
The speed prior account:

A new theory to explain multiple phenomena regarding dynamic information

Simon Merz¹, Paula Soballa¹,

Charles Spence², & Christian Frings¹

¹Department of Psychology, University of Trier, Germany

²Department of Experimental Psychology, University of Oxford, United Kingdom

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Address for correspondence : Simon Merz
Department of Psychology, Cognitive Psychology
Universitätsring 15
54286 Trier
Germany
Email : merzs@uni-trier.de
Phone : +49 651 / 201 2907

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2. Abstract

Our perception of moving stimuli is prone to systematic biases. Different biases, for example concerning the perceived speed, or spatial location, of a dynamic, moving stimulus, have consistently been reported in the literature. Different lines of experimental research, together with different theoretical explanations, have emerged analysing and discussing these biases separately. In the present study, we propose a new theoretical account to unite various effects relating to dynamic / moving stimuli: The speed prior account. The perceived location of a stimulus is suggested to reflect the combination of the sensory input, which is associated with uncertainty, and a prior expectation concerning stimulus speed. Discrepancies between the prior speed expectation and the actual speed of a stimulus then result in a distortion of perceived stimulus speed, leading to the various perceptual biases that have been observed. In the present study, we demonstrate that this new theory can already account for robust data patterns currently unexplained in the literature, while we additionally directly test the predictions of the new speed prior account across four experiments. The influence of stimulus speed was manipulated in two visual, as well as two tactile studies (all $N = 30$). The results reveal a clear data pattern, consistent with the speed prior account, as perceived onset and offset location reveal strong interdependencies. The implications and possible future questions for the perception of moving stimuli, in particular, and dynamic information, more generally, are discussed.

Keywords: Speed prior account; Localization; Motion perception; Representational Momentum; Fröhlich effect; Onset Repulsion Effect; Touch; Vision

3. Introduction

In our everyday lives, we are constantly exposed to dynamic objects. Perhaps unsurprisingly, therefore, research into the cognitive mechanisms underlying the perception of dynamic stimuli have long been of interest (e.g., Fröhlich, 1923; Wertheimer, 1912). To date, many different perceptual biases relating to dynamic objects have been evidenced and explored, for example, concerning stimulus localization (see Hubbard, 2005, 2014a; 2018b; Müsseler & Kerzel, 2018), angular trajectory in 3D space (Welchmann et al., 2008), hierarchical (global and local) motion (Gershman et al., 2016; Yang et al., 2021), approaching and receding motion (Neuhoff, 1998, 2018), spatio-temporal interactions (e.g., Goldreich, 2007), and the contrast-dependent speed perception of dynamic objects (Thompson, 1982; Thompson et al., 2006). Interestingly, however, although the investigators who have demonstrated the different perceptual biases share a common interest in trying to understand the cognitive mechanisms underlying the perception of dynamic objects, these biases, and especially the theoretical accounts used to explain them, have been developed in isolation. Here, we propose a novel theoretical account that prior expectations concerning stimulus speed, an extension of a theory originally proposed to explain the Thompson effect (static prior account, Weiss et al., 2002), can be adapted to make qualitative predictions concerning the perceived localization of the onset and offset location of a dynamic stimulus (subsequently called the speed prior account). Additionally, we test the predictions of the speed prior account against the predictions of classical localization accounts and evidence a stronger fit of the results observed to the predictions of the former account.

3.1. Localization biases for dynamic stimuli

In 1923, Fröhlich described a new phenomenon in which the onset of a suddenly appearing, dynamic object was perceived to be shifted in the direction of its subsequent motion (for a visualization, see Figure 1A). This forward shift in the direction of motion, subsequently

1 termed the Fröhlich effect, initially received a great deal of attention from researchers (e.g.,
2 Fröhlich, 1925; Metzger, 1932), and was ‘rediscovered’ in the 1990s (e.g., Kirschfeld & Kam-
3 mer, 1999; Müsseler & Aschersleben, 1998). Over the years, different theoretical accounts have
4 been put forward to explain this forward shift, discussing this perceptual bias as a possible result
5 of lateral inhibition or sensation time / processing latencies (for an extensive discussion, see
6 Kerzel, 2010; Müsseler & Kerzel, 2018). Yet, the research (and theoretical formulations) only
7 focused on this specific phenomenon, the forward shift at stimulus onset. Interestingly, in con-
8 trast to most accounts of the Fröhlich effect, activation models such as the bow-wave model
9 (Müsseler et al., 2003) or the neuronal dynamic field model (Erlhagen & Jancke, 2002; Jancke
10 & Erlhagen, 2010) were proposed with the expressed intent to not just explain one bias. That
11 is, while the account explained the forward shift at the onset position (Fröhlich effect), it also
12 explained the commonly observed forward shift at stimulus offset, termed Representational
13 Momentum (Freyd & Finke, 1984; for reviews, see Hubbard, 2005, 2014a, 2018a).¹

14 The activation models describe the forward shift at stimulus onset in part as a conse-
15 quence of the time taken for the relevant neuronal activation, corresponding to the moving
16 stimulus, to build up (for a visualization, see Figure 1B). While the stimulus moves, the corre-
17 sponding neuronal activation also shifts in the direction of motion. As the activation reaches
18 the threshold (at which the stimulus can be perceived), the activation has already shifted in the

¹ Over the years, a number of different theoretical accounts have been put forward to explain the Fröhlich effect (for reviews, see Kerzel, 2010; Müsseler & Kerzel, 2018) and Representational Momentum (for review, see Hubbard, 2010). Yet, the activation model was chosen as one example of the classic existing theories as those who proposed it envisioned that it would not only explain localization biases at either onset or offset, but would actually explain both. Additionally, the other existing theories all predict an increase of the forward shift with increasing speed (see the aforementioned reviews), therefore meaning that their predictions are not substantially different than the predictions of the activation models. For the sake of clarity, only the activation models are used as the example of the classical localization theories.

1 direction of motion, thus resulting in the forward shift. Similarly, as the stimulus disappears,
2 the activation takes time to decay and fall below the activation threshold. While the activation
3 decays, the momentum from the motion carries the activation even further in the direction of
4 motion, resulting in the forward shift at stimulus offset as well. This account can explain much
5 of the observed evidence concerning the perceived forward shift at stimulus onset as well as
6 offset (Müsseler et al., 2003).

7 In 2002, a new observation was reported in which the onset was not shifted in the direc-
8 tion of subsequent motion, but rather against it (known as the Onset Repulsion effect; Thornton,
9 2002). As the stimulus onset was actually perceived at a location at which the stimulus had
10 never been presented, this introduced a robust challenge to the theories explaining the Fröhlich
11 effect, such as the activation models. A backward shift could not be easily explained in terms
12 of the existing theories. Subsequent research has indicated that the main factors influencing the
13 occurrence of either a forward or backward shift at stimulus onset are stimulus velocity (slower
14 speed: Onset Repulsion effect; faster speed: Fröhlich effect, e.g., Kerzel & Gegenfurtner, 2004)
15 and stimulus context / onset position predictability (random onset position: Onset Repulsion
16 effect; constant onset position: Fröhlich effect; e.g., Müsseler & Kerzel, 2004; Müsseler et al.,
17 2008; Müsseler & Tiggelbeck, 2013). Müsseler and Kerzel (2018) discussed a number of at-
18 tempts that have been made over the years to incorporate the possibility of a backward shift at
19 stimulus onset, but eventually concluded that no satisfactory theoretical explanation yet exists.
20 Moreover, this backward shift was not just observed in some circumstances for the perceived
21 onset location, but also for the perceived offset location, especially when stimulus speed was
22 fast (Offset Repulsion effect; e.g., Merz, Deller, et al., 2019; Munger & Owens, 2004; Müsseler
23 et al., 2003). Even more critically, in those studies that explicitly investigated both perceived
24 stimulus onset as well as offset within a single experimental paradigm, a forward shift at one
25 end of the stimulus trajectory was found to go hand-in-hand with a backward shift at the other

(i.e., a Fröhlich effect together with an Offset Repulsion effect: Müsseler et al., 2003; Onset Repulsion effect together with a Representational Momentum effect: Actis-Grosso & Stucchi, 2003; Actis-Grosso et al., 2008; Hubbard & Motes, 2002, 2005; see also Thornton, 2002³). This observation constitutes a strong challenge to all of the models that have been proposed thus far, as no theory specifically predicts a forward shift at stimulus onset simultaneously with a backward-shift at stimulus offset, or vice versa. What is more, the possible occurrence of the Offset Repulsion effect on its own is not typically discussed and systematically explained in the literature, comparable to a lack of explanation for the Onset Repulsion effect. Therefore, any new account to explain biases in the localization of dynamic stimuli needs to be able to explain the occurrence of all four perceptual biases (forward shift and backward shift for the onset as well as the offset location). Furthermore, any new theory should also be able to explain why a forward shift at stimulus onset should go hand-in-hand with a backward shift at stimulus offset, or vice versa. Here, we propose just such an account.

3.2. Expectations about stimulus speed as a determinant of perceived stimulus speed

³ Readers familiar with Thornton's (2002) study might be interested in the fit of the study's results with the suggestion of a forward shift at the one end and a backward shift at the other end of the trajectory, especially given that the study's data seemingly does not fit in this categorization. That is, while a robust backward shift at stimulus onset was evidenced across the experiments and the different speed conditions, results at stimulus offset were much less clear, sometimes with an observed backward shift, sometimes with an observed forward shift (e.g., Experiments 1 and 2 in that study). In our view, the results of perceived stimulus offset are difficult to interpret, because some likely confounding influence might not have been accounted for. That is, the study was designed to investigate perceived stimulus onset (since it was the first introduction of a backward shift at stimulus onset in the literature). Therefore, the experiments were designed to prevent confounding influences at stimulus onset. For example, by restricting stimulus onset to occur within a 4° visual angle square centered on the center of the screen to prevent eccentricity effects to systematically influence perceived onset results (e.g., Sheth & Shimojo, 2001). Yet, with a fixed distance travelled of 3° to 6° visual angle, the eccentricity of stimulus offset was much greater, confounding the perceived offset results with possible eccentricity effects. Since after stimulus offset, the center of the screen needed to be fixated as the cursor to indicate perceived location was presented there, this might have introduced systematic eccentricity effects (this might be even more pronounced in Experiment 2 in which the center of the screen needed to be fixed during stimulus presentation). Even more problematic, these eccentricity effects might have been different for different stimulus speed conditions, making an interpretation of perceived stimulus offset very difficult. Additionally, participants were asked to respond to the onset location first before then indicating the offset location. This might have introduced systematic biases due to first fixating on the perceived / remembered onset location, which then might have biases the subsequent localization of the offset towards the onset location.

