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Implied tactile motion: Localizing dynamic stimulations on the skin

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27.11.2018

Dear Dr. van Dam,

We write regarding our manuscript, “Implied tactile motion: Localizing dynamic stimulations on the skin” (PP-ORIG-18-076.R1), for which you are Action Editor at *Attention, Perception, and Psychophysics*.

Based on the two reviews, you requested that we address the reviewers’ comments in a revision before the paper might be accepted for publication. We have now done exactly as requested. In particular, please find below detailed responses to the reviewers’ various comments and suggestions. The manuscript itself has also been revised accordingly. Let us start by saying that all of your comments as well as those of the two reviewers were once again most constructive and helpful in terms of clarifying the expression of our central ideas in the revised manuscript. In response to the reviews, we now include a discussion in our manuscript about the proposed control condition of Reviewer 1. Further, we have revised our existing figures as well and provide the raw data with the corresponding model predictions at a subject-by-subject level, as proposed by the reviewers. We look forward to hearing from you concerning whether this body of research is now acceptable for publication in the journal.

Thanks again for your careful consideration of our manuscript.

Yours sincerely,

Simon Merz, Hauke S. Meyerhoff, Charles Spence, & Christian Frings

Dear Mr. Merz:

I am writing concerning your paper, manuscript PP-ORIG-18-076.R1 entitled "Implied tactile motion: Localizing dynamic stimulations on the skin," that you submitted to Attention, Perception, & Psychophysics. I apologize for the uncharacteristic delay in getting the reviewer comments back to you. I am however pleased to inform you that the response was generally positive about the changes in the analysis of the experimental results and I believe that the manuscript is close to acceptance pending some revisions of the manuscript itself.

Please address the following concerns in a revision: Reviewer 2 was generally happy with the changes but mentions some worthwhile additions to complete the presentation of the modelling results. Importantly, Reviewer 1 furthermore points out an alternative for a no motion control condition that the authors should at least discuss. Furthermore, Reviewer 1 points out several places (including Figures) where the manuscript can still be improved in terms of the text and presentation. For a comprehensive list see the comments by Reviewer 1.

We are delighted to hear that our revision elicited once again positive responses and we are happy to resubmit our reworked manuscript. In line with your and the reviewers suggestions, we are now providing the raw data as well as modelling results on the level of individual participants via PsychArchives for open access (see <https://hdl.handle.net/20.500.12034/741.2> for a direct link to the published material).. Further, we added a discussion about our control condition with the control condition suggested by Reviewer 1 to the manuscript as well as improving our manuscript based on the detailed suggestions made by the two reviewers.

Responses to Reviewer 1

NOTE: Page numbers reflect the numbers typed in the manuscript and not the numbers generated by the pdf. Line numbers do not count skipped or blank lines.

General Issues: A. "Implied Motion" and "Control". I mentioned this issue in my previous review, but as this wasn't addressed in manuscript, I feel I should mention this issue again. Both the "implied motion" and "control" conditions can be considered as exhibiting implied motion. I say this because in the representational momentum literature, discrete presentations of inducing stimuli that are separated by brief temporal intervals and presented at different spatial locations, but which are not blurred or merged into continuous or apparent motion, are typically referred to as "implied motion". This description fits both the implied motion condition and the control condition in the current experiments. The difference between the implied motion condition and the control condition in the current experiments is that in the implied motion condition, the direction of motion is consistent (e.g., tactors A, B, and then C), whereas in the control condition, the direction of motion can change between different inducing stimuli (e.g., tactors B, A, and then C). As noted in my previous review, these types of stimuli were referred to as "coherent motion" and "incoherent motion", respectively, in the early work of Freyd and colleagues. Indeed, the authors seemed to embrace this terminology in their response letter, and so I was surprised to see that this was not addressed in the revision. I'm not suggesting the stimuli in the control condition were not a useful control (they were, as they provided unpredictable motion), but if the authors wanted a motion-free control, then what they should have done was present stimulation only at the target location (whether just a single stimulus or perhaps three repeated stimulations to mirror the use of three inducing stimuli). See also Specific Issues 9, 11, 13, 19, and 28.

We agree with the reviewer on this topic. As described in the previous submission, we think your proposed description of an implied motion in a single consistent direction describes our stimuli more accurately, therefore we implemented it in most parts of the revised version. But as the reviewer correctly points out in the specific issue section, at a few points of the manuscript the old wording was not changed. We have now done so and further discuss your proposed alternative

motion free control in the manuscript, to really make clear to the reader that both our conditions involve motion (pp. 26-27).

B. Relative Probe Judgments. In Experiment 1 (page 15, lines 8-10), participants judged whether the final tactor stimulus was closer to the elbow or closer to the wrist, and this is suggested to parallel the use of relative probe judgments in studies of forward shift. However, the use of relative probe judgments in studies of representational momentum rarely (if ever) involved participants comparing the remembered location of the probe to some other location or landmark. Rather, the use of relative probe judgments in studies of representational momentum typically involved presenting a probe at a location that could have been the same as or different from the final location of the target, and participants judged whether that probe was at the same location where the target vanished or at a different location. Judging which of two distant landmarks the final location of the target was closest to is different from the types of relative probe judgments used in studies of representational momentum. I don't know if this difference is important, but it seems like it should at least be noted.

We concur that we do indeed deviate from classical representational momentum studies in this regard. To make this deviation more transparent, we now describe in more detail the similarity between our dependent measures and classical representational momentum studies in the Overview section.

