


# Tactile motion lacks momentum

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**Abstract** The displacement of the final position of a moving object in the direction of the observed motion path, i.e. an overestimation, is known as representational momentum. It has been described both in the visual and the auditory domain, and is suggested to be modality-independent. Here, we tested whether a representational momentum can also be demonstrated in the somatosensory domain. While the cognitive literature on representational momentum suggests that it can, previous work on the psychophysics of tactile motion perception would rather predict an underestimation of the perceived endpoint of a tactile stimulus. Tactile motion stimuli were applied on the left and the right dorsal forearms of 32 healthy participants, who were asked to indicate the subjectively perceived endpoint of the stimulation. Velocity, length and direction of the trajectory were varied. Contrary to the prediction based on the representational momentum literature, participants in our experiment significantly displaced the endpoint against the direction of movement (underestimation). The results are thus compatible with previous psychophysical findings on the perception of tactile motion. Further studies combining paradigms from classical psychophysics and cognitive psychology will be needed to

resolve the apparently paradoxical predictions by the two literatures.

## Introduction

In the cognitive literature, the term representational momentum (RM) refers to the displacement of the final position of a moving object in the direction of the observed or anticipated motion path, usually presented in the visual domain (Freyd, & Finke, 1984; Hubbard, & Bharucha, 1988). The term is chosen in analogy to the physical momentum (Hubbard, 2014), as some factors of the physical world such as velocity (e.g. Freyd, & Finke, 1984) have been shown to influence the size of RM. However, RM is observed even when the presented stimuli solely imply motion, i.e. when two static photographs of a moving object are flashed in temporal succession (e.g. Freyd, & Finke, 1984; Freyd, & Johnson, 1987). Likewise, an influence of gravity may only be implied, yet clearly impact an observer's perception of a movement's endpoint (Hubbard, 1990, 1995b, c). It is argued that such dynamic mental representations are important to better survive in a dynamic environment (Freyd, 1992). This is also in line with current theories of predictive coding which advocate a top-down structure of perception based on generative internal (dynamic) models (e.g. Hohwy, 2013). Thus, RM is considered a higher level phenomenon (for exhaustive reviews see Hubbard, 2005, 2014). This suggests that the effect should be modality independent, which seems confirmed by the observation of a RM also for auditory motion or pitch changes (Freyd, Kelly, & DeKay, 1990; Getzmann, & Lewald, 2009; Getzmann, Lewald, & Guski, 2004; Hubbard, 1995a; Johnston, & Jones, 2006). However, the notion of RM being a higher level phenomenon has been

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disputed as other studies focusing on other dimensions of dynamic changes, for instance in brightness (Brehaut, & Tipper, 1996) or facial expressions (Thornton, 2014; Yoshikawa, & Sato, 2008) have not always found an RM-like effect. In this context Kerzel (2002) has shown that the occurrence of RM is strongly dependent on the target's predictability.

The absence of relevant studies of RM in extra-visual domains appears particularly puzzling in the case of touch, as there is a vast literature on tactile motion processing (Essick, 1998; Essick et al., 2010; Whitsel et al., 1986), and tactile and visual motion have recently been outlined as using highly similar canonical computations (Pack, & Bensmaia, 2015). Especially in research fields investigating non-veridical perceptions, cross-modal comparisons may be helpful to uncover underlying mechanisms (Christopher Bill, & Teft, 1972; Helson, 1930; Sarrazin, Giraudo, & Pittenger, 2005). Evidence of a tactile RM would allow to disentangle body-centered and space-centered frames of references, which are relevant for patients with spatial processing deficits, in whom RM has previously been shown to be altered (Lenggenhager et al., 2012). Against this background, we set out to test whether RM is reproducible in the somatosensory domain.

We investigated in healthy participants where on the skin they would perceive the endpoint of a trajectory of stimuli being moved along their right or left arms with different velocities and directions. We considered two alternative hypotheses stemming from two different literatures. (A) If RM is a genuinely supramodal effect and the "tactile RM" thus postulated follows the basic properties of its analogues in the visual and auditory modalities, we would expect the experienced endpoint of a motion on the skin to be displaced in the direction of the movement, and increasingly so with increasing velocities. In line with this hypothesis, in a recently described tactile illusion, we found that a motion on the volar forearm lead to an overestimation of the perceived motion path length (Brugger, & Meier, 2015). (B) However, some observations from the literature on tactile motion perception would suggest a more complex pattern of findings, i.e. a mislocalization of tactile motion in the direction of movement (overestimation) with slow stimuli and a decrease in perceived distance with increasing stimulus velocity (underestimation; Whitsel et al., 1986 for the dorsal forearm). Such a finding would predict an absent, or reverse RM at least for relatively fast tactile movements.

