

---

The contradictory influence of velocity:  
Representational momentum in the tactile modality

---

Simon Merz<sup>1,4</sup>, Julia Deller<sup>2</sup>, Hauke S. Meyerhoff<sup>3</sup>,  
Charles Spence<sup>4</sup>, & Christian Frings<sup>1</sup>

<sup>1</sup> Department of Psychology, University of Trier, Germany

<sup>2</sup> Department of Psychology, University of Leipzig, Germany

<sup>3</sup> Leibniz-Institut für Wissensmedien, Tübingen, Germany

<sup>4</sup> Department of Experimental Psychology, University of Oxford, United Kingdom

Word count: 3911 words (main text & references, without figures, tables, and footnotes)

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

## **ABSTRACT**

Representational momentum (RM) is the term used to describe a systematic mislocalization of dynamic stimuli, a forward shift, that is, an overestimation of the location of a stimulus along its anticipated trajectory. In the present study, we investigate the effect of velocity on tactile RM, as two distinct and contrasting predictions can be made, based on different theoretical accounts. According to classical accounts of RM, based on numerous visual and auditory RM studies, an increase of the forward shift with increasing target velocity is predicted. In contrast, theoretical accounts explaining spatio-temporal tactile illusions like the tau or cutaneous rabbit effect predict a decrease of the forward shift with increasing target velocity. In three experiments reported here, a tactile experimental set-up modelled on existing RM set-ups was implemented. Participants indicated the last location of a sequence of three tactile stimuli, which either implied motion in a consistent direction toward the elbow / wrist or not. Velocity was manipulated by changing the interstimulus interval as well as the duration of the stimuli. The results reveal that increasing target velocity led to a decrease and even a reversal of the forward shift resulting in a backward-shift. This result is consistent with predictions based on the evidence from tactile spatio-temporal illusions. The theoretical implications of these results for RM are discussed.

**KEYWORDS:** Tactile localization – Representational momentum – Motion perception – spatio-temporal perception – Velocity perception

### **New and Noteworthy**

This study tests two distinct predictions concerning the influence of velocity on the localization of dynamic tactile stimuli. We demonstrate for tactile stimuli that with increasing velocity, a misperception in the direction of anticipated motion (termed *Representational Momentum*) turns into a misperception against the direction of motion. This result is in line with predictions based on tactile spatio-temporal illusions, but challenges classical theoretical accounts of representational momentum based on evidence from vision and audition.

## Introduction

The localization of moving stimuli is undoubtedly important for the effective interaction with our surroundings. In our everyday life, we experience different moving objects (e.g., cars) and people. In order to navigate around them, and to avoid collisions, the accurate localization of these objects is essential. Interestingly, decades of visual research have revealed that any object that is seen to move in a predictable manner is typically not localized accurately, but is instead systematically misperceived along its anticipated trajectory (*representational momentum (RM)*; Freyd and Finke 1984). More specifically, a systematic mislocalization of a moving object in the direction of anticipated motion, a forward shift, has been evidenced in many different studies (e.g., Freyd and Finke 1984, 1985; Hubbard and Bharucha 1988; see Hubbard 2005, 2014, for reviews). By now, this effect has been demonstrated in the visual (e.g., Freyd and Finke 1984, 1985), auditory (e.g., Feinkohl et al. 2014; Getzmann and Lewald 2007) and, more recently, in the tactile modality (Merz et al. 2019), as well.

In studies of visual and auditory RM, the velocity of the target turns out to be “one of the most robust influences” (Hubbard 2005, p. 828; Hubbard 2014) on the forward shift. The momentum of an object is defined as the product of its mass and velocity (Hubbard 2010), and with greater velocity, the momentum (and therefore the expected forward shift) increases (see Figure 1a). This effect is predicted by all theories of RM (see Hubbard 2010, for an overview) and has been documented in numerous studies (e.g., De Sa Teixeira et al. 2013; Freyd and Finke 1985; Hubbard and Bharucha 1988; for reviews, see Hubbard 2005, 2014). However, based on previous studies on tactile spatio-temporal perception, it seems unlikely that this pattern of results will necessarily generalize to the tactile modality.