C. References. Hubbard and Courtney (2010) is cited on page 7, line 15 but is not listed in the References section. Gardner and Spencer is listed as 1973 in Footnote 2 but as 1972 in the References section. Flach and Haggard is listed as 2005 in Footnote 2 but as 2006 in the References section. Bates et al. is listed as 2015 on page 18, line 4 but as 2014 in the References section. Also, there should be an entry in the References section for the R Core Team, given that it is cited on page 18, line 4.

Thank you for pointing us to these inconsistencies / missing. All have been corrected now.

Specific Issue:

1. Page 3, line 19: Perhaps "static tactile stimuli" should be changed to "a static tactile stimulus" to match the singular "location" later in the sentence.

2. Page 4, line 23: It's not just "the direction of perceived motion", but rather the direction of anticipated motion. This is illustrated in the displacement of an object that vanishes at the moment a change in direction is expected; displacement is in the anticipated new direction and not in the previously perceived direction (e.g., Hubbard & Bharucha, 1988). Indeed, use of "anticipation" in the description of Berry et al. in the following sentence is consistent with this.

3. Page 5, line 13: As "effect" wasn't part of the name of representational momentum, it probably shouldn't be part of the name of representational gravity.

All corrected, thanks.

4. Page 5, line 18; page 6, lines 24-25: Is it correct formatting to say "... and colleagues" and then list in the subsequent parentheses only the year? It looks odd to me, but that might just be my bias.

That is right. Furthermore, as it is the first reference to their study, all authors must be presented. The sentence was changed accordingly.

5. Page 6, lines 9-11: It isn't clear why having differences in spatial acuity therefore makes an area good for the study of forward shift. If one is interested in effects of acuity on forward shift, then I can see the logic, but if one is simply interested in whether a forward shift occurs, then it is not clear why one would want differences in acuity.

You are right, the sentence at this part of the manuscript leads to unnecessary confusion, and therefore it has now simply been deleted.

6. Page 6, lines 12-13: The statement “Assessing the forward shift at different locations therefore indicates the influence of spatial acuity on the forward shift” seems too strong. Differences in forward shift might reflect differences in acuity, but it is possible that other factors (some of which the authors discuss later, e.g., bias toward proximal as “closer to the self”, a possible landmark effect of the head [or torso], etc.) might be responsible for such differences. Also, is “side” correct in line 13? I’ve heard the expression “on the other hand”, but not “on the other side”.

In line with your suggestion, we now weaken this expression by writing “... therefore might indicate the influence of spatial acuity on the forward shift” and use the expression “On the other hand,...”.

7. page 6, line 19: I mentioned this in my previous review, but it does not appear to have been addressed. The term “tactor” is used several times in the introduction and in the experiments. However, not all readers of the journal will be familiar with this term (indeed, researchers interested in forward shift but who aren’t familiar with research in tactile perception won’t understand this until they read through the Methods section and examine Figures 1 and 2). I think this term should be briefly defined or described (even if only parenthetically) when it is first mentioned.

We now define briefly the term tactor when it is first mentioned (p.6, second paragraph).

8. Page 7, lines 1 and 2: I’m not sure this is as fatal as the authors suggest. In comparing the observed shift to the actual location, researchers usually test whether the magnitude of displacement is significantly different from zero (with zero being the “true-same” position). Representational momentum predicts a clear and systematic displacement in a specific direction. Without motion, there would be no reason to predict a significant and consistent direction of displacement (ignoring for the moment other factors such as representational gravity that might also introduce a mislocalization). A target expected to continue moving rightward exhibits a strong displacement toward the right, and a target expected to continue moving leftward exhibits a strong displacement toward the left; however, a stationary target (in isolation) would not be expected to exhibit systematic and consistent rightward or leftward displacement. This anticipation of motion in a specific direction is responsible for the displacement in that direction.

We totally agree with the reviewer regarding representational momentum in the visual modality. In vision, a stationary target is not expected to exhibit systematic / consistent displacement (ignoring representational gravity). But in the tactile modality, there is an abundance of literature (see the second paragraph of the Introduction) showing that the actual location of a stationary tactile stimulus is not always in line with the perceived location. To date, there is still a discussion about the relevant moderators (e.g. head / eye orientation, Harrar & Harris, 2009; Ho & Spence, 2007; stimulus intensity, Steenbergen et al., 2014; for a discussion about tactile localization errors, see Medina & Coslett, 2016) underlying these mislocalizations of static / singular tactile targets. Therefore, to be able to attribute a mislocalization to the anticipated motion of a stimulus in any tactile RM experiment, a control stimulus to account for general mislocalizations is critical. Please note that the comparison with a control stimulus is not new to the representational literature, as Getzmann and Lewald (2007, 2009) used a control stimulus in their auditory representational momentum experiments.

9. Page 7, lines 6-7: One type of control is to measure displacement of a stationary stimulus, but the authors actually use a different type of control that exhibits motion but not consistent (predictable) motion. As noted in my previous review and in General Issue A, in some of the early papers of Freyd and colleagues, coherent motion (e.g., like stimulating tactors A, B, C in that order) was contrasted with incoherent motion (e.g., like stimulating tactors B, A, C in that order).

Corrected, in line with General Issue A

10. Page 10, line 4 from bottom: “their” should be changed to “his or her” to match the singular “the participant’s” earlier in the sentence.