## Methods

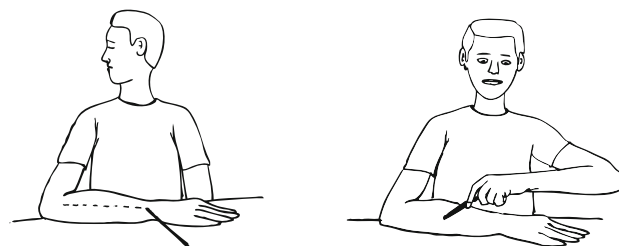
### Participants

Thirty-two healthy volunteers participated in this study (16 female, mean age 52.8, SD 14.1). All participants were

right-handed according to the inventory by Chapman and Chapman (1987) and a performance test by Tapley and Bryden (1985). None of the participants reported a history of neurological or psychiatric disorders. The study was approved by the local Ethics Committee of the University of Basel. All participants gave written informed consent before the experiment.

### Procedure

First, participants were instructed about the experimental procedure and filled in questionnaires regarding medical history and handedness, and performed the handedness test by Tapley and Bryden (1985). RM for the left and right arm was established with half of the participants starting with the left and the other with the right arm. Participants sat in front of a table and positioned their lower arms perpendicular to the upper arm on a cushion and held a stylus with the free, contralateral hands (see Fig. 1). Subsequently, participants were instructed to turn their heads away from the stimulated arm and to close their eyes. The experimenter manually applied 24 motion paths on the participants' lower arms. Stimuli were delivered with the aid of a stylus (26.5 cm), and the motion differed in velocity, length and direction (proximodistal vs. distal-proximal). They were applied always by the same experimenter (author R. Meier). To standardize the lines on the skin, two color-coded plates made of cardboard with the lengths 8 and 16 cm were used. These were neither visible to the participants at any time of the experiment nor did the plates ever touch the participants' skin. They assisted the experimenter to apply different combinations of velocity, direction and length in a pseudorandom order (indicated on a protocol sheet), which was identical for each participant. Two different velocities of tactile stimulation (6 and 27 cm/s) were selected based on a range of velocities used in previous experiments on the lower arm (Essick, Bredehoeft, McLaughlin, & Szaniszlo, 1991). These velocities



**Fig. 1** *On the left* during the tactile movement stimulation participants hold their heads turned and their eyes closed. The *dotted line* indicates the trajectory stimulation on the lower arms, which was done using a long needle. Direction, length and velocity of the movement were varied between trials and were presented either on the left or on the right arms. *On the right* participants indicated the felt endpoint of the trajectory with a pencil while having their eyes open

are at the extremes of a velocity range over which distance was perceived to be invariant with movement velocity in Whitsel et al. (1986). After each stimulation, participants were asked to open their eyes and to indicate the felt endpoint of the felt motion path with the stylus (see Fig. 1 for the setup). The whole procedure was videotaped for offline analysis. The camera and tripod were put on a fixed position on the table, with the camera facing the participants' lower arms from above in a fixed distance from an individual arm's surface. The deviation of a participant's felt endpoint from the actual endpoint of stimulus motion was measured offline on screen to the nearest mm.

## Analysis

Analyses were run using the statistical programming language R version 3.0.2 (R Core Team, 2013) including the *yarr* (Phillips, 2016), *tidyverse* (Wickham, 2016) and *ez* package (Lawrence, 2016). Data points are always relative to the actual stopping point. Positive values represent a mislocalization in direction of motion, i.e. an RM (overestimation), while negative values correspond to a displacement opposite to the direction of motion (underestimation). Data and analysis script are publicly available on the OpenScience Framework (osf.io/wx776).

Outliers were defined as values above or below three standard deviations from the mean for each measured variable and excluded from the analysis. For the overall mean of the RM data a two-tailed one sample *t* test was calculated and compared to a mean of zero (i.e. no displacement). An ANOVA with within-subject factors arm (right, left)  $\times$  velocity (fast, slow)  $\times$  direction (proximal, distal)  $\times$  length (short, long) was calculated.