Evidence from the tau effect (i.e., shorter temporal intervals between two stimuli reduces the perceived spatial distance between them; Helson 1930) or the cutaneous rabbit illusion (whereby illusory tactile percepts localized as occurring in-between two spatially separate tactile stimulations; i.e., Geldard and Sherrick 1972) both suggest a different pattern of results. This is, with increasing velocity, the forward shift is expected to diminish and might even reverse into a backward shift (that is, systematic misperception against the direction of motion, see Figure 1a). This prediction has been corroborated by the perceptual length contraction account (Goldreich 2007; Goldreich and Tong 2013; Tong et al. 2016). According to this account, perception reflects the product of the prior expectation concerning the stimulus and the likelihood of the sensory information. The authors argue that since most experiences with tactile stimuli are either static, or slowly moving (e.g., feeling clothes moving over the skin), observers develop an expectation for slow velocities in the tactile modality. When fast velocities are present, this expectation is violated and the stimulus is perceived as being shorter than its actual length. As presentation time is constant, the velocity of the stimulus is subsequently perceived to be slower than it actually was. Accordingly, the implied forward shift is expected to decrease in size or perhaps might even turn into a backward shift with increasing velocity in the tactile modality.

### **Overview**

We set out to investigate these contrasting predictions by conducting a task that was designed to investigate tactile RM (see Merz et al. 2019), by presenting static tactile vibrations to different locations along the participant's forearm. In each trial, three discrete vibrotactile stimuli were delivered to three of five different locations, arranged in a straight line from the wrist to the elbow, on the left forearm. The vibrations were either presented from adjacent stim-

ulators in a consistent direction, therefore ‘implying’ the motion of a stimulus in a single direction (motion stimulus; for a review of the neural processing of tactile motion stimuli, see Pei and Bensmaia 2014), or else were located at three random locations along the forearm (control stimulus). The forward shift or motion displacement (‘*M displacement*’, Hubbard 2005) is assessed as the difference between the perceived location of the motion and the control stimulus.

In Experiment 1, the duration, as well as the interstimulus interval (ISI) of the vibrotactile stimuli, were manipulated separately in order to present varying velocities on the forearm. To ensure that changes in the perceived (forward) shift stem from the manipulation of the velocity, not from changes in the quality of the percept of the motion trajectory (see Cholewiak and Collins 2000), participants rated the perceived continuity of the stimulus sequence. Experiment 2a constitutes a replication of Experiment 1 with a slightly-reduced experimental design in order to replicate the findings of Experiment 1. In Experiment 2b, the control stimulus was omitted as the mix of motion and control stimulus is not common in RM experiments in the visual and auditory modalities (e.g., see Freyd and Finke 1984). To foreshadow the results, the forward shift decreases and even reverses with increasing velocity, in line with the prediction based on the evidence from other spatio-temporal tactile illusions.

## Methods

### Experiment 1

#### Participants

To elicit at least medium effect sizes ( $d_z$  around 0.6) for an effect of velocity on the forward shift, we aimed for 32 participants in Experiment 1 ( $\alpha < .05$ ;  $1-\beta > .95$ ; power analyses were run with G-Power 3.1.9.2; Faul et al. 2009). The final sample consisted of 32 (17 female; 7 left-handed; 20-30 years, mean age: 24.38 years) students from the University of Trier. All of

the participants reported normal or corrected-to-normal vision, no sensory impairment on the forearm and gave written informed consent prior to participation.

### Design

*Experiment 1.* The participants were tested in a  $2 \times 2 \times 2 \times 2 \times 3$  design with the five within-participants factors of *stimulus type* (implied motion vs. control), *direction* (proximal vs. distal), *duration* (100 vs. 250 ms), *interstimulus interval (ISI)* (100 vs. 250 ms), and *location* (central: 0 cm vs. outer:  $\pm 3.5$  cm vs. outermost:  $\pm 7$  cm). For the subjective rating, the participants were tested in a  $2 \times 2 \times 2$  design with the within-participants factors of *direction* (proximal vs. distal), *duration* (100 vs. 250 ms), and *ISI* (100 vs. 250 ms).

### Apparatus, stimuli and procedure

A detailed description of the apparatus, stimuli, and procedure can be found in Merz et al. (2019; Experiment 2). With the help of an arm bandage, five tactors (Model C-2, Engineering Acoustic, Inc.; 3 cm in diameter, centrally located skin contactor of 0.76 cm) were used to present vibrotactile stimuli ( $\sim 250$  Hz, about 126  $\mu\text{m}$  peak-to-peak amplitude) to the volar side of the left forearm (see Figure 1b). Seven tactors (two more tactors were attached to increase uncertainty about the location of the vibrations) were attached in a straight line, one next to the other (3.5 cm inter-tactor spacing). A 250 mm ruler (0 mm at the wrist, 250 mm at the elbow) was attached to the top of the arm bandage. The participants wore ear-plugs (Noise reduction: 29 dB) on top of which Brown noise (simultaneously-presented frequency distribution with higher intensities at lower frequencies) was presented over headphones (over-ear headphones: about 85 dB) to block the lower frequency sounds ( $\sim 250$  Hz) elicited by the vibrotactile stimulation.