Onset and Offset localization of dynamic stimuli

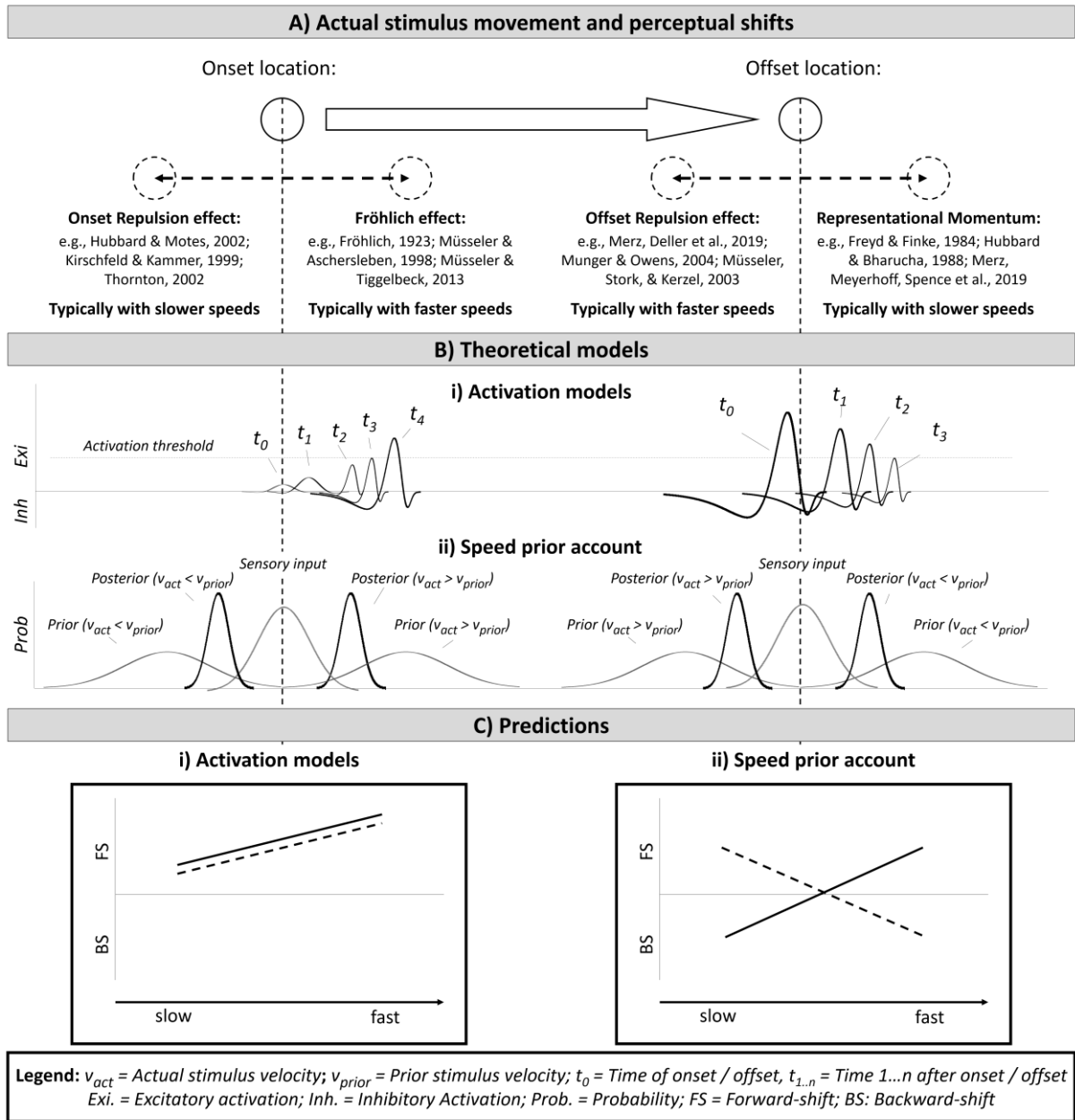


Figure 1. Illustration of the stimulus moving from left-to-right and the perceptual shifts evidenced in the literature (A) and the two theoretical models (B) to explain these perceptual biases concerning stimulus onset (left side) and offset (right side). Additionally, the contrasting predictions (C) concerning the influence of speed on perceived onset (solid line) and perceived offset (dotted line) from the activation models (left side) and speed prior account (right side). See main text for further information.

- 1 In 1982, Thompson evidenced a perceptual bias in which a dynamic stimulus was per-
- 2 ceived to be moving more slowly when it was presented with lower contrast (relative to the
- 3 background). That is, under increased uncertainty (lower contrast), the perceived speed of the
- 4 stimulus was shown to diminish. Weiss and colleagues (Weiss et al., 2002; see also Stocker &

Simoncelli, 2006) proposed that this perceptual bias occurred as a result of prior expectations concerning stimulus speed. This model predicts that spatial perception is primarily based on two assumptions. First, the neural response to a stimulus is assumed to be noisy, causing uncertainty about the exact nature of the perceptual input. Second, a prior expectation about dynamic stimuli exists, which is that the stimulus does not move at all (static prior account; for a detailed argument as to why we might have such a prior expectation, see Weiss et al., 2002; see also Goldreich, 2007). To date, this notion has provided an explanation for many different perceptual biases in vision (Thompson, 1982; Weiss & Adelson, 1998; Welchmann et al., 2016), audition (Senna et al., 2015), and touch (Goldreich, 2007). The work of Daniel Goldreich (2007) and colleagues (see Goldreich & Tong, 2013; Tong et al., 2016) is especially interesting here, as they adopted this static prior idea to explain not just biases in perceived stimulus speed, but also biases concerning perceived stimulus location. That is, as soon as two successive stimuli, presented at two different locations, are perceived, a speed is estimated and combined with the static prior expectation (following Weiss et al., 2002). Therefore, a length contraction is always predicted, the final perception of the stimulus is always slower than its actual speed as the prior of no speed decreases the final perceived speed, subsequently leading to length contraction.

The static prior account provides an explanation for classical spatio-temporal illusions, for example, the cutaneous rabbit illusion (whereby illusory tactile stimuli are localized as occurring in between two spatially separate tactile stimulations; i.e., Geldard & Sherrick, 1972) or the tau effect (i.e., shorter temporal intervals between two stimuli reduces the perceived spatial distance between them; Helson 1930). In these and related illusions, the distance between two (or more) successive tactile stimuli (e.g., taps) is typically underestimated (the perceived distance is shorter than the actual distance between successive taps; see Goldreich, 2007). Subsequently, according to this static prior account, a forward shift is always expected at stimulus

onset and a backward shift at stimulus offset. Yet, in its original form, the static prior account has several shortcomings. For one thing, it cannot explain a forward shift at stimulus offset (the Representational Momentum effect) or a backward shift at stimulus onset (the Onset Repulsion effect), which have been evidenced repeatedly and robustly over the last few decades. Additionally, evidence from studies of speed perception (e.g., Thompson et al., 2006; Hassan & Hammett., 2015) indicated that decreasing stimulus contrast does not always lead to the perception of a slower speed, but sometimes also increases the perceived speed of a stimulus. Additionally, studies have shown that perceived speed of a stimulus can be changed/adapted over the course of an experiment (Sotiropoulos et al., 2014). Similarly, for the localization of stimulus onset, changes in the experimental context / environment have been shown to change the perceived onset location (Müsseler & Kerzel, 2004; Müsseler & Tiggelbeck, 2013). These results cannot be explained by the static prior account that proposes a fixed and unchangeable prior expectation of zero (no speed). Therefore, these data pattern raise doubts about the fit of the static prior account in its current form as a generalizable principle for the perception of dynamic stimuli.

In line with the accumulated experimental evidence not fitting with the static prior account (as outlined in the preceding paragraph), it might also be questioned from an evolutionary perspective whether such a prior expectation is reasonable. In fact, always predicting a speed of zero as being the most likely percept would always lead to an underestimate of the speed of all moving objects. That is, perceiving a slower stimulus speed than is actually the case, thus never leading to an accurate estimation. It is not likely that our cognitive system is designed to always make judgment errors when it comes to moving stimuli, especially as always underestimating the speed of a stimulus might have negative consequences. For example, underestimating the speed of an approaching object will likely result in our being hit by it, as reaction time is probably too slow. It should be noted here that the localization of approaching / looming

objects has been investigated extensively over the years, and the accumulated data indicates that looming objects are typically localized further along their motion path, not fitting with the assumption of the static prior account (e.g., Neuhoff, 1998, 2018; for a more detailed discussion, see the General Discussion section).

3.3. The speed prior account

Therefore, we propose that the prior expectation is not centered on zero, but on a specific speed (for an illustration, see Figure 1B). In our view, this is a generalized principle concerning the perception of moving stimulus, that is, that the actual stimulus speed is combined with a prior expectation about stimulus speed giving rise to the final percept. This principle is thought to underlie and inform motion perception across different task settings (e.g., localization, interception, temporal and speed assessment), different motion types (e.g., implied motion, apparent motion, continuous motion) as well as across different sensory modalities (e.g., vision, audition, touch). In contrast to the static prior account, this change of a prior centring on an actual speed enables a correct perception of stimulus speed for moving stimuli in case of matching prior speed expectations and actual stimulus speed, whereas for the static prior account, this was not possible for any speed (for an extensive discussion, see the General Discussion section). Importantly, this new account makes several, testable predictions. The central prediction is that the occurrence of either a forward or backward shift at stimulus onset or offset should be strongly influenced by stimulus speed. When the predicted speed is slower than the actual stimulus speed, a contraction of the stimulus distance travelled is expected, in line with the predictions of the static prior account. That is, a forward shift at stimulus onset and a backward shift at stimulus offset is expected. More interestingly, when the predicted speed is faster than the actual speed, an extension of the stimulus distance travelled is predicted. That is, a backward

shift at stimulus onset, and a forward shift at stimulus offset is expected.⁴ Another important prediction is that changes in sensory acuity should change the influence of the prior expectation on the final, sensory percept. That is, with increased sensory acuity, the influence of the prior expectation decreases, leading to a weaker / no perceptual shift and to a more accurate localization of the stimuli. In our view, the prior speed expectation is likely to be flexible, possibly adapting to specific features of the experimental environment or to (short) term trial history, which we discuss in more detail in the General Discussion.

Before explicitly testing the central prediction of this new speed prior account, a closer look at the literature already shows a promising fit of the existing peer-reviewed empirical data to the predictions of the speed prior account (for a more extensive discussion, see the General Discussion section). That is, in general, the Onset Repulsion effect (backward shift at stimulus onset) and Representational Momentum effect (forward shift at stimulus offset) are typically elicited at slower speeds, around 20°/s and below (e.g., Freyd & Finke, 1984; Kerzel & Gegenfurtner, 2004), whereas those studies that have evidenced the forward shift at stimulus onset (Fröhlich effect, e.g., Müsseler et al., 2003) or a backward shift at stimulus offset (Munger & Owens, 2004) have typically used higher stimulus speeds. Furthermore, as evidenced by those studies that have investigated both perceived onset as well as offset (e.g., Actis-Grosso & Stucchi, 2003; Actis-Grosso et al., 2008; Hubbard & Motes, 2002; Müsseler et al., 2003; Thornton, 2002), the speed prior account predicts that a forward shift at one end of the stimulus will be accompanied by a backward shift at the other. This shows that the speed prior account is con-

⁴ See Tong et al. (2016, p. 377) for a discussion of the possibility of a length extension when the prior expectation is not centered on zero speed in the context of possibly training participants to build a prior expectation centered on a specific speed.

sistent with many different results that have been published already (at least in a *post hoc* manner); yet, we designed further experiments in order to explicitly test and contrast the different predictions of the two accounts.