## Results

Several outliers in the different variables were attributed to only one participant. Hence, this participant was excluded, resulting in a sample of  $n = 31$ , 15 female, mean age  $52.1 \pm 13.7$ . A simple *t* test showed that the mean of each participant over all conditions was significantly different from 0 (mean  $-12.90$ , SD  $7.33$ ,  $t_{(30)} = -9.80$ ,  $p < 0.001$ ,  $d = -1.76$  Fig. 2), indicating that there was a general underestimation. The repeated measures ANOVA with factors arm  $\times$  velocity  $\times$  direction  $\times$  length resulted in significant main effects of velocity ( $F_{(1,30)} = 46.53$ ,  $p < 0.001$ ,  $\eta^2 = 0.065$ ), with faster stimuli producing more underestimation, direction ( $F_{(1,30)} = 18.08$ ,  $p < 0.001$ ,  $\eta^2 = 0.13$ ), with more underestimation by the wrist, and length ( $F_{(1,30)} = 10.17$ ,  $p = 0.003$ ,  $\eta^2 = 0.018$ ), with longer distances leading to more underestimation, and significant interaction effect of length  $\times$  direction ( $F_{(1,30)} = 7.62$ ,

$p = 0.01$ ,  $\eta^2 = 0.006$ ). The interaction indicated a larger underestimation by the wrist. Also, by the wrist, no difference between long and short motion stimuli was apparent, but in the distal–proximal condition short motion stimuli showed the least underestimation. Moreover, the interaction velocity  $\times$  direction  $\times$  length ( $F_{(1,30)} = 13.38$ ,  $p < 0.001$ ,  $\eta^2 = 0.006$ ) was also significant (Fig. 2) and reflected an attenuation of the length  $\times$  direction interaction for the slow moving stimuli. Underestimation was greatest for distally directed fast motion.

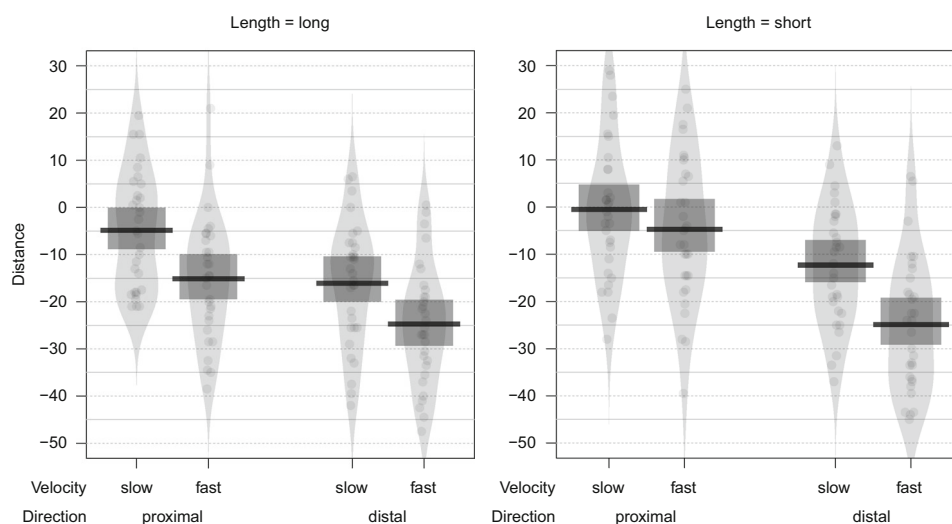
## Discussion

We set out to investigate RM in the tactile modality and found participants to displace the perceived endpoint towards the starting point of the motion, i.e. an underestimation. This finding was especially pronounced for longer and faster motion trajectories. The pattern of results is thus contrary to the simple prediction, based on RM in the visual modality, that the perceived endpoint would be displaced in the direction of motion. Instead, we have confirmed some findings of the previous literature on tactile motion perception, whose relevance for a cross-modal comparison of perceived motion (in the visual fields vs. on the skin) has never been considered.

In two experiments similar to ours but not designed in the framework of RM, Whitsel et al. (1986) showed significant underestimation. These authors described a decrease in perceived distance with increasing stimulus velocity, an observation first reported in 1885 (Hall, & Donaldson, 1885) and later also by Langford, Hall, & Monty (1973). In the Whitsel et al. (1986) experiments, the effect of tactile velocity on subjective perception was assessed meticulously using a range of velocities from 1 to 256 cm/s. It was found that only the slowest tested velocity (1 cm/s) led to a misperception of the endpoint in the direction of motion—analogueous to a RM and reminiscent of a recently published illusion, in which a distal–proximal tactile motion starting at the wrist leads to an anticipation of the perceived touch of the elbow crook (Brugger, & Meier, 2015). With increasing velocity, however, the tactile path length perception changed into an underestimation. The decrease in experienced path length was not linear but interrupted by a plateau at velocities 5–25 cm/s, where there was no relationship between velocity and perceived endpoint. In our study, we applied stimulus velocities at the borders of this range (6 and 27 cm/s) and, similar to Whitsel et al. (1986), found a main effect of velocity on subjective distance with faster stimuli perceived more in the direction of the starting point.