Corrected, thanks.

11. Page 11, last line: These instructions are ambiguous, as “a random pattern” could be perceived as involving changes in the direction of motion as different tactors were activated. In other words, both the “motion pattern” and the “random pattern” involved motion, but in the former case, motion was in a consistent direction across stimuli in a given trial, whereas in the latter case, the direction of motion changed across stimuli within a given trial.

We concur that both, implied motion and control trials, involve motion (see also General Issue A). But we do not believe that these instructions were ambiguous. Participants rated the resemblance of the three different conditions with a random or a motion pattern on a continuous scale. In fact, the Pilot study helps to answer the raised question as both, motion and control trials, involve motion. Asked about the resemblance of motion (item 3), the control condition was rated on 4.5 out of 9. Therefore, both the implied motion and the control trials have motion characteristics. For the implied motion conditions, the motion characteristics were more consistent / stronger.

12. Page 12, Figure 4: I don't know how to read the three graphs near the top of the figure. What are the different bars in each graph? The legend seems to be missing. Similarly, what are the different horizontal bars for items 2, 3 and 4? Again, the legend seems to be missing. Also, the translations for items 3 and 4 are not quite standard English. Something like “To what extent did the last sequence of vibrations feel like...” would be better.

The reviewer is correct. The legend was missing and has now been added to the figure. Further, the translation was updated based on your suggestion, thanks.

13. Page 13, lines 15-16; page 14, line 5; etc.: “extend” should be “extent”. Also, it seems inappropriate to ask about the existence of a “motion pattern” as all conditions involved motion. Indeed, to the extent that the control condition potentially involved changes in direction across a single trial, the control condition could be viewed as exhibiting a more complex motion pattern than did the simpler continuations in a single direction of motion in the proximal and distal conditions. The pilot experiment might have addressed this somewhat, but given my uncertainty about Figure 4 (see Specific Issue 12), that was not clear to me.

As mentioned already in our reply to the specific issue 11, we don’t think this question (item 4), as well as the question about motion (item 3), is inappropriate, as it gives a qualitative assessment of the conditions used in the experiment. Further, it helps to answer the questions raised in these two issues.

14. Page 14, lines 10-11: I’m not sure “stronger” is the best way to characterize this. Something like “more consistent” might be better.

We agree and have thus changed the sentence accordingly.

15. Page 16, lines 19-21: If the target location was at location C (cf. page 13, lines 9-10), and given the tactor letters in Figure 1, then the proximal direction appears to move from A, B, to C. However, this is actually toward the wrist, not toward the elbow. Similarly, the distal direction condition appears to move from E to D to C, but this is actually toward the elbow, not toward the wrist. This seems opposite to the use of “proximal” and “distal” elsewhere in the manuscript. Is this a typo? Also, the order of the tactor locations in the text should probably parallel the order in which those locations are activated. Given this, I would change “B and A” to “A and B”. Or have I misunderstood?

In fact, there is a misunderstanding here. In this part, we describe the different end location, not the stimulus sequence. To avoid misunderstanding, we have now

rewritten this part of the manuscript and provide the different end locations together with the corresponding stimulus sequence.

16. Page 18, line 7: Perhaps “different” or “additional” should be added before “fixed effect”? Otherwise, this could be misread as suggesting the same fixed effect was added in each model. Or have I misunderstood?

We are not sure what exactly the reviewer means with this issue. Our modelling approach was as follows: Model 1 was comprised of only the intercept (Model 1: intercept only). For Model 2, Model 1 was extended to incorporate the fixed effect of location (Model 1: fixed effect location). For Model 3, Model 2 was extended to incorporate the additional fixed effect of experimental condition (Model 3: fixed effects of location and experimental condition). For Model 4, Model 3 was extended to incorporate the interaction (Model 4: fixed effects of location, experimental condition as well as their interaction)). To make this analytical approach more clear, we have now extended the description of our analysis and refer to it in a subsection of the Method section (in line with Reviewer 2’s suggestion). Further, we published the raw data as well as our R-script for open access and reference them in the manuscript.

17. Page 19, lines 2-3 from bottom; page 23, lines 1-2. Given the apparent inconsistency between the descriptions of proximal and distal (see Specific Issue 15), I was not sure whether this meant an effect was obtained for movement toward the elbow or for movement toward the wrist.

An effect for movement toward the elbow was obtained. With the changes made (see specific issue 15), this inconsistency should not occur any more.

18. Page 20, lines 6-7: It isn’t clear if “this pattern” refers to the pattern observed in Experiment 1 or to the pattern speculated to be obtained in Experiment 2.

It refers to the pattern of results in Experiment 1. The sentence has been updated accordingly.

19. Page 20, line 10: “which either implied a motion along the forearm or did not”. Again, it’s not whether motion was implied or not (as there was presumably perceived motion between tactors in all conditions), but whether that motion was in a consistent (and hence predictable) direction. In the consistent motion conditions (analogous to coherent motion in early representational momentum studies), that consistency allowed prediction of future motion (and so there was a forward shift), whereas in the “control” condition (analogous to incoherent motion in early representational momentum studies), the lack of predictability did not allow prediction of future motion (and so there was no forward shift).

Corrected, thanks. We now refer to “a motion in a single consistent direction”

20. Page 21, lines 13-14: What does “and to proceed on to the next trial” mean? Did the experimenter rather than the participant initiate each trial? If so, why?