4. The present study

The present study directly tests the different predictions of the activation models and the speed prior account. The two accounts make specific predictions about the influence of speed on the perceived onset as well as offset position (for an overview of the predictions, see Figure 1C), which are tested across four experiments. Classical localization theories such as the activation models predict a forward shift for the onset as well as the offset location, as both should increase with increasing stimulus speed. In contrast, according to the speed prior account, the perceived onset and offset should mirror each other. For slow speeds, a backward shift at stimulus offset and a forward shift at stimulus onset are expected. For fast stimulus speeds, a forward shift at stimulus onset, and a backward shift at stimulus offset, are predicted. Four experiments were designed to test the differing predictions by the speed prior account as well as the activation models. That is, the first two used a typical visual experimental set-up with circular, continuous motion stimuli, which were always presented briefly (i.e., for just a short time - 250 ms) across all different stimulus speeds. The experimental set-up of the other two experiments was designed to differ in some regards to increase the generalizability of the results. Therefore, a tactile, implied motion sequence, presenting horizontal motion along the forearm and using a different localization task (direct localization of the target with a stylus on a touchscreen for the tactile experiments vs. indicating perceived location with the help of a probe stimulus) was used. Stimulus presentation time differed with changes in stimulus speed, but travelled distance was kept constant across speeds.

To foreshadow the results, the patterns of data observed across all experiments were in line with the speed prior account, but not with activation models. That is, for slower speeds, perceived onset indicated a backward shift (Onset Repulsion effect), whereas perceived offset indicated a forward shift (Representational Momentum effect). With increasing speeds, this data pattern reverses, that is, a forward shift at stimulus onset (Fröhlich effect), and a backward shift at stimulus offset (Offset Repulsion effect), was evidenced.

5. Experiment 1a

In our first experiment, a dynamic visual target stimulus was used. This moved continuously along a circular path, and perceived stimulus onset and offset was assessed by asking participants to move a probe stimulus (identical to the moving target) around the circle in order to indicate perceived first or final location (for a comparable task designs, see Müsseler et al., 2003). Indicating perceived onset or offset was manipulated blockwise. This experimental set-up allowed us to test perceived onset and offset location across multiple different speed condition, that is, six (from 2 to 0.0625 revolutions per second) different speed conditions were tested in Experiment 1a. The dynamic target stimulus was always presented for 250 ms.

5.1. Method

5.1.1. Participants

Visual localization biases on their own typically elicit medium to large effect sizes (d_z around 0.6), therefore we aimed for at least 26 participants to find a shift at the minimum ($\alpha < .05$; $1-\beta > .90$; power analyses were run with G-Power 3.1.9.2, option ‘means: difference from constant’; Faul et al., 2009). To account for possible drop-outs, 30 participants were tested, four of whom were excluded from the final sample (for more details, see the Design, data-preparation and analysis section). The final sample (18 female, 8 male, 1 left-handed, 19-28 years,

mean age: 22.08 years) consisted of 26 students from the University of Trier who participated for partial course credit. All of the participants gave active informed consent prior to participation.

5.1.2. Apparatus and stimuli

The experiment was conducted online and programmed with PsychoPy and its built-in online translation PsychoJS (Peirce et al., 2019), data was collected via pavlov.org. The participants were asked to use a computer or laptop of their choosing, no tablets, touchscreens or smartphones were allowed. If an operating system for a mobile device was detected, the experiment was not started. The final experimental set-ups were different for the participants - in the following, number of participants is given in brackets. Participants used the touchpad of a laptop as mouse (16) or an external computer mouse (10) following self-report. As operating system, the Apple Mac OS (7) as well as Microsoft windows (19), and as browser, Google Chrome (11), Safari (5) and Mozilla Firefox (10) were detected. All screens used a 60 Hz refresh rate, yet, resolutions different markedly between participants: 2560x1440 (1); 1920x1080 (1); 1600x900 (1); 1536x864 (5); 1440x900 (5); 1368x912 (3); 1366x768 (3); 1280x800 (2); 1280x720 (5). Actual size of the screen (e.g., in cm or inch) was not assessed. The circular path was centred on the center of the screen (circle line width of 1 pixel), the radius of the circle was 160 pixels (see Figure 2A) and presented in white (RGB-value: 0,0,0) on a grey background (RGB-value: 127,127,127). A white fixation cross ('+') in 15 x 15 pixels was used and presented at the center of the screen. The moving target and the probe were filled white circles with a radius of 7 pixels. JASP (Version 0.14.1; JASP Team, 2020) was used for frequentist data analyses as well as for Bayesian data analyses (for an introduction to the interpretation of Bayesian ANOVA, see Van den Bergh et al., 2020).

5.1.3. Procedure

The trial procedure is visualized in Figure 2B. Each trial started with the presentation of the circular path and the fixation cross for 600 ms. Following this, the target stimulus was presented, and directly started to move in a clockwise direction. The target was presented for 250 ms, and the target travelled with different, constant speeds: 0.0625 rotations per second (in the following *rps*), 0.125 rps, 0.25 rps, 0.5 rps, 1 rps, and 2 rps. One rotation corresponds to the target travelling along the complete circular path one time (360° angular distance). The values can be transformed to distance along the circular path in pixels by multiplying it with two times the radius of the circle (2*160) and with the number pi. Therefore, in pixels, these values corresponds to 62.8 pix/s; 125.7 pix/s, 251.3 pix/s; 502.7 pix/s; 1005.3 pix/s; 2010.6 pix/s. Before the onset of the probe stimulus, a 500 ms blank interval was presented to prevent any spurious motion between the probe and target stimulus. The onset location of the probe stimulus, as well as of the target stimulus, was chosen at random. Participants could move the probe along the circular path in either a clockwise or counterclockwise direction with the help of the “d”, “f”, “j”, and “k” keys of the keyboard. Specifically, the probe was shifted in bigger steps (1/20 rotation; letters “d” and “k”) or smaller steps (1/1000 rotation; letters “f” and “j”) to allow for most accurate localization of the target stimulus. To save the indicated location, the space bar was pressed, which then started a new trial.

The experiment consisted of two experimental blocks (in which either perceived stimulus offset or onset was assessed, this was randomized across participants) and one short practice block. The participants completed 6 practice trials (one from each speed condition) to get familiar with the task in general. This was followed by 96 experimental trials per block (16 repetitions of 6 different stimulus speeds).

5.1.4. Design, data-preparation and analysis

Onset and Offset localization of dynamic stimuli

The participants were tested in a 2 x 6 design with the two within-participants factors of *task* (onset vs. offset localization) and *speed* (62.8 pix/s vs. 125.7 pix/s vs. 251.3 pix/s vs. 502.7 pix/s vs. 1005.3 pix/s vs. 2010.6 pix/s). The dependent variable was computed as the localization error. Absolute x- and y-axis scores in pixels and the respective orientation on the circle (in degree; with 0 corresponding to the x/y-coordinate in pixel of 160/0 pixel; 90° equals 0/-160 pixel; 180° equals -160/0; and 270° equals 0/160) were obtained for each trial.

In a first step, trials from the practice block were discarded. In a second step, trials in which the initial (randomly selected) and final (indicated location by the participant) probe location were identical were discarded from data analysis, as this indicates no active localization

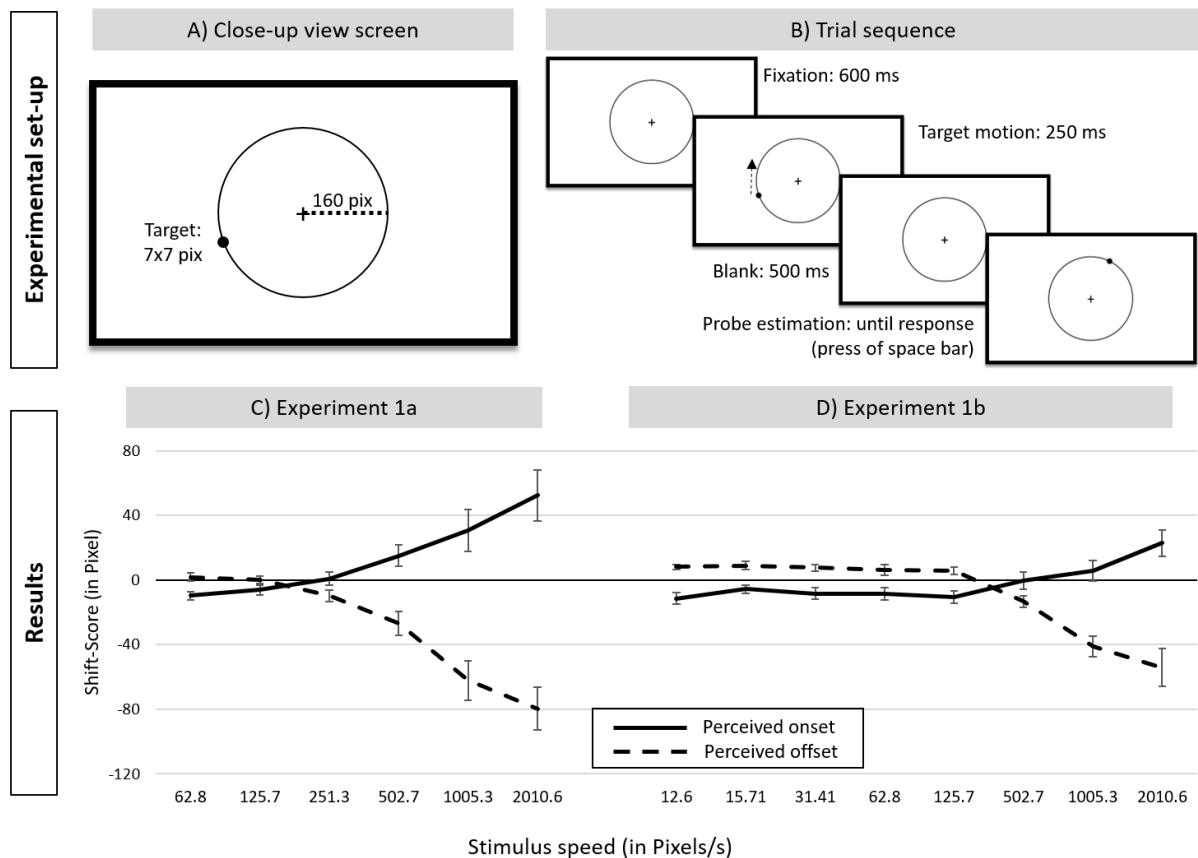


Figure 2: Experimental set-up and results of Experiments 1a and 1b. Experimental Set-up: Close-up view of the screen with a circle radius of 160 pixels and the target size of 7x7 pixels (A), and a sample trial sequence of the experiment (B). Results: Mean shift scores as a function of task (onset vs. offset) and speed for Experiment 1a (C) and 1b (D). The solid lines represent the perceived onset location, whereas dotted lines represents perceived offset location. Error bars represent the standard errors of the mean.

(e.g., erroneous bar press). Yet, it might also have been a strategy to finish the task as rapidly as possible. Therefore, the number of trials still included per participant were analysed. Four participants, were above the 1.5 interquartile range below the first quartile (Tukey, 1977). Therefore, these four participants were excluded from data analysis. In a next step, shift scores were computed. A positive value indicates a shift in the direction of the continuous motion, while a negative value indicates a shift in the direction opposite to that of continuous motion. Shift scores in pixels along the circular path are reported. Yet, the values can be easily transformed into angular errors by multiplying the shift scores in pixels by 360° and then dividing it by the product of twice the radius of the circle (2×160 pix) and the number pi. A 2 (task) \times 6 (speed) analysis of variance (ANOVA) was conducted. Note that all experimental procedures, raw data as well as analyses scripts are available via OSF (Merz, 2021).