However, there are notable methodological differences between the two studies.

**Fig. 2** The interaction effect involving direction, velocity and length. The *y-axis* represents the distance between the perceived endpoint and the stimulated endpoint in mm (*negative numbers* indicate underestimation, *positive numbers* overestimation). For each condition the mean of each participant is presented as a dot. Moreover, the distribution for each relevant condition is depicted, as well as the mean over all participants for each condition and the 95% high density interval around the mean



While in the experiments by Whitsel et al. (1986), participants had to make an explicit estimate of the length of the stimulation path with the aid of a visual figure, our measure was selected to match the methodology of the classical RM, i.e. in visual paradigms. Another difference to the experiments by Whitsel et al. (1986) concerns stimulus application. While these authors used robot-controlled tactile stimulation, we relied on manually applied touch. It cannot be excluded that the situation of interpersonal touch leads to a neural response that is different from that of automated stimulation (Gallace, & Spence, 2010). In the illusion experiment by Brugger and Meier (2015), mentioned above, a tactile motion stimulus elicited an RM-like effect, but there the endpoint was predefined (crook of the elbow) and participants had to indicate when this endpoint was reached. The conditions in their experiment can thus not readily be compared with the conditions employed here.

The magnitude of the mislocalization error in the present study is in line with previous findings in slightly different paradigms. Using dynamic tactile stimuli Seizova-Cajic and Taylor (2014) found a systematic mislocalization bias towards the central regions of the forearm. This tendency would fit with the results of the present study. Interestingly, when no motion was present, the elbow and wrist served as ‘anchors’, resulting in an elongated representation of the forearm (Trojan et al. 2006), of potential interest also for the findings by Brugger and Meier (2015). The elongated representation would be consistent with overestimated trajectories in the visual (Actis-Grosso, & Stucchi, 2003; Hubbard, & Motes, 2002) modality. Together, these authors’ findings suggest that tactile motion might be directly related to the mislocalization error also found in the present study, but that future studies of RM on the skin should ideally use both dynamic and static tactile stimuli.

Still different methodological setups may be relevant to the discussion of whether or not RM can be observed in the somatosensory modality or the sensorimotor system. Brouwer et al. (2004) presented participants with dumbbells of increasing or decreasing size and had them “grasp” the final size. They found significant RM in grip aperture between thumb and index finger. Although their study used visual stimulation, RM was not of the type of the classical mislocalization of the endpoint in a pointing response, but manifested itself in the postural-haptic modality. An effect related to RM is the flash-lag effect, which consists in the perceptual impression that a flash around a (non-fixated) moving object would lag behind the object (Nijhawan, 2002). It is known that when the object’s movement is yoked to the observer’s head or body movement (and hence, any retinal motion signal is absent) there is still a flash-lag effect (Cai, Jacobson, Baloh, Schlag-Rey, & Schlag, 2000; Schlag, Cai, Dorfman, Mohempour, & Schlag-Rey, 2000). This suggests that vestibular signals and postural information can lead to an underestimation response with respect to a visual stimulus. Finally, Nijhawan, & Kirschfeld (2003) described a cross-modal flash-lag effect in the visuomotor system, i.e. the lagging behind of a flash aligned with the observer’s invisible hand they voluntarily turned by the wrist. Recently, the same phenomenon has also been reproduced in the haptic modality, dubbed the buzz-lag effect (Cellini, Scocchia, & Drewing, 2016). To the extent that the flash-lag effect may rest on RM of the invisible target (Hubbard, 2014), this finding would indicate that internal dynamic representation are valid in the sensory and motor system alike.