Yes, the experimenter initiated each trial. That was done so that the experimenter had sufficient time to note the indicated location before a new trial started. A new trials only started when the participant as well as the experimenter were ready. The manuscript was updated accordingly.

21. Page 23, line 22: Perhaps something like “to be” or “as” should be inserted before “further”.

Added, thanks.

22. Page 24, line 9: So my wrist is less a part of my self than is my elbow? What about professionals who do skilled labor with their hands (e.g., artists, surgeons, etc.). Would their hands be less a part of their “selves” (or their

self-identity) than their wrists or elbows? Even if I grant that the “self” seems to “live” or “be focused” in the head, that doesn’t necessarily mean that other parts of the body aren’t part of the self, too (if they weren’t, then losing a limb shouldn’t be so traumatic, as that limb wouldn’t be part of the self).

Apparently, our wording could be misunderstood in this instance. We never wanted to imply that the wrist or elbow are more or less a part of the self. The idea is that if we perceived the self at a specific location in our body (the head / torso), a motion along the forearm then approaches or recedes from this location. Therefore, a motion along the forearm is perceived differently as it either approaches the perceived location of the self or not. As we discuss in the following paragraphs, changing the body posture / bending the arm might change the present results. Nevertheless, to avoid the misunderstanding highlighted by the reviewer, we have specified the self with “(i.e. the head/torso)”.

23. Page 24, line 12: Perhaps “was” should be “were”.

Corrected, thanks.

24. Page 24, last two lines: I suspect this is an idiom that I’m not familiar with, but what does “coming toward you at speed” mean?

Reworded.

25. Page 25, lines 1-7: Neuhoff’s (2018) chapter in Hubbard’s edited volume on “Spatial Biases in Perception and Cognition” develops this evolutionary argument regarding looming beyond his earlier speculations.

Thank you for pointing us to this interesting book chapter which we have now incorporated into the revised version of the manuscript.

26. Page 25, line 4: For clarity, I might expand “than receding stimuli” to “than are receding stimuli of the same objective distance from the observer”.

Corrected, thanks.

27. Page 27, line 5: I would insert a comma after “backward”.

Corrected, thanks.

28. Page 27, lines 11-12: Actually, I think the same comment can be made about the current experiments, as I would suggest there was no “motion-free” stimulus in the current experiment, either (e.g., activating B, A, and C can be seen as a proximal motion from B to A followed by a faster distal motion for A to C). If the authors wanted a motion-free control condition, they should have presented a single tactor and had observers indicate the location of the stimuli (e.g., compare a control in which only C is activated with a condition in which activation of C is preceded by activation of A and then activation of B). In this “motion free” control condition, one would predict no systematic shift in a particular direction, whereas in the motion conditions, one would predict systematic shifts in the direction of motion.

Corrected accordingly (see General Issue A).

Responses to Reviewer 2

Comments to the Author: The authors investigated the occurrence of apparent motion in touch, and evaluated whether a sequence of vibrotactile stimulus affects the location of the last stimulus of the series. Overall, the last stimulus was perceived as closer to the elbow, with a small increase of the bias for the “proximal” motion

condition. The authors addressed all my previous issues and changed the analysis to include catch trials. Aside from some minor points (see below), I endorse the publication of the study.

We are happy to hear that the revision dealt adequately with the reviewer's previous issues.

Applying GLMM, it is a good practice to show either in the main text or in the supplementary materials the model predictions and the raw data at the single subject level, see for example Fig. 2 in (Barrea, Delhayé, Lefèvre, & Thonnard, 2018) and Fig. 3-5 in (Dallmann, Ernst, & Moscatelli, 2015).

In line with your suggestion, we now present data on the single subject level as well as the corresponding model predictions for every subject. Together with the raw data as well as the R-scripts, we published this information via PsychArchives for open access and explicitly reference the publication in the newly created Analysis-subsection of each experiment (see <https://hdl.handle.net/20.500.12034/741.2> for a direct link to the published material).

In each experiment, please report the estimate of the fixed-effect parameters of the best fitting model. This is necessary to estimate the size of the effect, as estimated by the GLMM/LMM.

Table 1 was updated in line with your suggestion.

Data analysis was briefly explained in the results section. Please extend it and move it to Methods section (subsection Analysis).

In line with your suggestion, we now moved the data-analysis description to the Methods section and have further revised the paragraph in order to prevent future misunderstandings (see also Reviewer 1, specific issue 16). Additionally, we published the raw data as well as the R-script via PsychArchives for open access.

"than the categorical predictor experimental condition" → "then the categorical..."

Corrected, thanks.

Implied tactile motion: Systematic mislocalization

Implied tactile motion:

Localizing dynamic stimulations on the skin

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Localizing implied tactile motion stimuli

Abstract

We report two experiments designed to investigate how the implied motion of tactile stimuli influences perceived location. Predicting the location of sensory input is especially important as far as the perception of, and interaction with, the external world is concerned. Using two different experimental approaches, an overall pattern of localization shifts analogous to what has been described previously in the visual and auditory modalities is reported. That is, participants perceive the last location of a dynamic stimulus further along its trajectory than is objectively the case. In Experiment 1, participants judged whether the last vibration in a sequence of three was located closer to the wrist or to the elbow. In Experiment 2, they indicated the last location on a ruler attached to their forearm. We further pinpoint the effects of implied motion on tactile localization by investigating the independent influences of motion direction and perceptual uncertainty. Taken together, these findings underline the importance of dynamic information in localizing tactile stimuli on the skin.