5.2. Results & Discussion

The 2 (task: onset vs. offset) \times 6 (speed: 62.8 pix/s vs. 125.7 pix/s vs. 251.3 pix/s vs. 502.7 pix/s vs. 1005.3 pix/s vs. 2010.6 pix/s) ANOVA revealed a significant main effect of task, $F(1, 25) = 15.03$, $p < .001$, $\eta_p^2 = .375$, indicating an overall negative shift (-29.3 pix) for the offset location, and a positive shift for the onset location (13.8 pix). No main effect of speed, $F(1.79, 44.76) = 1.78$, $p = .182$, $\eta_p^2 = .067$, but, crucially, a significant interaction between task and speed was observed, $F(1.33, 33.19) = 36.34$, $p < .001$, $\eta_p^2 = .592$. As shown in Figure 2C, the influence of speed was opposite for stimulus offset and onset, as predicted by the speed prior account. That is, for the slowest speed condition (62.8 pix/s), a backward shift was observed for stimulus onset (-9.71 pix), $t(25) = -3.75$, $p < .001$, $d = 0.74$, $BF_{10} = 36.68$, whereas no shift was observed for stimulus offset (1.72 pix), $t(25) = 0.68$, $p = .500$, $d = 0.13$, $BF_{10} = 0.26$. Importantly, this completely reversed for the fastest speed condition (2010.6 px/s), in which a forward shift for stimulus onset (52.4 pix), $t(25) = 3.33$, $p = .003$, $d = 0.65$, $BF_{10} =$

14.58, and a backward shift for stimulus offset, $t(25) = -5.94$, $p < .001$, $d = 1.16$, $BF_{10} = 5779.29$, was observed. Importantly, the same 2 (task: onset vs. offset) x 6 (speed: 62.8 pix/s vs. 125.7 pix/s vs. 251.3 pix/s vs. 502.7 pix/s vs. 1005.3 pix/s vs. 2010.6 pix/s) Bayesian ANOVA with uniform prior probabilities indicated the model including the interaction as the best model, $BF_M = 5.32 \times 10^{16}$, and this model was much more likely than the next best model, $BF_{01} = 1.35 \times 10^{16}$.

The results of this first experiment are in line with the predictions of the speed prior account, that is, the influence of stimulus speed at stimulus onset is opposite to the influence of speed at stimulus offset. Even more, not finding a main effect of speed indicated a symmetrical course of change between the perceived onset and offset location. Whereas an Onset Repulsion effect (backward shift) at stimulus onset was observed for slower speeds, this gradually changed into a Fröhlich effect (forward-shift) with increasing speed. In contrast, this data pattern was reversed for stimulus offset, although for the slow speed condition, a descriptive Representational Momentum effect was observed, but not statically indicated.

6. Experiment 1b

Experiment 1b was designed as a conceptual replication of Experiment 1a, but with an even greater number of stimulus speed conditions, especially focusing on the slower speed range. That is, in Experiment 1a, the faster stimulus speed conditions were in line with the predictions of the speed prior account (Fröhlich effect and Offset Repulsion effect), in the slower speed condition, only the expected Onset Repulsion effect, but not the Representational Momentum effect was observed.

6.1. Method

6.1.1. Participants

Sample size calculations were identical to Experiment 1a. One participant was excluded from the final sample. The final sample (15 female, 14 male, 3 left-handed, 19-31 years, mean age: 23.32 years – one participant did present his birth year instead of age, 1996, corresponding to 24/25 years of age) consisted of a total of 29 participants, 7 of which participated without any compensation, all other were students from the University of Trier who participated for partial course credit. All of the participants gave active informed consent prior to participation.

6.1.2. Apparatus and stimuli, procedure, design, data-preparation and analysis

Experiment 1b was identical to Experiment 1a except for the following changes. The final experimental set-ups were different for the participants - in the following, number of participants is given in brackets. Participants used the touchpad of a laptop as mouse (15) or an external computer mouse (14) following self-report. As operation system, the Apple Mac OS (10) as well as Microsoft windows (19), and as browser, Google Chrome (12), Safari (7) and Mozilla Firefox (10) were detected. All screens used a 60 Hz refresh rate, yet, resolutions different strongly between participants: 2560 x 1440 (1); 1920x1080 (4); 1536x864 (6); 1525x858 (1); 1440x900 (10); 1440x810 (1); 1368x912 (1); 1366x768 (2); 1280x720 (3). A credit-card size procedure was conducted at the beginning of the experiment, in order to match pixel resolution to actual screen size. Yet, half of the participants did not adjust the size of the card in any regard, indicating a lack of conducting this task, and therefore, this data was not analysed.

The task design was adopted to a 2 (task: Offset vs. Onset) x 8 (speed: 12.6 pix/s vs. 15.71 pix/s vs. 31.41 pix/s vs. 62.8 pix/s vs. 125.7 pix/s vs. 502.7 pix/s vs. 1005.3 pix/s vs. 2010.6 pix/s) design. The practice trials was adjusted to eight (one for each stimulus speed), trial number per block was still 96 (12 repetitions of 8 different speeds). One participant was excluded from data analysis following the same data preparation criteria.

6.2. Results & Discussion

The 2 (task: onset vs. offset) x 8 (speed: 12.6 pix/s vs. 15.71 pix/s vs. 31.41 pix/s vs. 62.8 pix/s vs. 125.7 pix/s vs. 502.7 pix/s vs. 1005.3 pix/s vs. 2010.6 pix/s) ANOVA revealed in contrast to Experiment 1a no main effect of task, $F(1, 28) = 2.74$, $p = .109$, $\eta_p^2 = .089$, but a main effect of speed, $F(2.10, 58.79) = 5.67$, $p = .005$, $\eta_p^2 = .168$. Once again, as for Experiment 1a, a significant interaction between task and speed was observed, $F(2.19, 61.43) = 34.53$, $p < .001$, $\eta_p^2 = .552$. As Figure 2D shows, the influence of speed was opposite for stimulus offset and onset, as predicted by the speed prior account. That is, for the slowest speed condition (12.6 pix/s), a backward shift was observed for stimulus onset (-11.48 pix), $t(28) = -3.16$, $p = .004$, $d = 0.59$, $BF_{10} = 10.52$, whereas a forward shift was observed for stimulus offset (8.19 pix), $t(28) = 5.18$, $p < .001$, $d = 0.96$, $BF_{10} = 1326.21$. Importantly, this completely reversed for the fastest speed condition (2010.6 px/s), in which a forward shift for stimulus onset (22.87 pix), $t(28) = 2.84$, $p = .008$, $d = 0.53$, $BF_{10} = 5.28$, and a backward shift for stimulus offset (-54.15 pix), $t(29) = -4.69$, $p < .001$, $d = 0.87$, $BF_{10} = 391.58$, was observed. Importantly, the same 2 (task: onset vs. offset) x 8 (speed: 12.6 pix/s vs. 15.71 pix/s vs. 31.41 pix/s vs. 62.8 pix/s vs. 125.7 pix/s vs. 502.7 pix/s vs. 1005.3 pix/s vs. 2010.6 pix/s) Bayesian ANOVA with uniform prior probabilities indicated the model including the interaction as the best model, $BF_M = 1.03 \cdot e^{31}$, and this model was much more likely than the next best model, $BF_{01} = 4.65 \cdot e^{30}$.

The results of Experiment 1b replicated the central findings of Experiment 1a. That is, in line with the predictions of the speed prior account, the influence of stimulus speed at stimulus onset is opposite to the influence of speed at stimulus offset. Furthermore, all four perceptual biases have been evidenced within one experimental design, with slower speeds resulting in the Onset Repulsion effect and Representational Momentum effect, and faster speed resulting in the Fröhlich effect and the Offset Repulsion effect. Crucially, these results cannot be explained by existing frameworks such as the activation models.

Interestingly, the two experiments differ regarding the findings of the main effects. That is, a main effect of task, but not of speed, was observed for Experiment 1a, which was reversed for Experiment 1b. Changes in the main effect of task were not surprising. As the first experiment used faster stimulus speeds overall, averaging across all stimulus speeds should have resulted in more observations in forward shifts at stimulus onset, and more backward shifts at stimulus offset, following the speed prior account. This trend was observed in Experiment 1a, but not in Experiment 1b. Yet, this is not so surprising as more slower speeds were used as well as one faster stimulus speed was dropped from the design (251.3 pix/s). The main effect of speed can be seen as an indication of a symmetrical (no main effect) or asymmetrical (main effect) course of change between perceived stimulus offset and onset. The speed prior account would predict a symmetrical course of change between perceived stimulus offset and onset, as the influence of the prior expectation should influence perceived offset and onset comparably across the different speed conditions. Therefore, when averaged across task, shift scores should be similar across speed conditions. This was observed for Experiment 1a, but not for Experiment 1b. This is surprising, especially since the asymmetry in Experiment 1b is driven by the faster speed conditions in Experiment 1b (see Figure 2D, the three fastest speed conditions). Yet, these three conditions were identical in Experiment 1a, which did not indicate an asymmetrical course of change between perceived onset and offset location. Possibly, the uncontrolled nature of online tasks might have contributed to this observation, so subsequent laboratory studies need to be conducted in order to answer this specific question more clearly.

7. Experiment 2a

This second line of experiments (Experiment 2a and 2b) was designed to test the generalizability of the speed prior account in a different sensory modality, touch. Experiment 2a was

designed to investigate the localization of a dynamic stimulus in touch. Tactile research is sparse (although there is no particular theoretical reason for this; see Gallace & Spence, 2014), and the theories discussed in this manuscript don't make modality specific predictions for the spatial senses (e.g., vision, audition, & touch; for the activation models, see the review by Hubbard, 2010, J Müsseler, personal communication, 03 June 2019; for the static prior account, see Weiss et al., 2002; Goldreich, 2007). The neural processing of motion is, in many respects, very comparable between vision and touch (for an extensive discussion, see Pei & Bensmaia, 2014). Therefore, the tactile experiments allow for an additional test and generalization of the results that were observed in Experiments 1a and 1b. However, a few differences in the specific experimental tasks (implied motion vs. continuous motion; linear motion vs. circular motion; direct localization vs. probe localization) should be noted. This variation helped to make sure that the results were not simply the result of specific task settings, and to match the variety of tasks that have been used in the literature (for reviews, see Hubbard, 2018a; Müsseler & Kerzel, 2018). These studies also allow for an analyses of the (a)symmetrical course of change between the perceived offset and onset location, for which the two visual experiments indicated differing results. Please also note that in contrast to the visual experiments, shift scores are not computed by comparing perceived location of the dynamic stimulus to actual location as in Experiment 1a and 1b, but by comparing the perceived location of the dynamic stimulus to the perceived location of a speed independent control stimulus. The usage of a speed-independent comparison condition is necessary to account for general, motion-independent localization biases, which are often observed during tactile localization (e.g. Brooks et al., 2019; see Merz, Meyerhoff et al., 2019, for a discussion).

7.1. Methods

7.1.1. Participants

Tactile localization biases on their own typically elicit medium to large effect sizes (d_z around 0.6), therefore we aimed for at least 26 participants to find a shift at the minimum ($\alpha < .05$; $1-\beta > .90$; power analyses were run with G-Power 3.1.9.2, option ‘means: difference from constant’; Faul et al., 2009). To account for possible drop-outs, 30 participants were tested. The sample (19 female, 2 left-handed, 19-27 years, mean age: 22.1 years) consisted of students from the University of Trier. All of the participants gave written informed consent prior to participation.