## Localizing dynamic tactile stimuli with differing velocity

Each trial started with the presentation of a visual plus sign for 400 ms. Thereafter, three vibrotactile stimuli were presented successively for a duration of 100 or 250 ms and at a varying ISI of 100 or 250 ms. Stimulus duration as well as ISI was not changed during trials, but rather between them. Following the offset of the third vibration, the participants indicated the location of the last vibration, the target vibration, by pointing with their right index finger toward the corresponding location on the ruler, which the experimenter then noted. For the subjective rating, participants judged the continuity (not velocity) of the implied motion trials on a visual analogue scale, ranging from 0 (impression of separate vibrations/events at distinct places) to 100 (impression of one continuously moving vibration / event).

In half of the trials, the vibrotactile stimuli were presented adjacent to each other in one single consistent direction (implied motion stimulus). Therefore, these stimuli implied a motion from one tactor to the next along the participant's forearm. For each direction condition (proximal direction: toward the elbow; distal direction: toward the wrist), three target locations were used, that is the central (0), outer ( $\pm 3.5$ ), and outermost ( $\pm 7$ ) location; see Figure 1b). In the other half of trials, the control trials, the locations of the vibrations locations were selected randomly without replacement with the restriction that implied motion condition trials never occurred. Overall, the participants completed eight practice trials (random selection) and 384 experimental trials, 2 (stimulus type) x 2 (direction) x 2 (duration) x 2 (ISI) x 3 (location) x 8 (repetitions). For the subjective rating, 32 implied motion trials at the outer target location were used, 2 (direction) x 2 (ISI) x 2 (duration) x 4 (repetitions).

## Analysis

Sixty-five trials (0.53%) in which the experimenter could not reliably recognize the indicated location were excluded from the analysis. The control trials were averaged to calculate a control estimate for each of the five tactor locations. Analyses were computed with shifts (in



mm) as the dependent variable. The shift is the difference between the location estimation of the implied motion and control conditions. A positive value indicates an estimation of the implied motion trials in the proximal (distal) direction as closer to the elbow (wrist) than the control trials (comparable to classic ‘M displacement scores’, Hubbard 2005). In a first step, the shift score of the fastest (duration and ISI = 100 ms) and slowest (duration and ISI = 250 ms) were tested against 0 (Bonferroni-adjusted p-values are reported). For the slowest condition, the existence of a forward shift is expected based on visual and auditory RM studies (for reviews, see Hubbard, 2005, 2014) as well as our previous tactile RM study (Merz et al. 2019). In a second step, we conducted a 2 (direction)  $\times$  2 (duration)  $\times$  2 (ISI)  $\times$  3 (location) multivariate analysis of variance (MANOVA)<sup>1</sup> with Pillai’s trace as criterion. For the sake of readability, only the effects of velocity, that is the effect of ISI and duration on the forward shift, are reported here, the full model as well as all mean scores are reported in the Appendix. For the subjective rating scores, we conducted a 2 (direction)  $\times$  2 (duration)  $\times$  2 (ISI) MANOVA with Pillai’s trace as criterion.

## **Experiment 2a & b**

### **Participants**

For Experiments 2a and b, only the fastest and slowest velocities were used, therefore the expected effect size was slightly increased ( $d_z$  of 0.7). We aimed for at least 24 participants in Experiments 2a and 2b. Due to an organizational error in Experiment 2a, the final sample consisted of 28 (Experiment 2a: 17 female; 4 left-handed; 18-42 years, mean age: 24.32 years), and 24 (Experiment 2b: 17 female; 3 left-handed; 18-24 years, mean age: 20.21 years) students

---

<sup>1</sup> Note that all repeated-measures designs are inherently multivariate and the MANOVA has the advantage that sphericity cannot influence the results (see e.g., Tabachnick et al. 2007).

from the University of Trier. All of the participants reported normal or corrected-to-normal vision, no sensory impairment on the forearm and gave written informed consent prior to participation.