Keywords: Tactile Localization, Representational Momentum, Motion Perception, Direction Perception

Localizing implied tactile motion stimuli

Introduction

Children sometimes play a game in which one child extends his or her arm, palm upwards, and closes his/her eyes. The other child then runs his/her finger slowly along the skin surface from wrist to elbow. The first child has to indicate when the finger of the other has reached the elbow joint. Typically, the first child will indicate the arrival of the other child's finger at their elbow too early (that is, before the finger had actually reached the elbow joint). In other words, the finger is perceived as occupying a location further along in its trajectory than is actually the case. While this example is nothing more than a children's game, knowing where people localize dynamic tactile stimuli turns out to be of both theoretical and practical importance. Yet, until now, only a pure replication (Brugger & Meier, 2015), and a first experiment looking at such endpoint-localization of dynamic tactile stimuli (Macauda, Lenggenhager, Meier, Essick, & Brugger, 2018) have been published. The present study was designed to systematically investigate the influence of implied motion on tactile localization.

Event localization is an important task for our senses and, in particular, for multisensory integration. For instance, if we feel an insect on our skin, we need to know where it is in order to be able to engage with or act on it. Interestingly, even the localization of static, tactile events (e.g., a tap on the skin) is not always error-free. It has, for example, often been reported that a static tactile stimulus may be systematically misperceived at a different spatial location (Harrar & Harris, 2009; Ho & Spence, 2007; Longo, 2017; Mancini, Longo, Iannetti, & Haggard, 2011; Margolis & Longo, 2015; Steenbergen, Buitenweg, Trojan, & Veltink, 2014; Trojan et al., 2006, see Medina & Coslett, 2016, for a discussion). Even at the hand and fingers, locations that are very sensitive to two-point discrimination and localization (see Gallace & Spence, 2014; Stevens & Choo, 1996; Weinstein, 1968), systematic mislocalizations have been documented (e.g., Mancini et al., 2011; Margolis & Longo, 2015). Tactile localization can also

Localizing implied tactile motion stimuli

be biased due to the changing orientation of the head (Ho & Spence, 2007) as well as the position of the eyes (Harrar & Harris, 2009). Moreover, the perceived location of a tactile stimulus can be shifted toward the location of a preceding or succeeding tactile stimulus (this is known as *tactile saltation*; Geldard & Sherrick, 1972). When two tactile stimuli are presented simultaneously or else in rapid succession, only one stimulus somewhere between the two stimuli may be perceived (this is known as *funneling*; Chen, Friedman, & Roe, 2003; Gardner & Spencer, 1972). Those examples show that the precision in tactile localization is variable and can be poor.

In the visual and auditory modalities, it is well-known that the localization of stimuli is influenced by their (implied) motion. Freyd and Finke (1984) were the first to report that the location of a stimulus is displaced in the direction of (implied) motion if the stimulus seems to rotate in a single consistent direction (Experiment 1) as compared to a condition in which the stimulus does not (Experiment 2). This forward shift, when the last location of a moving stimulus is perceived further along its trajectory, is a robust and oft-replicated finding in the literature on *representational momentum* (see Hubbard, 2005, 2014, 2018, for reviews). Many theories have tried to explain the forward shift, ranging from internalization accounts (e.g., Freyd, 1987; Freyd & Finke, 1984) to network-models (e.g., the *bow-wave model*; Müsseler, Stork, & Kerzel, 2002), as classified by Hubbard (2010) in his overview of theories of representational momentum. On a neuronal level, the forward shift might also be explained with the help of the theory of *dynamic predictive coding* (e.g., see Clark, 2013; Huang & Rao, 2011; Rao & Ballard, 1999). Following on from this idea, we constantly predict upcoming sensory inputs. Hence, if a stimulus moves, it would be reasonable for the sensory system to predict the next sensory input in the direction of anticipated motion. In line with such a suggestion, Berry and colleagues (1999) found an anticipation effect for visual stimuli moving across the retina (see De Sá Teixeira, 2016; Hubbard, 2005, 2014; Kerzel, 2000, for discussion

Localizing implied tactile motion stimuli

concerning the influence of eye movements on representational momentum). Interestingly, most theories of representational momentum consider this effect to be modality-independent (see Hubbard, 2010).¹

Localization of dynamic tactile stimuli: Influence of direction and (perceptual) uncertainty

One of the main moderators of the forward shift is the direction of (implied) motion of the moving target. Horizontal moving stimuli elicit a stronger forward shift as compared to stimuli moving vertically (Hubbard, 1990; Hubbard & Bharucha, 1988). In the horizontal plane, most studies have not reported any difference between left- and rightward movement (Cooper & Munger, 1993; Hubbard, 1990, 1995a; Hubbard & Bharucha, 1988; but see Halpern & Kelly, 1993). In the vertical plane, downward movement / descending stimuli tend to elicit stronger forward shifts than upward movement / ascending stimuli, known as *representational gravity* (e.g. De sá Teixeira, 2016; De sá Teixeira, Hecht, & Oliveira, 2013; Hubbard, 1990, 1995b, 2005). For stimuli that move in the depth plane, a forward shift has been evidenced, yet consistent differences between approaching and receding events have not been reported. Hubbard (1996) documented larger forward shifts for receding targets in his Experiment 1, but was unable to replicate this finding in a subsequent experiment (Experiment 2). Meanwhile, Nagai, Kazai, and Yagi (2002) also failed to find any differences between approaching and receding targets (Experiment 2 – upright posture condition). Overall, these results can be taken to show that the direction of (implied) motion is an important moderator of the forward shift. In this present study, we present dynamic stimuli along the forearm, heading either toward the elbow or the wrist.