7.1.2. Apparatus and stimuli

The participants were tested in a dark, sound-attenuated laboratory. A touchpad (7', resolution: 1680 x 1050 pixels; PPI: 265), operated with the corresponding touch stylus was attached to the left forearm. On the back of the touchpad, five tactors (Model C-2, Engineering Acoustic, Inc.; 3 cm in diameter, centrally located skin contactor of 0.76 cm) were attached and used to present vibrotactile stimuli (~250 Hz, about 126 μm peak-to-peak amplitude) to the volar side of the forearm (see Figure 3A). The five tactors were arranged in a straight line with an approximate center-to-center distance of 3.5 cm (365 pixels, see Figure 3B). To avoid any distraction from the sound elicited by the tactors, the participants wore earplugs (noise reduction: 29 dB) and over-ear headphones through which brown noise (simultaneously-presented frequency distribution with higher intensities at lower frequencies, about 85 dB) was presented

7.1.3. Procedure

Each trial consisted of the successive presentation of three vibrotactile stimuli (for an illustration, see Figure 3C). To manipulate the speed of the stimuli, both the duration and ISI were either 100 ms (fast condition) or 250 ms (slow condition). Furthermore, a medium speed was realized by either using a duration 250 ms and ISI 100 ms, or vice versa. Duration and ISI were kept constant for the whole trial. Therefore, final speed of the stimuli were approximately

17.5 cm/s (fast), 10 cm/s (medium) and 7 cm/s (slow), respectively. After the third vibration, the participants indicated the perceived location of the first or last stimulus with the stylus on the touchpad. With their response, the participants completed the current trial and automatically started the next one. The participants indicated either stimulus onset (first vibration) or offset (last vibration) in two separate blocks. In half of the trials (motion condition), the three tactile stimuli implied motion, that is, the stimuli were presented adjacent to each other translating in a consistent direction in every trial. In the other half of trials (control condition), the locations were selected randomly without replacement with the restriction that motion trials never occurred. Depending on the current task, all the trials started or ended on the middle three factors locations (B, C or D, see Figure 3B). For a motion in the proximal direction (i.e., towards the elbow), the central location C (sequence: E – D – C) or the outer location B (sequence: D – C – B) were used as the relevant locations. For those trials indicating motion in the distal direction (i.e., toward the wrist), the central location C (sequence: (A – B – C) or the outer location D (sequence: B - C – D) were used.

At the start of each block, the participants completed 16 practice trials (random selection). This was followed by 256 experimental trials per block, 2 (stimulus type) x 2 (location) x 2 (direction) x 3 (speed) x 8 (repetitions). Please note, as the medium speed condition was comprised of either an ISI of 250 ms and a duration of 100 ms or vice versa, medium speed trials were presented twice as often compared to slow or fast speed trials.

7.1.4. Design, data-preparation and analysis

The participants were tested in a 2 x 2 x 2 x 2 x 3 design with the five within-participants factors: *task* (onset vs. offset localization), *stimulus type* (motion vs. control), *location* (central vs. outer), *direction* (proximal vs. distal), and *speed* (fast vs. medium vs. slow). The dependent

variable was computed as the localization error. Absolute x- and y-axis scores in pixels were obtained for each trial.

In a first step, a speed-independent comparison condition was conducted by averaging all control trials over the different speed conditions for each estimated factor location and task condition separately. The usage of a speed-independent comparison condition is necessary to account for general, motion-independent localization biases, which are often observed during tactile localization (e.g., Brooks et al., 2019). The dependent variable was then computed as the difference of the x-axis scores in pixels between the location estimation of motion trials and the speed-independent comparison condition. A positive value indicates a shift in the direction of the implied motion, while a negative value indicates a shift in the direction opposite to that of implied motion. For example, a positive shift (forward shift) indicates a mean localization closer to the elbow for the proximal implied motion condition as compared to the comparison condition. Since the focus of the study was on the influence of speed on the localization of the onset or offset location, the analysis reported in the main text was reduced to a 2 (task) x 3 (speed) ANOVA. For violations of sphericity, Greenhouse-Geisser corrections were used. The full 2 (task) x 2 (location) x 2 (direction) x 3 (speed) ANOVA with mean shift scores as the dependent variable is reported in Appendix Table 1, all data will be made publicly available via OSF upon publication.

7.2. Results and discussion

A 2 (task: onset vs. offset) x 3 (speed: fast vs. medium vs. slow) ANOVA revealed neither a significant main effect of task, $F(1, 29) = 2.70, p = .111, \eta_p^2 = .085$, nor of speed, $F(2, 58) = 0.24, p = .787, \eta_p^2 = .008$. Yet, crucially, a significant interaction between task and speed was observed, $F(1.32, 38.19) = 12.84, p < .001, \eta_p^2 = .307$ (for an illustration, see Figure 3D).

That is, just focusing on stimulus *offset*, a significant forward shift occurred in the *slow* condition, $t(29) = 4.03$, $p < .001$, $d = 0.74$, $BF_{10} = 80.00$, and for the fast condition, no shift was evidenced, $t(29) = 0.08$, $p = .934$, $d = 0.015$, $BF_{10} = 0.20$. Interestingly, focusing on stimulus *onset*, this pattern was reversed. Here, a significant forward shift occurred in the *fast* condition, $t(29) = 3.02$, $p = .005$, $d = 0.56$, $BF_{10} = 8.45$, indicating a Fröhlich effect. Decreasing stimulus speed resulted in an Onset Repulsion effect for the fast speed condition, $t(29) = -2.91$, $p = .007$, $d = 0.53$, $BF_{10} = 6.21$. Additionally, a 2 (task: onset vs. offset) x 3 (speed: fast vs. medium vs. slow) Bayesian ANOVA with uniform prior probabilities was conducted. The results are in line with the frequentist approach, that is, the model including the interaction was the best-fitting model, $BF_M = 283.23$, and was over 100 times more likely than the next best-fitting model which just included the main effect of task, $BF_{01} = 107.67$.

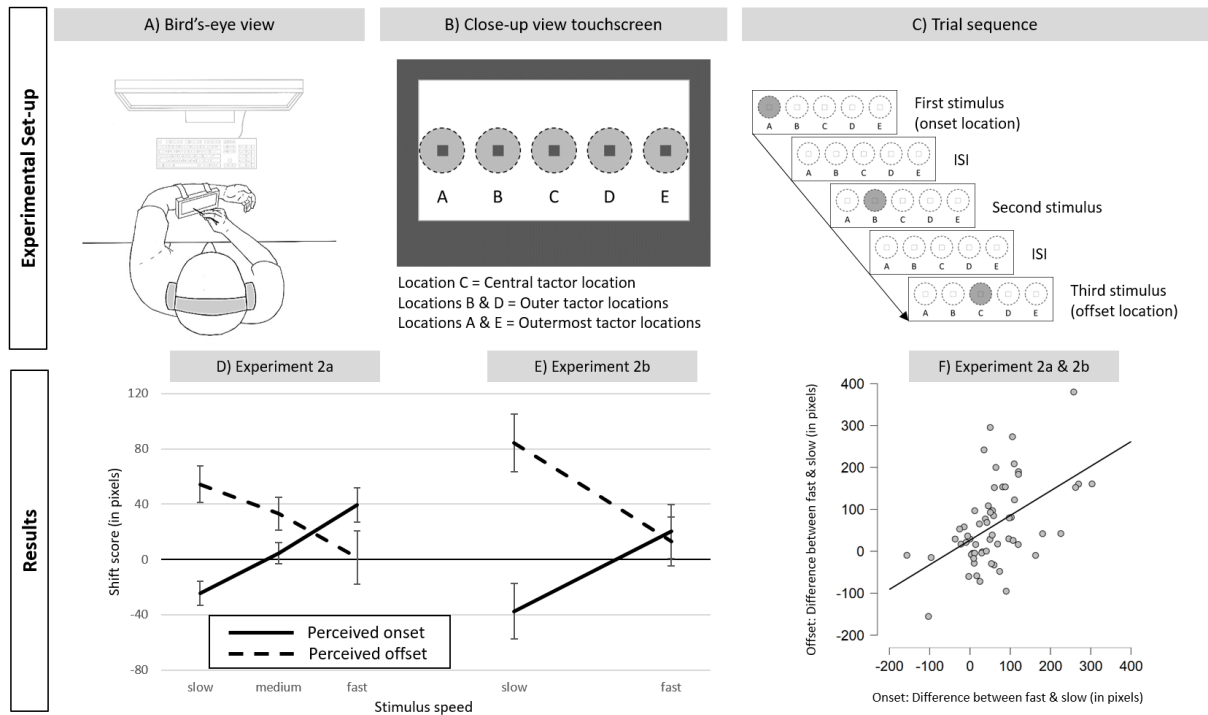


Figure 3: Experimental set-up and results of Experiments 2a and 2b. Experimental set-up: Bird's-eye view of the set-up (A), close-up view of the tactors attached to the back of the touchpad (B), and a sample trial sequence of the experiment (C). Results: Mean shift scores as a function of task (onset vs. offset) and speed (fast vs. medium vs. slow) for Experiment 2a (D) and for Experiment 2b (E). The solid lines represent the perceived onset location, whereas dotted lines represent the perceived offset location. Error bars represent the standard errors of the mean. (F) Correlation of the speed difference score (fast vs. slow condition) between the onset (x-axis) and offset (y-axis) localization, both experiments.

The results of Experiment 2a are in line with the prediction that speed has an opposing influence on the localization of either the onset or offset location. That is, for the offset location, a forward shift was evidenced for slower speeds, indicating the classical Representational Momentum effect, which subsequently decreased with increasing speed. In contrast, for the onset location, a backward-shift (Onset Repulsion effect) turned into a forward shift (Fröhlich effect) with increasing speed. These results are in line with the predictions of the speed prior account, and deviate from the predictions of the activation models (backward shift at stimulus onset, as well as decrease of the forward shift with increasing stimulus speed at stimulus offset not predicted). Moreover, not evidencing a main effect of speed is in line with the predictions of the speed prior account, given the symmetrical course of change between perceived offset and onset location. Yet, in Experiment 2a as well as all Experiment 1a and 1b, the estimation of either the onset or offset locations were manipulated in a blockwise manner, therefore the participants did not have to keep the complete trajectory of the stimulus in mind. Therefore, Experiment 2b was designed to replicate the central finding concerning the influence of speed on perceived onset and offset location from Experiment 2a, while manipulating onset and offset estimation trialwise.

8. Experiment 2b

8.1. Method

8.1.1. Participants

Once again, thirty students (24 female, 4 left-handed, 19-32 years, mean age: 23.4 years) from the University of Trier took part in the study. All the participants gave written informed consent prior to participation.