### **Design, apparatus, stimuli, and procedure**

The design, apparatus, stimuli, and procedure was identical to Experiment 1 with the following exceptions. Only two target locations (central vs. outer) as well as two velocities (duration & ISI: 100 vs. 250 ms) were used. Therefore, the two factors of ISI and duration from Experiment 1 were combined to one factor of velocity. Additionally, in Experiment 2b, no control trials were presented. Participants worked through 128 experimental trials in Experiment 2a, 2 (stimulus type)  $\times$  2 (direction)  $\times$  2 (velocity)  $\times$  2 (location)  $\times$  8 (repetitions), and 80 experimental trials in Experiment 2b, 2 (direction)  $\times$  2 (velocity)  $\times$  2 (location)  $\times$  10 (repetitions).

### **Analysis**

16 trials (0.45%, Experiment 2a) and two trials (0.10%, Experiment 2b) were excluded from the analysis. As in Experiment 1, the forward-shift was computed and tested in Experiment 2a with a 2 (direction: proximal vs. distal)  $\times$  2 (velocity: duration & ISI = 100 vs. 250 ms)  $\times$  2 (location: central vs. outer) MANOVA with Pillai's trace as criterion. Once again, only the effect of velocity is reported here. The full model is reported in the Appendix. For Experiment 2b, the same 2  $\times$  2  $\times$  2 MANOVA was conducted, but with the mean localization scores (possible range: 0 – 250 mm; high scores indicate a localization close to the elbow) as the dependent variable as the control trials were omitted in this experiment. Therefore, the critical effect is now the interaction between velocity and direction. We expect localizations closer to the elbow (i.e., higher mean localization scores) for slow rather than for fast velocities for proximal motion trials. For distal motion trials, the reversed pattern was expected. We expect localizations

closer to the wrist (i.e., lower mean localization scores) for slow rather than for fast velocities for distal motion trials. The full model is reported in the Appendix.

## Results

### Experiment 1

*Location estimation.* A significant forward shift with a duration and ISI of 250 ms was found as expected,  $t(31) = 2.49$ ,  $p = .018$  (one-tailed),  $d = 0.44$ . Increasing the velocity of the presented stimulus sequence led to a significant shift from a forward to a backward shift,  $t(31) = -4.88$ ,  $p < .001$ ,  $d = 0.86$  (duration and ISI of 100 ms, see Figure 1c). That is, the MANOVA revealed significant main effects of duration,  $F(1, 31) = 74.36$ ,  $p < .001$ ,  $\eta_p^2 = .706$ , as well as ISI,  $F(1, 31) = 14.06$ ,  $p = .001$ ,  $\eta_p^2 = .31$ . Further, an ordinal interaction between the two effects was evidenced,  $F(1, 31) = 4.84$ ,  $p = .035$ ,  $\eta_p^2 = .135$ . As indicated in Figure 1c, shortening the ISI had a weaker effect on the shift score at a duration of 250 ms (250 ms: +3.35 mm; 100 ms: +2.30 mm) than at a duration of 100 ms (250 ms: -3.24 mm; 100 ms: -7.49 mm). Overall, the results of Experiment 1 clearly highlight that with increasing velocity, the forward shift decreases and then reverses to become a backward shift.

*Subjective rating.* The subjective rating scores show a different pattern than the shift scores. A shorter ISI (100 ms: 42.71 vs. 250 ms: 34.49) indicated a more continuous impression of the stimulus sequence,  $F(1, 31) = 24.25$ ,  $p < .001$ ,  $\eta_p^2 = .44$ . In contrast, a shorter duration (100 ms: 34.33 vs. 250 ms: 42.71) tended to indicate a less continuous impression, but just failed to reach statistical significance level,  $F(1, 31) = 3.61$ ,  $p = .067$ ,  $\eta_p^2 = .10$ . None of the other effects were significant,  $F_s < 2.11$ ,  $p_s > .156$ . As the fastest (100 ms duration & ISI: 38.77) and slowest (250 ms duration & ISI: 39.09) velocity conditions were perceived to be similar,  $t(31) = -0.06$ ,  $p = .952$ , we used these conditions in Experiments 2a and 2b.

## Experiment 2a & b

*Experiment 2a:* Comparable to Experiment 1, a backward shift for the fastest velocity,  $t(27) = -4.82$ ,  $p < .001$ ,  $d = 0.91$ , was found (Figure 1c). The forward shift for the slowest velocity was barely not significant,  $t(27) = 1.74$ ,  $p = .094$  (one-tailed),  $d = 0.33$ .<sup>2</sup> Additionally, the MANOVA revealed the significant main effect of velocity,  $F(1, 27) = 49.84$ ,  $p < .001$ ,  $\eta_p^2 = .649$ .

