attentional baseline by arousing a peak at attended locations and by suppressing all other locations (for neuronal evidence see e.g. Bestmann et al., 2007; Smith, Singh, & Greenlee, 2000). Empirical and modelling data showed that localization precision was improved when the static target was presented in the attended area (Bocianski et al., 2010).

When instead of stationary stimuli, a moving target is presented at the attended area, the only assumption to add is that the target might have left the region of the attentional peak already before a suprathreshold activity is reached. Moreover, the new incoming information of the target may interact within the previous activation pattern, which may additionally impair localization performance. In a sense, the postulated mechanism is similar to that accounting for effects of spatial disengagement from previously attended positions.

Note, that this extension of the neuronal dynamic field model can only account for the observed differences between the random and constant context; that is, for the clear mislocalizations in motion direction in the constant-context condition and the more or less precise localizations in the random-context condition. It cannot account for the onset-repulsion effect per se, that is for the error opposite to motion direction.

4. Conclusion

The present paper focuses initially on the Fröhlich effect -- the localization error at the onset position in motion direction. In the nearly century-old scientific debate on this illusion, different accounts were considered and discarded, among them the sensation-time account and masking account. But it is worth emphasizing that these

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[5] Interestingy, the opposite finding is observed with representational momentum, where a cue decreases (but does not eliminate) forward displacement (Hubbard, Kumar, & Carp, 2009).

accounts did not simply disappear, but have been modified by additional findings. For instance, the sensation-time assumption is still discussed in the context of the flash-lag effect, with different latencies for the flash and the moving target (e.g., Baldo & Klein, 2008; Krekelberg, 2008; Whitney, 2008), or in the context of the Fröhlich effect, with longer latencies at the onset position than at later positions on the trajectory (e.g., Aschersleben & Müsseler, 1999; Kirschfeld & Kammer, 1999).

The underlying processing mechanisms in localizing the onset position of moving stimuli were further clarified by the discovery of the onset-repulsion effect, that is, the error opposite to motion direction. As it turned out in several studies, the localization judgments varied strongly with trial context. Perceived starting positions were in the direction of motion in constant-context conditions and opposite to motion direction (or -at least- essentially reduced) in random-context conditions (Müsseler & Kerzel, 2004; Müsseler et al., 2008; Müsseler & Tiggelbeck, 2013). It is likely that when stimuli always appeared at predictable positions, as is the case in the constant-context condition, observers direct their attention to the positions in advance. However, one would then expect that localization precision is improved, but the opposite was found. Localization precision and discrimination performance was worse with constant than with random context.

Trial context was also found to affect localization judgments with stationary stimuli (Bocianski et al., 2008, 2010), but here the findings were as expected (see also Tsal & Bareket, 1999, 2005; Tsal, Meiran, & Lamy, 1995; Yeshurun & Carrasco, 1999). Localization precision was better with constant-context conditions than with random-context conditions. To account for these differences in the findings between stationary and moving stimuli, we speculated that moving stimuli require a spatial disengagement from the previously attended onset position in order to follow the target. It seems plausible that this attentional disengagement could impair processing. Certainly, this idea needs further confirmation, but if this conclusion proves to be true, attentional disengagement should be at the heart of explanations of the Fröhlich effect.

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