8.1.2. Design, apparatus, stimuli, procedure, and analysis

The design, apparatus, stimuli and procedure were mainly identical to Experiment 2a with the following exceptions. Instead of three speeds, only two (the fast and the slow from Experiment 2a) were realized. Furthermore, the different tasks (onset and offset estimation) were no longer tested in separate blocks of trials but were selected at random on every trial. Therefore, after the third vibration, the whole background of the touchpad changed colour indicating whether the participants should react to the first or last vibration. A red signal implied the estimation of the stimulus offset, while a green signal should lead to the estimation of the stimulus onset. The background colour stayed red/green until the participants responded. After that, the colour of the touchpad turned back to black and the next trial started automatically. The participants completed 16 practice trials (random selection), followed by 320 experimental trials, 2 (task) x 2 (stimulus type) x 2 (location) x 2 (direction) x 2 (speed) x 10 (repetitions). The dependent variable was calculated as in the previous experiment. Once again, the analysis reported in the main text was reduced to a 2 (task) x 2 (speed) ANOVA. For the full 2 (task) x 2 (location) x 2 (direction) x 2 (speed) ANOVA with mean shift scores as dependent variable, see the Appendix (see Table 1).⁵

8.2. Results and Discussion

A 2 (task: onset vs. offset) x 2 (speed: fast vs. slow) ANOVA was conducted. As in Experiment 2a, neither the main effects of task, $F(1, 29) = 3.30$, $p = .080$, $\eta_p^2 = .102$, nor of

⁵ Due to the experimental change, namely that the participants were informed after stimulus presentation about which stimulus location they were to estimate, this might have introduced errors by responding to the wrong stimulus location (stimulus offset compared to stimulus onset, and vice versa). Although this might have introduced erroneous responses, it is very unlikely that these errors would have systematically biased / changed performance in specific conditions due to the completely within-participants nature of our experimental design. Yet, to account for this possibility, we excluded those trials with a location estimation (in pixels) whose x- or y- axis scores differed more than 1.5 interquartile ranges from the first or third quartile of each individual participant (Tukey, 1977). This was done for each of the three estimated locations (locations B, C, and D) and task types (onset vs. offset localization) individually (for similar approaches to data preparation, see Merz et al., 2020; Steenbergen et al., 2014). The same pattern of results was obtained as reported in the main text.

speed, $F(1, 29) = 0.61$, $p = .442$, $\eta_p^2 = .021$, were evidenced, but a significant interaction between task and speed was obtained, $F(1, 29) = 18.85$, $p < .001$, $\eta_p^2 = .394$. This result was supported by the Bayesian ANOVA analyses, which indicated the model including the interaction as the best fitting model, $BF_M = 21.05$. As Figure 3E indicates, the results closely resemble those of Experiment 2a. In particular, increasing speed led to a decrease of the shift scores for the offset location, while it led to an increase of the shift scores for the onset location. Therefore, the results of Experiments 2a and 2b were directly compared in a 2 (Experiment: 2a vs. 2b) x 2 (task: onset vs. offset) x 2 (speed: fast vs. slow) ANOVA, omitting the medium speed condition of Experiment 2a. Crucially, this analysis revealed no significant main effect or interaction involving Experiment, $F_s < 1.00$, $p_s > .321$, indicating similar results across both experiments. Once again, a significant interaction between task and speed was observed, $F(1, 58) = 34.55$, $p < .001$, $\eta_p^2 = .373$. This result was supported by the Bayesian ANOVA, which indicated the model including the interaction of task and speed as the best fitting model, $BF_M = 55.23$, and the next best-fitting model including the main effect of Experiment was more than 6 times less likely, $BF_{01} = 6.14$. For the offset location, a significant forward shift in the slow condition, indicating Representational Momentum, was documented, $t(59) = 5.58$, $p < .001$, $d = 0.72$, $BF_{10} = 24284.1$, but no shift in the fast condition was observed, $t(59) = 0.56$, $p = .578$, $BF_{10} = 0.164$. For the onset location, a significant backward shift for the slow condition, indicating an Onset Repulsion effect, occurred, $t(59) = -3.06$, $p = .003$, $d = 0.39$, $BF_{10} = 9.1$, which turned into a significant forward shift (Fröhlich effect) with increasing speed, $t(59) = 2.45$, $p = .017$, $d = 0.32$, $BF_{10} = 2.19$.

In a next step, the interdependencies between the perceived onset and offset locations were analysed at the level of the single participant. That is, mean shift scores (averaged across the fast and slow speed) for the onset and offset location correlated negatively, $r(60) = -.560$, p

1 < .001; $BF_{10} = 6288.24$, indicating that a stronger forward shift at the offset location (Representational Momentum effect) is accompanied by a weaker forward shift (Fröhlich effect) or a
2 stronger backward shift (Onset Repulsion effect) at the onset location. Furthermore, the data
3 from those participants whose responses indicated a strong effect of speed (difference between
4 the fast and slow condition) at stimulus offset also indicated a strong effect of speed at stimulus
5 onset, $r(60) = .521$, $p < .001$; $BF_{10} = 1183.32$ (for an illustration, see Figure 3F). This indicates
6 strong interdependencies between the influence of speed at stimulus offset and stimulus onset,
7 as predicted by the speed prior account. Additionally, testing the size of the influence of speed
8 at stimulus onset (mean difference of 61.5 Pixels) against the size of the influence of speed at
9 stimulus offset (mean difference of 62.2 Pixels) across participants reveals no significant dif-
10 ference, $t(59) = -0.06$, $p = .953$; $BF_{01} = 1.07$.

12 The results of Experiment 2b closely resemble the evidence documented in Experiment
13 2a. Once again, as supported by the combined analysis of both studies, the pattern of data at
14 stimulus offset is mirrored by the data pattern at stimulus onset. While a forward shift at stim-
15 ulus offset (Representational Momentum effect) and a backward shift at stimulus onset (Fröh-
16 lich effect) was observed for slow speeds, these shifts decreased with increasing stimulus speed.
17 Furthermore, as in Experiment 2a, not evidencing a main effect of speed is in line with the
18 predictions of the speed prior account, given the symmetrical course of change between per-
19 ceived offset and onset location. Furthermore, data analysis at the level of the individual par-
20 ticipant revealed strong interdependencies between the onset and offset localization. Those par-
21 ticipants who indicated a stronger forward shift at the offset location (Representational Mo-
22 mentum effect) also indicated a weaker forward shift (Fröhlich effect) or stronger backward
23 shift (Onset Repulsion effect) at the onset location. This very closely resembles the evidence
24 with a visual experimental set-up, in which Hubbard and Motes (2002) also evidenced a strong
25 correlation between the perceived onset and offset shift (see their Experiment 1). Moreover, the

effect of speed at stimulus onset was correlated with the effect of speed at stimulus offset, indicating that those participants who evidenced a strong change of the shift scores with changes of stimulus speed at stimulus offset also revealed robust changes at stimulus onset. Overall, the results of both experiments can best be explained by the speed prior account.

9. General Discussion

In four experiments, the predictions of the activation models were tested against the predictions of the newly-introduced speed prior account. The observed data patterns in all experiments are in line with the predictions of the speed prior account, but not with the predictions of the activation models. In contrast to the activation model, the speed prior account is able to explain the existence of a backward shift at stimulus onset as well as a backward shift at stimulus offset. Moreover, the speed prior account was the only account to predict a forward shift at stimulus offset for slow speeds, accompanied by a backward shift at stimulus onset. Additionally, the strong interdependencies observed in the data concerning the size of the shift scores, as well as the influence of speed, was predicted by the speed prior account.

The present results are consistent with much of the existing evidence with visual stimuli (e.g., Actis-Grosso & Stucchi, 2003; Actis-Grosso et al., 2008; Hubbard & Motes, 2002, 2005; Müsseler et al., 2003; Thornton, 2002), which, comparably to our own experiments, investigated the onset and offset localization within a single experimental set-up. All of these studies, as well as our observed pattern of data, indicated the same result, namely that if a backward shift was observed at onset, a forward shift at stimulus offset would be observed, or vice versa. The present results additionally build on this previous evidence by using a visual as well as tactile set-up to see if the data pattern observed in the visual modality can also be observed in the tactile modality, indicating a strong, robust and modality independent mechanism.

9.1. The speed prior account

In the Introduction, we outlined the central predictions of the speed prior account as they relate to the influence of stimulus speed on perceived onset and offset location. That is, length extension (backward shift at stimulus onset, forward shift at stimulus offset) for slower speeds and length contraction (forward shift at stimulus onset, backward shift at stimulus offset) for faster speeds is predicted, and we briefly discussed the (post-hoc) fit of existing evidence with our new framework. In this section, we want to extend this discussion, providing a more detailed description of the speed prior account, and, importantly, make more precise predictions about the course of change of the perceptual biases with changing stimulus speed (see Figure 4A for an illustration)⁶. Yet, before discussing the newly-proposed speed prior account in detail, interested readers might be wondering why our perceptual system should use prior experience to update the sensory input in general – especially as the sensory input is centered on the actual, correct location of the event. Therefore, not using any prior expectation would result in correct estimations on average, making it rather puzzling why we propose that our cognitive system uses prior expectations to inform the perceptual process which then results in systematic biases.

The advantage for our perceptual / cognitive system of using prior expectations is an uncertainty reduction and precision gain on the level of a single trial / encounter with an event. Sensory perception is inherently imprecise, starting with a limited resolution within the sensory organs (e.g., Johansson & Vallbo, 1979; Wässle et al., 1990), further amplified by the fact that the neural response to a stimulus is a stochastic process, adding more uncertainty (e.g., Knill & Pouget, 2004; Ma & Jazayeri, 2014). For the actual trial, it is helpful for our perceptual system

⁶ We would like to thank Daniel Goldreich for providing us with a computer program implementing the predictions of the speed prior account (similar to the leaping lagomorph application: http://psych.mcmaster.ca/goldreich-lab/LL/Leaping_Lagomorphs.html).

to reduce this uncertainty by combining it with an expectation based on prior experiences, resulting in an overall more precise perception of the actual sensation. Therefore, the consequence of a biased percept (on average) might be the result of a cognitive / perceptual architecture designed to reduce an acute uncertainty (for similar and more detailed arguments, see Clark, 2013; Friston, 2005). In fact, increased acute certainty is likely an important trait to allow for a safe and good interaction with dynamic objects. A close link between action and perception has been proposed several times (e.g., Hommel, 2009; Prinz, 1990; for recent theoretical developments, see Frings et al., 2020), and using prior expectations to inform perception might be an important mechanism to increase perceptual accuracy and therefore to allow for a better interaction with the environment.

9.1.1. A closer look at the speed prior account

In a first step, static stimuli without any movement are considered. Similar to our argument in the introduction that it is not sensible for our cognitive system to predict no speed to occur for moving stimuli, we also argue that it is not sensible to predict any speed for stimuli that are actually static. That is, no motion related biases for static stimuli are predicted, and therefore no bias is expected (but, please see that non-motion related biases for the localization of static stimuli in the different sensory modalities have been reported, see Sheth & Shimojo, 2001; Brooks et al., 2019; which is why we used a control condition to account for these non-motion related biases in the tactile experiments). Therefore, for very slow stimulus speed, the precise localization for static stimuli, as well as the influence of the prior speed expectation, both exert influence on the final percept, with the influence of the precise localization for static stimuli diminishing with increasing speed. For stimulus localization, this therefore results in increasing length extension with increasing speed (stronger backward shift at stimulus onset,

stronger forward shift at stimulus offset; see Figure 4A, for an illustration). The length extension reaches its maximum approximately at about half the speed of the expected speed before then once again decreasing when the actual speed approaches the prior speed expectation. When the actual stimulus speed is identical to the prior speed expectation, no perceptual shifts should be expected. With actual speed being faster than the prior speed expectation, length contraction (forward shift at stimulus onset, backward shift at stimulus offset) is predicted by the speed prior account, which increases with even faster stimulus speeds.