*Experiment 2b:* The MANOVA revealed a significant interaction between direction and velocity,  $F(1, 23) = 6.25$ ,  $p = .020$ ,  $\eta_p^2 = .214$ . This pattern of results is consistent with those reported in Experiments 1 and 2a, that is, a slow motion stimulus is perceived further along its motion trajectory as compared to a fast moving stimulus. More specifically, the endpoint of a slow motion toward the elbow (proximal direction) is perceived closer to the elbow than a fast motion,  $t(23) = -3.73$ ,  $p = .002$ ,  $d_z = 0.73$  (see Figure 2). This pattern was reversed for a motion toward the wrist (distal direction) descriptively, although not statistically,  $t(23) = 1.20$ ,  $p = .482$ ,  $d_z = 0.25$ .

## Discussion

We set out to investigate the contradictory predictions concerning the influence of velocity on tactile representational momentum. Across three experiments, we used the same timing parameters, a duration as well as ISI of 250 ms, which we used in our previous study (Merz et al. 2019) and which are typical for implied motion stimuli in the RM literature (e.g., Freyd and Finke 1984; see Hubbard 2005, 2014 for reviews). We were able to replicate the existence

---

<sup>2</sup> Comparing the forward shift between Experiment 1 and 2a for the slowest velocity condition revealed an overall significant forward shift,  $t(59) = 3.03$ ,  $p = .004$ ,  $d = 0.39$ , and no difference between the experiments,  $t(58) = 0.50$ ,  $p = .622$ , indicating the existence of the forward shift across both experiments.

of the forward shift with these timing parameter in our experiments. Based on this reference condition, we decreased the duration as well as the ISI to increase the implied velocity of stimulation. Hereby, we identified a systematic pattern of results. That is, with increasing velocity, the forward shift of tactile stimulation decreased and then reversed to become a backward shift.

To investigate the effect of velocity on tactile RM, we used an implied motion sequence, comprising three stimulations, similar to the classical RM studies of Freyd and Finke (1984, 1985). In Experiment 1, we further asked participants about their perception of the different velocity conditions. Although the different velocity conditions were differently perceived (a shorter duration is perceived as less continuously), the pattern does not match the localization pattern. In fact, the fastest and slowest velocity patterns were perceived similarly, but showed a clear difference in the localization estimation. Additionally, in Experiment 2b, we omitted the control condition as the mixed presentation of control and implied motion stimuli is not common for studies of RM (e.g., Freyd and Finke 1984, 1985). Still, the pattern of results stayed the same, a slow-moving stimulus is perceived further along its motion trajectory compared to a fast-moving stimulus. Interestingly, evidence from related studies which have investigated the tactile localization of continuously moving tactile stimuli (i.e., drawing a continuous line on the forearm), not implied motion stimuli as in this study, indicate similar pattern of results (e.g., Macaуда et al. 2018; Nguyen et al. 2016; Whitsel et al. 1986).

The influence of velocity in the present study is in line with the prediction based on tactile spatio-temporal illusions and the perceptual length contraction account (Goldreich 2007; Goldreich and Tong 2013; Tong et al. 2016), but would appear to stand in contrast to the existing RM literature from the visual and auditory modality (see Hubbard 2005, 2014). Based on these results, should the conclusion be drawn that (endpoint-)localization in the tactile modality is functionally different than in the visual and auditory modalities? That is, is the tactile modality influenced by a slow velocity prior, and the visual and auditory modality by the momentum

of the object? Such an extreme conclusion is perhaps unwarranted, since the basic idea of the slow velocity prior was originally introduced on the basis of studies conducted with visual stimuli (Stocker and Simoncelli 2006; Weiss et al. 2002). Furthermore, the pure existence of a tactile forward shift would not be predicted by the perceptual length contraction account. Therefore, the present results suggest that at least two biases, a motion (which elicits the forward shift at slow velocities) and a slow velocity bias (which elicits the reversal of the forward to a backward shift), influence the estimation in all modalities, but that the impact of these biases is dependent on variables that have yet to be defined<sup>3</sup>. The modalities differ in their spatial resolution, so perhaps spatial localization acuity modulates the impact of these biases and is the driving factor underlining the differing results in the different modalities.