¹ For an exhaustive discussion of the tentative evidence regarding the interplay between localization and motion or motion-like sensations in the tactile modality, see the General Discussion.

Localizing implied tactile motion stimuli

Another influential factor on the magnitude of the forward shift is uncertainty. In fact, spatial uncertainty due to an increased blurring of the target (Fu, Shen, & Dan, 2001) or due to decreased spatial acuity (Schmiedchen, Freigang, Rübsamen, & Richter, 2013; see Kanai, Sheth, & Shimojo, 2004, for similar results on the flash-lag effect) has been shown to increase the magnitude of the forward shift. As for the tactile modality, it is well-known that different body sites differ in terms of their spatial acuity and discrimination abilities (Cholewiak, 1999; Cholewiak & Collins, 2000; Cholewiak & Craig, 1984; Cody, Garside, Lloyd, & Poliakoff, 2008; Craig & Lyle, 2002; Gallace & Spence, 2014; Green, 1982; Stevens & Choo, 1996; Weinstein, 1968). But even across one a specific region of the body surface such as the forearm, for example, spatial acuity can vary. Spatial acuity is highest at the wrist and the elbow and decreases toward the middle of the forearm (Cholewiak & Collins, 2003). Assessing the forward shift at different locations therefore might indicate the influence of spatial acuity on the forward shift. On the other hand, it is important to have at least one location which can be used to assess the forward shift for both motion direction conditions. Only then will spatial acuity be matched for both direction conditions, and hence any difference in the forward shift be attributed to the different directions of motion.

As a central aspect of this study, the tactor (a mechanical device used to present vibrotactile stimulation) location estimate of the implied motion condition is compared to that of the control condition, not to the actual tactor location. The comparison with a control condition is necessary in order to get an estimation of the effect of the implied motion on tactile localization, independent of any general mislocalization at that body site. Following the same reasoning, Getzmann and Lewald (2007, 2009) investigated the influence of motion in auditory space with the help of a control stimulus. In fact, the lack of any control estimate constitutes our main criticism of a previous study by Macaуда and colleagues (2018). For the tactile modality, the authors found a backward shift, but the estimated location was never compared

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to the perceived location of a control stimulus at that location, only to the actual tactor location. This shortcoming makes the interpretation of their results particularly problematic. At the forearm, the perceived location is not necessarily identical with the actual location, and the perceived location is further influenced by the intensity of the tactile stimulus (Steenbergen et al., 2014). Therefore, the difference between the actual and the perceived location in the study by Macaуда and colleagues might, in fact, constitute a general localization error, independent of any influence of a coherent motion in a single direction.

Overview

The goal of the present study was to investigate the influence of implied motion on tactile localization against the background of possible moderators such as motion direction and uncertainty. Five tactors were used to present vibrotactile stimuli to the participant’s left forearm. The tactors were attached in a straight line, one next to the other. Three 250 ms vibrations, separated by 250 ms empty intervals, were presented on each trial. These are the same timing parameters as documented in visual and auditory representational momentum experiments (e.g., Freyd & Finke, 1984; Hubbard & Courtney, 2010). With those timing parameters, three distinct vibrotactile stimuli were perceived. Further, these stimuli have the characteristics of a motion stimulus and imply a motion in a specific direction, but do not elicit tactile mislocalizations attributable to illusions such as the tactile saltation or funneling illusion. The latter are known to influence the perceived location of tactile sensations.² By being

² For the present series of experiments, it was our intention to avoid tactile mislocalization due to illusions like, for example, the funneling illusion (Chen et al., 2003; Gardner & Spencer, 1972). The basic funneling illusion occurs when two simultaneously-presented tactile stimuli are perceived as one tactile stimulus localized in-between the two stimulated locations. Successive tactile stimuli with an interstimulus interval of 250 ms were used in the present study to prevent the occurrence of this illusion. Another illusion which might have influenced the location perception is the tactile saltation or ‘cutaneous rabbit’ illusion (Cholewiak & Collins, 2000; Flach & Haggard, 2006; Geldard, 1982; Geldard & Sherrick, 1972). In this illusion, a tactile stimulus is mislocated toward the location of a preceding or succeeding tactile stimulus. Once again, the occurrence of this illusion in our experiments is very unlikely. A long interstimulus interval combined with a long vibrotactile stimulation duration (250 ms) was used. In contrast, those studies that have investigated the cutaneous rabbit illusion have typically