The underestimation we found in our data could either be related to lower-level processes, e.g. the neural representation of the forearm’s receptive fields in somatosensory areas (Whitsel, Favorov, Kelly, & Tommerdahl, 1991), or

to some higher level cognitive processes in the perception of velocity. It has been shown that velocity is underestimated in touch (Goldreich, 2007; Goldreich, & Tong, 2013; Tong, Ngo, & Goldreich, 2016). These authors argue that such an underestimation could be explained in a Bayesian framework by biased velocity priors favoring slow motion and being valid for the visual, auditory and tactile modality alike (Senna, Parise, & Ernst, 2015). This theory could explain our pattern of an increasing mislocalization of the endpoint towards the starting point with increasing velocity. The main effect of stimulation direction we found in our data, with proximal–distal stimulation leading to more mislocalization than distal–proximal stimulation would seem paradoxical in view of a higher locognosic acuity by the wrist (Cody, Garside, Lloyd, & Poliakoff, 2008), which would generally result in more noise by the wrist instead of an underestimation. However, given the larger cortical representation of the wrist than elbow, proximal–distal movement results in increasingly greater neural activity and engagement of inhibition as the stimulus progresses along its path, thus perhaps explaining the larger underestimation at the wrist site. The results could also indicate the presence of another bias, one that is directed towards the torso. According to this account, a body or a mass could have an attracting influence to moving objects, similar to the influence of gravity. However, direct evidence for such an additional, directional “torso bias” is lacking, and its existence must remain speculative.

Other perceptual illusions in the visual modality, which can be found in analogous form also in the auditory and tactile modalities, suggest a canonical mechanism common to vision, audition and touch. For example, the Tau and Kappa effects are two complementary illusions in which either stimulus timing presentation or spatial intervals between two sources lead to an illusion of distance or timing (Christopher Bill, & Teft, 1972; Helson, 1930; Sarrazin et al., 2005). In experiments on the Tau effect, subjects systematically underestimated the spatial distance between stimuli separated by shorter temporal intervals (faster imputed velocities). Another illusion in the visual and haptic modality possibly related to RM is boundary extension, where visual scenes are remembered beyond their physical boundary, suggesting top-down influences (Intraub, 2004; Intraub, Morelli, & Gagnier, 2015).

The contrasting finding of an underestimation could rest upon differences in the functionality of the three modalities. While the environment perceivable by vision and audition is potentially unlimited, the surface of the skin clearly defines the extent of tactile perception. The limited extent of the skin could serve as boundary, potentially provoking a rebound or cessation of the motion. Similarly, for visual stimuli it has been shown that a forward

displacement decreased or even reversed when a target stimulus was approaching a boundary with the backward displacement increasing as a function of distance from said boundary (Hubbard, & Motes, 2005), dubbed “framing effect” in Lenggenhager et al. (2012, p. 1325). Thus, it is possible that the wrist and the elbow are perceived as boundaries at which the movement direction would be reversed. This theory could be tested in future experiments with a manipulation of the distance of the endpoint from the wrist and elbow. Likewise, as proximal–distal and distal–proximal stimulations alternated (pseudo randomly) across the sequence of trials, participants may have built up a global sense of some oscillatory motion. This might have produced an underestimation response, as the trajectory of an oscillating object is typically underestimated (Cavanagh, & Anstis, 2013). Blockwise presentations of one motion direction could help to test this “oscillation hypothesis” in future experimentation.

Further studies using paradigms borrowed from both basic psychophysics and cognitive psychology will be needed to reconcile the apparent differences in motion perception across sensory modalities. These studies will reveal the nature of RM in the somatosensory modality and allow in judgement of whether, in fact, tactile motion lacks momentum.

A shortcoming of the present study could be that the response to the endpoint stimulation was given by the participant while visually inspecting the previously stimulated target skin-segment. This way the visual input could have influenced the somatosensory representation of distance, considering the observation that the spatial resolution of tactile perception improves when there is visibility of the touched body part (Kennett, Taylor-Clarke, & Haggard, 2001). Furthermore, literature on tactile line bisections has suggested more accurate response for bisecting one’s own seen body parts than for external objects (Bolognini, Casanova, Maravita, & Vallar, 2012), which could thus have increased precision in our study.

Future studies should carefully investigate purely visual RM observed on a body part, purely tactile RM felt on the same part and finally the combination of the two inputs to learn about any potential mutual benefits. Finally, eye movements should be assessed in all these cases as the role of ocular smooth pursuit could be related to RM (Kerzel, 2000, 2003; Kerzel, Jordan, & Müsseler, 2001). Similarly, with eye fixation RM has been found to be weaker for continuous motion (Kerzel, 2003) as used in the present study, which may partially explain the findings.

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## Compliance with ethical standards

**Conflict of interest** All authors declare that they have no conflict of interest.

**Ethical approval** The study was approved by the local Ethics Committee of the University of Basel. All participants gave written informed consent before the experiment.

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