The present study is in line with the growing interest in tactile and multimodal systems to present meaningful and helpful information, for example to alert car drivers of potential dangerous situations (see Gallace and Spence 2014; Meng and Spence 2015). Besides the interest in a pure warning function, recent interest has shifted towards presenting meaningful information to the driver (Brewster and Brown 2004; Meng and Spence 2015, e.g., orientation information or the location of a possible dangerous situations / objects via the location of a stimulus). Therefore, this line of research concerning the localization of dynamic stimuli in the different spatial modalities will be useful to improve the design of future information systems.

### Acknowledgements

---

<sup>3</sup> The present results further show a significant difference in the magnitude of the forward / backward shift between the directions of the motion. That is, a moving stimulus toward the elbow elicits stronger forward shifts / weaker backward shifts than a moving stimulus toward the wrist (for the data as well as statistical analyses, see the Appendix). For a detailed discussion about this effect please refer to our previous paper (Merz et al. 2019), where we report and discuss in detail these directional differences for the first time. No robust interactions between direction and velocity were evidenced in our data.

We would like to thank Stephanie Blasl for the drawings incorporated in Figure 1.

### Grants

The research reported here was supported by a grant from the Deutsche Forschungsgemeinschaft to Christian Frings and Charles Spence (FR2133/5-3).

### Disclosures

No conflicts of interest, financial or otherwise, are declared by the author(s).

### Author contributions

S.M., J.D., H.S.M., C.S., and C.F. conception and design of research; S.M. and J.D. performed experiments; S.M. analyzed data; S.M., J.D., H.S.M., C.S., and C.F. interpreted results of experiments; S.M. prepared figures and drafted manuscript; S.M., J.D., H.S.M., C.S., and C.F. edited and revised manuscript and approved final version of manuscript.

### References

- Brewster S, Brown, LM.** Tactons: Structured tactile messages for non-visual information display. *Proceedings of the Fifth Conference on Australasian User Interface* 28: 15-23, 2004.
- Cholewiak RW, Collins AA.** The generation of vibrotactile patterns on a linear array: Influences of body site, time, and presentation mode. *Atten Percept Psychophys* 62: 1220-1235, 2000.
- De Sá Teixeira NA, Hecht H, Oliveira AM.** The representational dynamics of remembered projectile locations. *J Exp Psychol Hum Percept Perform* 39: 1690-1699, 2013.

- Faul F, Erdfelder E, Buchner A, Lang AG.** Statistical power analyses using G\* Power 3.1: Tests for correlation and regression analyses. *Behav Res Methods* 41: 1149-1160, 2009.
- Feinkohl A, Locke SM, Leung J, Carlile S.** The effect of velocity on auditory representational momentum. *J Acoust Soc Am* 136, EL20-EL25, 2014.
- Freyd JJ, Finke RA.** Representational momentum. *J Exp Psychol Learn Mem Cogn* 10: 126-132, 1984.
- Freyd JJ, Finke RA.** A velocity effect for representational momentum. *Bull Psychon Soc* 23: 443-446, 1985.
- Gallace A, Spence C.** *In touch with the future: The sense of touch from cognitive neuroscience to virtual reality.* Oxford, UK: Oxford University Press, 2014.
- Geldard FA, Sherrick CE.** The cutaneous "rabbit": A perceptual illusion. *Science* 178: 178-179, 1972.
- Getzmann S, Lewald J.** Localization of moving sound. *Percept Psychophys* 69: 1022-1034, 2007.
- Goldreich D.** A Bayesian perceptual model replicates the cutaneous rabbit and other tactile spatiotemporal illusions. *PLoS One* 2: e333, 2007.
- Goldreich D, Tong J.** Prediction, postdiction, and perceptual length contraction: A Bayesian low-speed prior captures the cutaneous rabbit and related illusions. *Front Psychol* 4: 221, 2013.
- Helson H.** The tau effect – an example of psychological relativity. *Science* 71: 536-537, 1930.
- Hubbard TL.** Representational momentum and related displacements in spatial memory: A review of the findings. *Psychon Bull Rev* 12: 822-851, 2005.
- Hubbard TL.** Approaches to representational momentum: Theories and models. In: *Space and time in perception and action*, edited by Nijhawan R & Khurana B. Cambridge, UK: Cambridge University Press, 2010, p. 338-365.