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presented next to each other in a single consistent direction, the three vibrations implied motion in one direction (implied motion condition). The locations of the three vibrations were chosen at random for the control condition (for examples, see Figure 1). Using two different dependent variables, participants judged the location of the third vibration as closer to the elbow or wrist (Experiment 1) or else indicated the location on a ruler attached to the forearm (Experiment 2). These two dependent measures were derived and adapted from two of the most oft-used dependent measures, the probe comparison (e.g., Freyd & Finke, 1984; Freyd & Johnson, 1987; Kerzel, 2003) and the absolute estimation task (e.g., Hubbard & Bharucha, 1988; Kerzel & Gegenfurtner, 2003). Typically, probe comparisons involve a comparison of the moving targets final location with another target stimuli, presented either at the same or at a slightly different location (e.g. Kerzel, 2003). Due to the experimental set-up (tactors of 3 cm, tactor spacing of 3.5 cm), we could not conduct such a probe comparison. Instead, we used comparisons of each individual target stimulus with a predefined location (i.e. wrist and elbow). Please note that the pointing response which is evaluated in Experiment 2 is a conventional dependent variable used in representational momentum studies (e.g., Kerzel & Gegenfurtner, 2003).

used shorter interstimulus intervals (about 200 ms or less) as well as durations (about 100 ms and less; e.g., Blankenburg, Ruff, Deichmann, Rees, & Driver, 2006; Flach & Haggard, 2006; Geldard & Sherrick, 1972).

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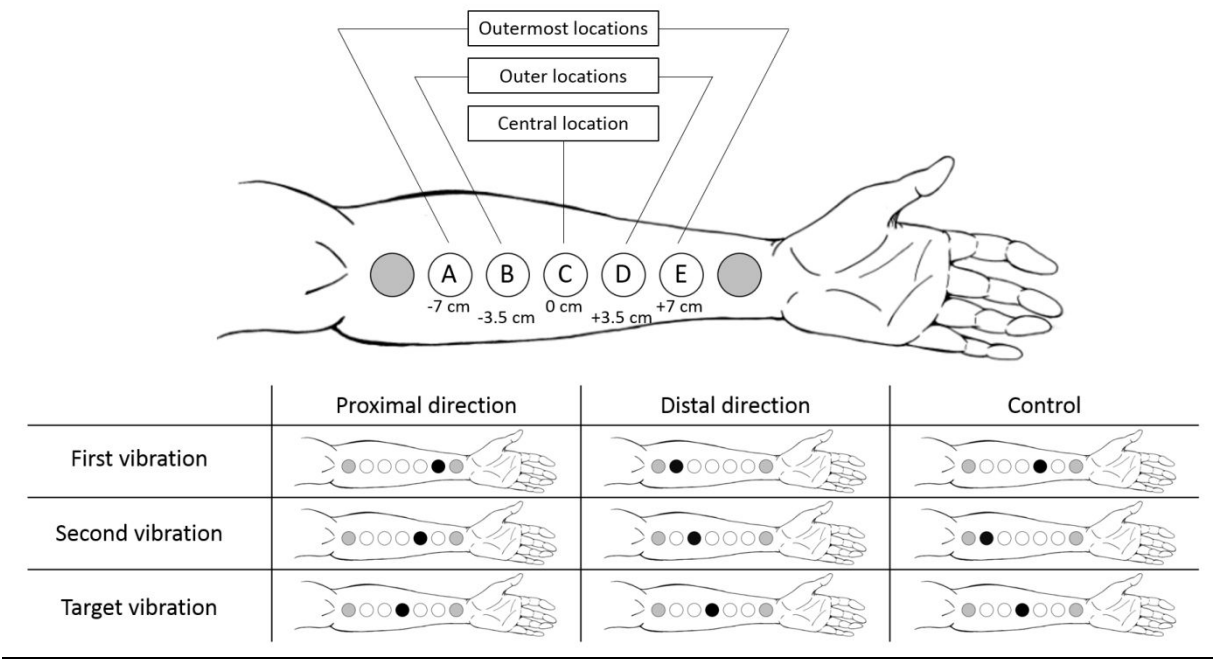


Figure 1: Mapping of actual tactor location and target location on the participant's arm. The outermost, outer, or central target locations for a distal direction are tactors E, D, and C, respectively; for the proximal direction, tactors A, B, and C, respectively. Schematic display of the three different trials types used for the central target location, namely implied motion trials with proximal and distal motion as well as control trials (one example presented, for detailed description see the main text). Filled black circles indicate a vibration at that location; Filled gray circles indicate those tactors that were attached to the arm bandage but never used during the experiments.

To foreshadow the results, systematic forward shifts for dynamic stimuli were observed and the direction of implied motion was identified as a moderating factor. The results of Experiment 2 further indicated that uncertainty (here the spatial acuity) independently of the direction of implied motion influenced forward shifts.

Pilot study: Questionnaire on the perception of the stimuli

A pilot study on the perception of the stimuli set-up used in the experiments reported here was conducted. Therefore, a short questionnaire, which focused on motion characteristics inherited by the presented stimuli, was devised.

Methods

Localizing implied tactile motion stimuli

Participants

Thirteen participants (9 female, 21-57 years, no left-handed) from the University of Trier took part in this study. All of the participants reported normal or corrected-to-normal vision and no sensory impairment on the forearm.