For the speed prior account, the central component is the prior speed expectation. This raises two important questions: On which speed is the prior speed expectation centred? And, is this speed expectation fixed or adaptable? In our own tactile results, the intersection between the biases at stimulus onset and offset occurred between the medium (10 cm/s) and fast (17.5 cm/s) condition in the tactile experiments. Therefore, based on these results, as well as similar evidence in the tactile literature (Whitsel et al., 1986), a speed expectation of about 10-15 cm/s

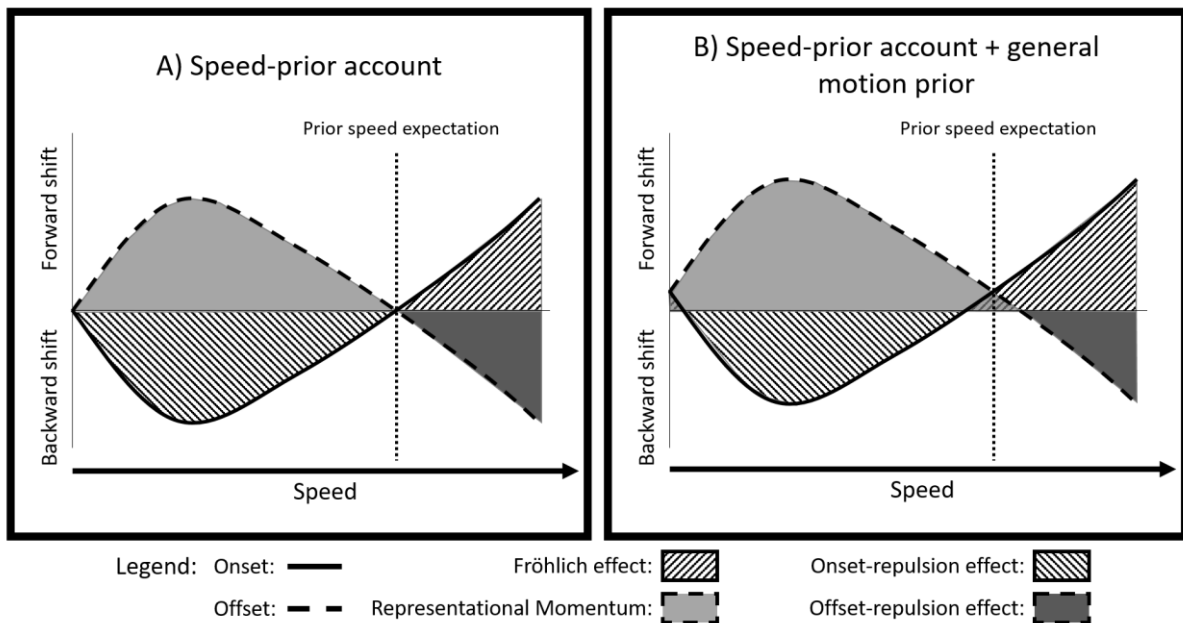


Figure 4: Visualization of the predictions concerning perceived onset (solid line) and offset (dotted line) location. (A) Predictions from the speed prior account solely. (B) Predictions by a combination of the speed prior account and general prior in motion direction, resulting in an overall tendency to localize a dynamic stimulus further along in its trajectory. That is, forward shift for onset as well as offset location become more likely. For further details, see main text.

1 is most likely. Interestingly, the spatio-temporal illusion for which the static prior account was
2 shown to have a high explanatory value (Goldreich, 2007; Goldreich & Tong, 2013; Tong et
3 al., 2016), typically used much faster stimulus velocities than 15 cm/s. Yet, for those speeds,
4 the speed prior account and the static prior account make comparable predictions, as length
5 contraction is predicted by the speed prior as well as static prior account. Yet, if and how these
6 values transfer to other sensory modalities, e.g., the visual modality, is unclear to this point⁷. In
7 fact, the absolute distance indication of stimulus speed by using cm/s is not typical in the visual
8 modality, that is, typically relative distance indications like degree of visual angle per second
9 ($^{\circ}/s$) is used. Given there is evidence that also tactile stimuli are perceived from a head centred
10 perspective (for discussion, see Arnold et al., 2017), the 10-15 cm/s on the forearm might be
11 approximated to about 19-28 $^{\circ}/s$ from a head-centred perspective (this was calculated by ap-
12 proximating the distance between the forearm and head at about 30 cm given the arm posture
13 in our experiment; please note that this is just an estimation, and this distance was not measured
14 in the experiment in any way). Interestingly, approximately around this speed range, the Onset
15 Repulsion effect (with slower speeds) turns into the Fröhlich effect (for an extensive discussion,
16 see Kerzel & Gegenfurtner, 2004). Similarly, the Offset Repulsion effect in vision is typically
17 evidenced with faster stimulus speeds than 20 $^{\circ}/s$ (e.g., Munger & Owens, 2004; Müsseler et al.,
18 2003), whereas the Representational Momentum effect typically uses slower motion stimuli
19 (e.g., Hubbard & Bharucha, 1988; Freyd & Finke, 1985).

⁷ Readers might be surprised by this sentence given the present study reports two visual experiments. Yet, due to the uncontrolled nature of the visual task (namely, an online study with the specific set-up, e.g., monitor size and resolution, not controlled; most importantly participants viewing distance and actual stimulus size are unknown), the results of Experiments 1a and 1b are not helpful in terms of this discussion. That is why we focus on the existing studies with much more controlled experimental settings, but think that future studies need to be designed to specifically investigate this question.

1 The second question concerns the adaptability of the prior speed expectation. In our
2 view, it would be sensible for our cognitive system that this is not a general / fixed expectation,
3 but that it can be adapted based on specific experiences. It might be likely that the general prior
4 speed expectation (as discussed in the previous paragraph) is shifted toward the speed statistics
5 of a specific experimental set-up. For example, when consistently presented with faster stimulus
6 speeds, the speed expectation is shifted towards a faster stimulus speed. There is already some
7 indication that human speed perception can be adapted due to long exposure to either high or
8 low stimulus speeds (e.g., Sotiropoulos et al., 2014). Similarly, the time perception literature
9 has identified many different local influences (e.g., the trial before) on perceived time, indicat-
10 ing a flexible mechanism underlying time perception (for discussions and reviews, see De Jong
11 et al., 2021; Grondin, 2010; Matthews & Meck, 2014; Shi et al., 2013). This resembles findings
12 in other perceptual judgments (e.g., magnitude estimation, Petzschner et al., 2015).

13 The adaptations discussed in the previous paragraph are thought to occur across blocks
14 (e.g., adaptation of speed expectation due to speed statistics of an experimental block / training)
15 or across trials (e.g., the trial before influences the upcoming trial). Yet, an adaptation might
16 also take place within a single trial⁸. In fact, at stimulus onset, the actual stimulus speed is very
17 much unclear, possibly leading to a stronger influence of any speed expectation than when ac-
18 tual speed could be more reliably sampled towards the end of the trajectory (stimulus offset).
19 That is, the weight of the prior speed expectation might decrease from the start towards the end
20 of the trajectory, or, alternatively, the sensory certainty about actual stimulus speed might in-
21 crease throughout a trial. While these are just speculations at this point, there is already some
22 evidence about within-trial changes of perceived stimulus speed. Illusory acceleration has been

⁸ We thank Ian Thornton who made this suggestion.

shown during the initial phase of a constantly moving stimulus, indicating different speed perception within one trial (e.g., Runeson, 1974).

9.1.2. *Explaining moderating influence with the speed prior account*

In the previous section, we showed how the speed prior account can explain the existence of all for perceptual localization biases evidenced in the literature, that is, the Fröhlich effect, the Representational Momentum effect, the Onset Repulsion effect as well as the Offset Repulsion effect. In the literature, several relevant moderators of the respective effects have been reported, and we want to discuss in the following sections some of the robust moderating influences reported in the literature and how the speed prior account could explain those.

First, researchers especially familiar with the Representational Momentum phenomenon might be interested in how the speed prior account could possibly explain “one of the most robust influences” (Hubbard, 2005, p. 828), that is that with increasing speed, the Representational Momentum effect typically increases⁹. This seemingly stands in contrast to the predictions of the speed prior account of a forward shift for lower speeds and a backward shift at faster speeds. Yet, a closer look on the predictions of the speed prior account for slower speeds (as briefly discussed in the section above) reveals a non-linear influence of speed (for an illustration, see Figure 4A). Because the influence of the prior speed expectation has first to build up for slow speeds, the forward shift at stimulus offset (see the dotted line in Figure 4) first increases with increasing speed. This is in line with the existing evidence in the literature (e.g.,

⁹ Interested readers might be wondering why our visual studies, especially Experiment 1b with 5 stimulus speeds slower than the prior expectation did not evidence this initial increase. The reason why we did not find this might be that our dependent variable was not sensitive enough (for a discussion about the relevance of different judgment types, see e.g., Kerzel, 2002). Also, the use of an online setting with less control might have introduced further variance which therefore has prevented to show this initial increase. Lastly, it might also have just been the fact that we should have used even slower stimulus speeds. Please also note the exponential increase of the used speeds along the x-axis in Figure 2, that is, whereas the difference between the first five stimulus speeds (12.6 pix/s to 125.7 pix/s) is about 112 pix/s, the difference between the 5th and 6th speed (125.7 pix/s and 502.7 pix/s) is more than three times higher (about 375 pix/s).

Freyd & Finke, 1985; Hubbard & Bharucha, 1988). Interestingly, as noted by Hubbard in his reviews (e.g., Hubbard, 2005, 2018a), the effect of speed is not found for relatively fast speeds, as well as evidence of backward shifts have been reported (e.g., Munger & Owens, 2004; Müsseler et al., 2003; Experiment 1a and 1b in the present manuscript). These results, which cannot be explained by classical theoretical frameworks, can now be accounted for by the speed prior account, as an Offset Repulsion effect is predicted for fast stimulus speeds.

Interestingly, taking a closer look at stimulus onset, the speed prior account could possibly resolve some of the inconsistencies in the existing patterns of data that have been reported to date. That is, for the Fröhlich effect (forward shift), a consistent increase in stimulus speed lead to an increase in the Fröhlich effect (e.g., Kerzel & Müsseler, 2002; Kirschfeld & Kammer, 1999; Müsseler & Aschersleben, 1998). Yet, more intriguingly, the influence of stimulus speed on the Onset Repulsion effect (backward shift) is not consistent, as report of an increase, decrease as well as no change with increasing stimulus speed exist (e.g., Hubbard & Motes, 2002; Kerzel, 2002; Kerzel & Gegenfurtner, 2004; Thornton, 2002). As can be seen by close inspection of Figure 4, all of these data patterns would be predicted by the speed prior account. The Fröhlich effect is predicted to only increase with increasing speed, yet, the Onset Repulsion effect would be expected to either increase, not change, or decrease, depending on the actual stimulus speeds and their relation to the prior speed expectation. Therefore, the speed prior account would possibly resolve these seemingly inconsistent findings.

In addition to the explanatory value of the speed prior account when it comes to the influence of speed, the speed prior account might also explain another puzzling finding in the onset-localization literature. That is, the Fröhlich effect decreases, perhaps even turns into an Onset Repulsion effect, with changes in stimulus context. More precisely, when the onset position of a dynamic object was fixed to two specific locations (constant context), a strong Fröhlich effect was evidenced, whereas no effect or even a backward shift was evidenced when the

onset location was random (random context; e.g., Müsseler & Kerzel, 2004; Müsseler et al., 2008). Yet, as subsequent analysis by Müsseler and Tiggelbeck (2013) revealed, it was not just the perceived onset location that was different for these two context conditions, but also the performance in a discrimination task (the identity of the target possibly changed in the initial phase of the motion trajectory and participants were asked if they had perceived any change in the object's identity). In fact, in the condition in which a strong Fröhlich effect was observed (constant context), discrimination performance was worse than in the condition in which no effect was observed (random context). The authors concluded that this indicates a potential attentional mechanism underlying the difference between the localization biases at stimulus onset.