- Hubbard TL.** Forms of momentum across space: Representational, operational, and attentional. *Psychon Bull Rev* 21: 1371-1403, 2014.
- Hubbard TL, Bharucha JJ.** Judged displacement in apparent vertical and horizontal motion. *Percept Psychophys* 44: 211-221, 1989.
- Macauda G, Lenggenhager B, Meier R, Essick G, Brugger P.** Tactile motion lacks momentum. *Psychol Res* 82: 889-895, 2018.
- Meng F, Spence C.** Tactile warning signals for in-vehicle systems. *Accid Anal Prev* 75: 333-346, 2015.
- Merz S, Meyerhoff HS, Spence C, Frings C.** Implied tactile motion: Localizing dynamic stimulations on the skin. *Atten Percept Psychophys* 81: 794-808, 2019.
- Nguyen E, Taylor J, Brooks J, Seizova-Cajic T.** Velocity of motion across the skin influences perception of tactile location. *J Neurophysiol* 115: 674-684, 2016.
- Pei YC, Bensmaia SJ.** The neural basis of tactile motion perception. *J Neurophysiol* 112: 3023-3032, 2014.
- Stocker AA, Simoncelli EP.** Noise characteristics and prior expectations in human visual speed perception. *Nat Neurosci* 9: 578-585, 2006.
- Tabachnick BG, Fidell LS, Ullman JB.** *Using multivariate statistics*. Boston, MA: Pearson, 2007.
- Tong J, Ngo V, Goldreich D.** Tactile length contraction as Bayesian inference. *J Neurophysiol* 116: 369-379, 2016.
- Weiss Y, Simoncelli EP, Adelson EH.** Motion illusions as optimal percepts. *Nat Neurosci* 5: 598-604, 2002.
- Whitsel BL, Franzen O, Dreyer DA, Hollins M, Young M, Essick GK, Wong C.** Dependence of subjective traverse length on velocity of moving tactile stimuli. *Somatosens Res* 3: 185-196, 1986.

## Appendix

Table A1.

Mean location estimation, shift-scores, as well as subjective rating scores with standard deviations in brackets for Experiments 1, 2a, and 2b. Data is presented as a function of target location (central, outer, or outermost), direction (proximal or distal), interstimulus interval (ISI: 100 or 250 ms), stimulus duration (100 or 250 ms), and condition (implied motion or control). Higher values indicate localization closer to the elbow / in the proximal direction (location estimation) or a higher perceived continuity (subjective rating). The shift-score indicates the difference between the implied motion and control trials. Positive shift-scores indicate a forward shift, negative shift scores indicate a backward shift.

			Central		Outer		Outer-most	
dura- tion (ms)	ISI (ms)	Varia- ble	Proxi- mal	Distal	Proxi- mal	Distal	Proxi- mal	Distal
<i>Experiment 1 - localization score</i>								
250	250	Control	127.85 (24.23)	127.85 (24.23)	159.53 (17.73)	101.77 (31.27)	190.42 (16.75)	68.60 (38.68)
		Implied motion	136.20 (22.88)	131.12 (31.75)	165.72 (19.61)	100.77 (35.04)	194.83 (16.62)	65.16 (34.88)
		Shift score	8.35 (16.92)	-3.27 (17.24)	6.20 (11.02)	0.99 (11.65)	4.41 (10.05)	3.44 (8.85)
250	100	Implied motion	132.81 (22.82)	128.40 (31.03)	163.01 (20.89)	100.05 (33.05)	192.94 (19.79)	66.97 (38.69)
		Shift score	4.97 (16.37)	-0.55 (17.71)	3.49 (14.31)	1.72 (12.14)	2.53 (8.59)	1.64 (8.55)
100	250	Implied motion	128.45 (21.70)	135.45 (28.93)	158.36 (20.40)	108.82 (33.36)	189.28 (19.56)	71.70 (37.56)
		Shift score	0.60 (15.32)	-7.60 (18.30)	-1.16 (9.88)	-7.06 (14.47)	-1.14 (10.65)	3.09 (7.90)
100	100	Implied motion	119.09 (24.18)	136.61 (30.47)	150.14 (20.91)	110.06 (32.23)	186.17 (18.97)	74.11 (35.55)
		Shift score	-8.75 (15.54)	-8.76 (18.20)	-9.38 (13.24)	-8.30 (14.82)	-5.51 (10.44)	-4.25 (9.97)
<i>Experiment 1 - subjective rating</i>								