Interestingly, the speed prior account offers a different explanation. As Müsseler and Tiggelbeck (2013) reported, higher sensory acuity (better discrimination performance) was observed in the random context condition, as evidenced by the better change detection in the random context condition compared to the constant context condition. Under higher sensory acuity, the influence of the prior is expected to be reduced (e.g., Tong et al., 2016). Therefore, the speed prior account would predict a weaker / no influence with increased sensory acuity, which is what was evidenced. For the condition with higher sensory acuity / better change detection (random context), no shift / a weak (backward) shift was evidenced, as the influence of the prior speed expectation is decreased. For the condition with lower sensory acuity / worse change detection (constant context), a stronger (forward) shift is evidenced. Therefore, this puzzling finding might be resolved by the speed prior account.

9.1.3. Identifying a general prior in motion direction

As we discussed above, the speed prior account has a strong explanatory value for a variety of existing evidence in the literature. Yet, there is one interesting shortcoming. As a

close inspection of Figure 4A reveals, the speed prior account would typically predict the simultaneously evidenced forward and backward shifts at any given speed to be identical in magnitude (please note one exception, that is when considering possible within-trial adaptations of the prior as discussed in Section 9.1.1). Yet, this is typically not observed, but instead many studies have (at least descriptively) evidenced the forward shift (independent from being observed at stimulus onset or offset) to be higher in magnitude than the backward shift (e.g., Actis-Grosso et al., 2008; Müsseler et al., 2003; although see Hubbard & Motes, 2002). We propose that a general bias in motion direction might additionally have an influence on perceived location, that is, a general shift of perceived location in motion direction, resulting in stronger forward shifts and weaker backward shifts across all stimulus speeds (for a visualization, see Figure 4B).

The crucial question is why the perceptual system might use such a general prior in motion direction. We argue that it is helpful to act safely within a dynamic, changing world. In fact, this is not a new argument, but was already proposed to account for the so called looming effect, in which the time-to-contact for moving, approaching stimuli has to be estimated and is typically underestimated (Rosenblum et al., 1993; Schiff & Oldak, 1990; for a recent discussion of this argument as well as review of the literature, see Neuhoff, 2018). By shifting the moving stimulus further along the motion trajectory, participants make an error on the “side of safety” (Neuhoff, 2001, p. 88). This error might help to give rise to faster responses and might increase the chance to be able to respond (if necessary) to the approaching / moving stimulus, especially

when uncertainty about the approaching stimulus exists (e.g., when surprised by the approaching object or when perception occurs under bad conditions like a foggy day)¹⁰. Therefore, the usage of a general prior in motion direction might be a helpful bias to navigate and act safely in a dynamic, changing world.

The general prior in motion direction might also underlie another robust phenomenon in the perception of moving objects literature, the flash-lag effect, in which a moving stimulus is perceived further along its motion trajectory compared to a static flash, aligned during its short presentation with the moving stimulus (e.g., Nijhawan, 1994; for a recent discussion, see Hubbard, 2014b, 2018b). In fact, this general prior in motion direction might be very similar to the motion extrapolation idea originally proposed to explain the flash-lag effect (Nijhawan, 1994, 2008), yet, as recent reviews show, the mechanisms underlying the flash-lag effect are still debated and unclear (see Hubbard, 2014b, 2018b).

Up to this point, we mostly discussed the perception of motion of an external stimulus/object across space over time. Yet, dynamic changes also occur in other situations, and interestingly, biases related to motion / dynamic change have been observed too. For example, in attention research, a target stimulus has been shown to be responded to faster when it was located in the trajectory of the attentional movement (called attentional momentum, e.g., Pratt et al., 1999). Similarly, in math cognition, if two quantities have to be added together (or subtracted, one from the other), a tendency to overestimate (underestimate) the actual result has been evidenced, comparable to a general motion prior discussed previously (called operational

¹⁰ Please note that this does not mean that veridical perception cannot occur anymore. As a closer inspection of Figure 4B shows, this general bias only make a bias which has probably less negative consequences (a forward shift) more likely, but veridical perception is still very much possible. Please also note that for everyday encounters with moving / approaching objects like hitting or catching a ball in sports, it is very unlikely that the prior expectation or the general motion bias formulated here have any crucial role. When catching a ball, the ball can be observed throughout its trajectory, allowing the sensory input to be repeatedly updated. Therefore, the sensory input is likely to be very precise, making any meaningful influence of the priors unlikely, and making it possible to hit or catch the ball accurately.

momentum, e.g., McCrink et al., 2007). In fact, Hubbard (2017, 2019) proposed that these phenomena (and more) can be accounted for by one mechanism and reviewed evidence about similar modulations across these effects. The proposed speed prior and general motion prior idea might possibly be this underlying mechanisms. In fact, our idea is that whenever something is in motion / changes dynamically, it is likely that we (or our cognitive system) have a general idea / expectation about what is going to happen in order to navigate safely and smoothly with our external world. Given physical constraints of the encountered objects (cars can only move forward/backward, not sideways) as well as their likely properties (an older car probably cannot accelerate as fast as a modern sports car), we build expectations about their motion, which we update by gathering more sensory information. The combination of both, prior knowledge / expectations as well as (repeated updating of) the sensory input in order to come to a better idea about the actual stimulus event lies at the heart of the here proposed speed prior account, but also, more generally, might be a central feature whenever we encounter dynamic / changing information in general.

10. Conclusion

In the present study, we propose a novel theoretical account to explain perceptual biases of the perceived location of dynamic stimuli, the speed prior account. The speed prior account proposes that the observed perceptual biases at stimulus onset (Fröhlich effect, Onset Repulsion effect) as well as offset (Offset Repulsion effect, Representational Momentum effect) are elicited due to a mismatch between a prior expectation of stimulus speed and actual stimulus speed. Discussing published evidence and the shortcomings of the existing theories to explain the gathered evidence to this point, we show how the speed prior idea might account for these, providing a new way to explain many existing perceptual biases observed to date. Furthermore,

we explicitly tested the predictions of the new speed prior account against the predictions of the classical theories, specifically the activation models, in vision as well as in an under researched sensory modality, touch. The observed data pattern were in line with the predictions of the speed prior account, underlining the importance of the speed prior account to explain perception-biases of moving stimuli.

11. Context of the Research

The ideas for this new theory were developed due to the accumulation of observations with mainly tactile, but also visual stimuli in our lab which could not be explained with existing theoretical formulations, as well as the identification of more, already published but not satisfactorily explained patterns of data which we have discussed throughout the manuscript. Additionally, personal communications about rudimentary ideas of the speed prior account between the first author (SM) and Jochen Müsseler (involved in formulating the activation idea, e.g., Müsseler et al., 2003) as well as Daniel Goldreich (extended the static prior idea into the tactile modality; Goldreich, 2007; and who provided us with a rudimentary application of the speed prior account) helped to shape the present formulation of the speed prior account. Future plans involve modelling of the speed prior idea to make more precise predictions as well as identify further areas / stimulus set-ups to test and contrast the existing theoretical frameworks. Furthermore, our research has mostly focused on the spatial characteristics of dynamic stimuli (e.g., perceived spatial location), yet, extending the research to investigate the speed prior accounts predictions for the temporal (e.g., perceived duration) or spatio-temporal (e.g., perceived speed) characteristics will be future lines of research.

12. Open Practice Statement

Onset and Offset localization of dynamic stimuli

1 Our experiment files, data, as well as analyses scripts are currently accessible for the
2 reviewer here: https://osf.io/zmrhe/?view_only=ee37eb2729d741b98718cda6902e94de. Fol-
3 lowing acceptance, all files will be made publicly available. None of the experiments reported
4 here was preregistered.

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14. Appendix

14.1. Table 1

Mean shift-scores with standard errors in brackets for Experiments 1 and 2. The shift-score indicates the difference in pixels between the implied motion and control trials. Positive shift-scores indicate a forward shift, whereas negative shift scores indicate a backward shift. For Experiment 1, the data are presented as a function of task (onset vs. offset localization), location (central vs. outer), direction (proximal vs. distal), and speed (fast vs. medium vs. slow). For Experiment 2, there was no medium speed condition.

			Onset localization		Offset localization	
Speed	Direction		Central	Outer	Central	Outer
Experiment 1						
Fast	Proximal		14.24 (17.10)	51.71 (17.95)	20.53 (27.52)	3.41 (20.03)
	Distal		54.15 (23.42)	31.22 (17.25)	-5.35 (26.33)	-12.09 (30.30)
Medium	Proximal		27.55 (12.36)	12.45 (15.37)	52.01 (18.48)	44.48 (11.06)
	Distal		13.11 (16.88)	-40.79 (8.57)	8.09 (16.62)	29.03 (16.53)
Slow	Proximal		-4.26 (18.06)	-28.82 (18.55)	82.18 (23.89)	68.03 (18.08)
	Distal		14.98 (19.81)	-84.99 (16.61)	16.19 (23.60)	52.01 (16.71)
Experiment 2						
Fast	Proximal		52.06 (27.54)	7.39 (23.74)	29.85 (27.15)	5.98 (19.32)
	Distal		54.44 (26.65)	-35.90 (25.56)	4.64 (27.50)	11.34 (24.05)
Slow	Proximal		-12.53 (25.43)	-30.78 (20.91)	96.16 (34.14)	76.47 (21.33)
	Distal		-37.11 (29.88)	-78.98 (24.21)	68.29 (32.50)	96.44 (20.34)

14.2. Table 2

Full ANOVA model in Experiments 1 and 2. For Experiment 1, the shift scores were submitted to a task (onset vs. offset localization), location (central vs. outer), direction (proximal vs. distal), speed (fast, medium, vs. slow) ANOVA. There was no medium speed condition in Experiment 2.

<i>Effect</i>	<i>F-value</i>	<i>p-value</i>	<i>partial eta²</i>
Experiment 1			
Task	2.70	.111	.085
Speed	0.24	.787	.008
Direction	7.04	.013	.195
Location	3.02	.093	.094
Task x Speed	12.84	< .001	.307
Task x Direction	1.53	.225	.050
Task x Location	2.84	.103	.089
Speed x Direction	1.68	.194	.055
Speed x Location	1.17	.310	.039
Direction x Location	0.66	.424	.022
Task x Speed x Direction	0.93	.377	.031
Task x Speed x Location	4.72	.013	.140
Task x Direction x Location	8.23	.008	.221
Speed x Direction x Location	0.22	.803	.008
Task x Speed x Direction x Location	0.71	.498	.024
Experiment 2			
Task	3.30	.080	.102
Speed	0.61	.442	.021
Direction	1.48	.234	.049
Location	6.12	.019	.174
Task x Speed	18.85	< .001	.394
Task x Direction	1.16	.291	.038
Task x Location	2.75	.108	.087
Speed x Direction	0.11	.741	.004
Speed x Location	2.78	.106	.087
Direction x Location	0.01	.918	< .001
Task x Speed x Direction	0.72	.402	.024
Task x Speed x Location	0.81	.375	.027

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Task x Direction x Location	2.64	.115	.084
Speed x Direction x Location	0.35	.556	.012
Task x Speed x Direction x Location	0.01	.926	< .001

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