# Localizing dynamic tactile stimuli with differing velocity

250	250	Rating score			38.05 (18.53)	40.12 (16.02)	
250	100	Rating score			44.06 (21.31)	48.60 (17.14)	
100	250	Rating score			29.03 (19.77)	30.76 (24.85)	
100	100	Rating score			27.91 (23.09)	19.62 (24.56)	
<i>Experiment 2a - localization score</i>							
		Control	136.41 (30.54)	136.41 (30.54)	155.96 (25.46)	112.74 (36.58)	
250	250	Implied motion	140.67 (29.06)	138.89 (31.74)	162.90 (26.16)	111.86 (38.89)	
		Shift score	4.25 (12.45)	-2.48 (12.54)	6.93 (9.61)	0.88 (9.68)	
100	100	Implied motion	129.71 (33.53)	146.67 (31.60)	147.30 (29.26)	121.27 (35.18)	
		Shift score	-6.70 (14.42)	-10.25 (10.79)	-8.66 (10.32)	-8.53 (10.50)	
<i>Experiment 2b - localization score</i>							
250	250	Implied motion	125.18 (28.84)	144.92 (26.82)	153.01 (28.84)	113.66 (26.46)	
100	100	Implied motion	115.77 (27.33)	146.69 (28.24)	145.45 (25.60)	118.52 (27.10)	

Table A2.

Full MANOVA model in Experiments 1, 2a, and 2b. For Experiment 1, the shift-scores were submitted to a Location (LOC: central vs. outer vs. outermost)  $\times$  Direction (DIR: proximal vs. distal)  $\times$  stimulus duration (DUR100 ms vs. 250 ms)  $\times$  interstimulus interval (ISI: 100 ms vs. 250 ms) MANOVA with Pillai's trace as the criterion. For Experiments 2a and 2b, a Location (LOC: central vs. outer)  $\times$  Direction (DIR: proximal vs. distal)  $\times$  velocity (VEL: DUR & ISI = 100 vs. 250 ms) MANOVA with Pillai's trace as the criterion was conducted. For Experiment 2a, the shift-scores were used as dependent variable, for Experiment 2b, the mean localization scores were used.

Effect	F-value	p-value	Partial eta <sup>2</sup>
--------	---------	---------	--------------------------

## Localizing dynamic tactile stimuli with differing velocity

---

### *Experiment 1 – Dependent variable: shift scores*

DUR	74.34	< .001	.706
ISI	14.04	.001	.312
DIR	5.47	.026	.150
LOC	0.39	.682	.025
DURxISI	4.84	.035	.135
DURxDIR	1.28	.267	.040
ISIxDIR	12.90	.001	.294
DURxLOC	2.26	.122	.131
ISIxLOC	0.11	.897	.007
DIRxLOC	1.21	.313	.074
LOCxDIRxDUR	1.19	.319	.073
LOCxDIRxISI	1.99	.154	.117
LOCxDURxISI	1.55	.229	.094
DIRxDURxISI	.92	.344	.029
LOCxDIRxDURxISI	.12	.887	.008

### *Experiment 2a – Dependent variable: shift scores*

VEL	49.84	< .001	.649
DIR	6.98	.014	.205
LOC	1.23	.277	.044
VELxDIR	4.13	.052	.133
VELxLOC	3.55	.070	.116
DIRxLOC	0.70	.411	.025
VELxDIRxLOC	0.81	.377	.029

### *Experiment 2b – Dependent variable: mean localization scores*

VEL	8.23	.009	.264
DIR	0.69	.413	.029
LOC	0.28	.600	.012
VELxDIR	6.25	.020	.214
VELxLOC	4.92	.037	.176
DIRxLOC	145.52	< .001	.864
VELxDIRxLOC	0.15	.706	.006

---

**Figure legends**

*Figure 1:* Predictions, experimental set-up, as well as the results of Experiments 1 and 2a. (a) Top left: Illustrative predictions of the influence of velocity on tactile representational momentum based on either visual and auditory RM studies (solid line) or tactile spatio-temporal illusions (dotted line). (b) Bottom: Depiction of the experimental set-up and its key characteristics illustrating a schematic view of the forearm with the seven tactors (gray circle indicates two tactors which were attached to the arm bandage but never used during the experiment). (c) Top right: Shift scores as a function of interstimulus interval (ISI) and stimulus duration of Experiment 1 and 2a. Gray lines represent single participant data, black circles represent the mean.

*Figure 2.* Localization scores of Experiment 2b as a function of direction (proximal or distal) and velocity (100 or 250 ms). Higher scores indicate a localization closer to the elbow, lower scores indicate a localization closer to the wrist. Gray lines represent single participant data, black circles represent the mean.