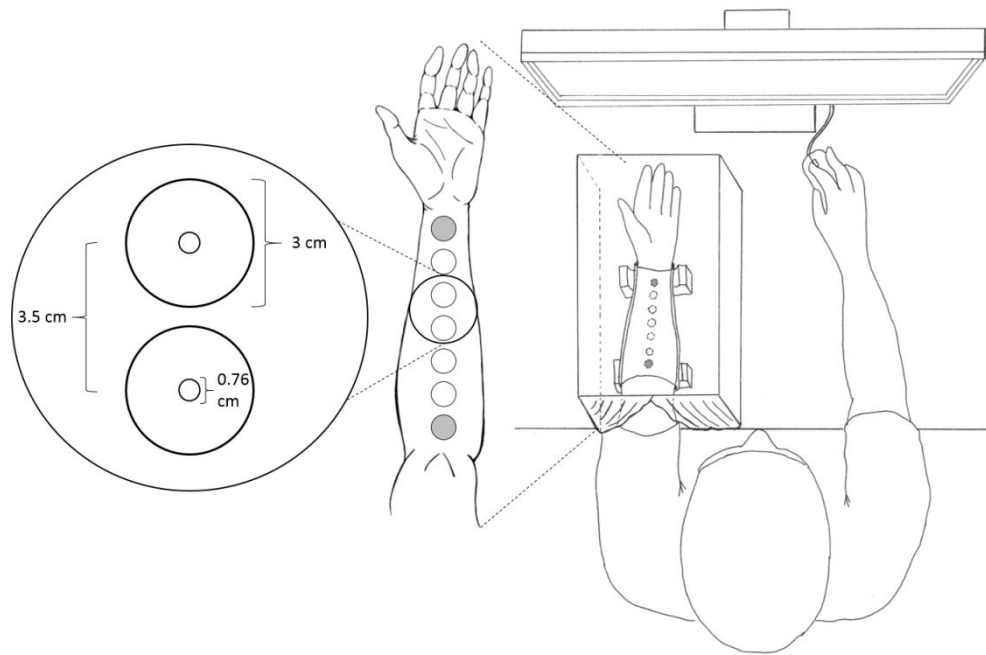


Figure 2: Bird's-eye view of the experimental set-up used during Experiment 1 with an additional inset panel showing the placement of the factors on the skin surface. In the pilot study, and in Experiment 2, the occluder box was omitted; see main text for details.

Design, Apparatus, and Stimuli

Each participant was tested individually in a dark, sound-attenuated room. All of the furniture was painted black, and all sources of illumination (e.g., from electrical equipment) were eliminated. All of the stimuli were coded in E-Prime (Version 2.0). Visual stimuli were presented on a 24-in. TFT screen controlled by a standard PC. The participant's forearm was oriented away from his or her body (see Figure 2), with the dorsal side facing upwards (see Figure 3). During the experiment, the participants wore a custom-made arm bandage with seven tactors (Model C-2, Engineering Acoustic, Inc.; controlled via the serial interface) on the interior surface.

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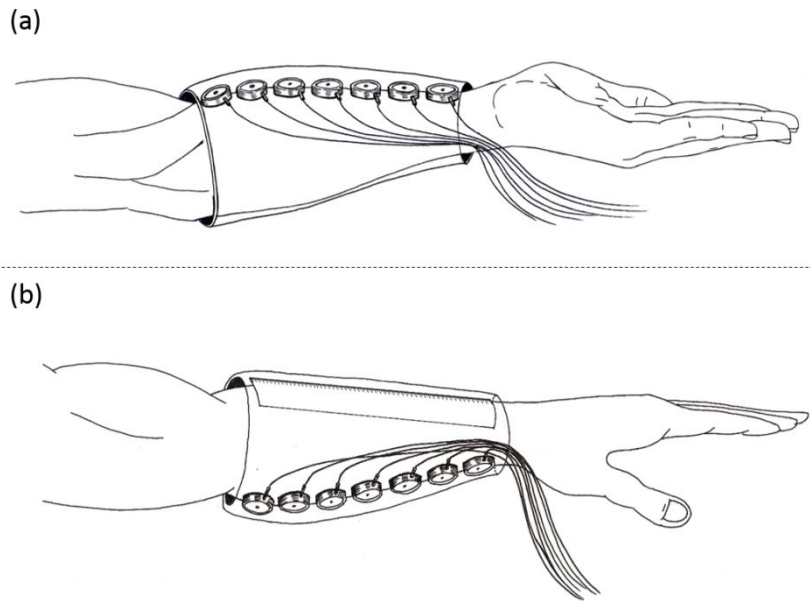
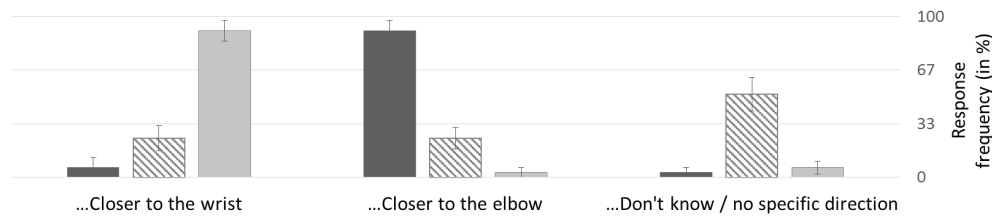


Figure 3: The two postures used for the two experiments. (a) In Experiment 1, the volar side of the forearm faced upward. (b) In Experiment 2 and the pilot study, the dorsal side of the forearm faced upward. For Experiment 2, a ruler was attached on top of the self-made arm bandage.

For this study and due to technical restrictions, only the inner five tactors were used. The tactors (3 cm in diameter; 0.79 cm thick; centrally located skin contactor of 0.76 cm) were ordered in a straight line with a center-to-center distance of 3.5 cm. The tactile stimuli (~250 Hz, about 200 μ m peak-to-peak amplitude) were applied to the volar side of the left forearm. In order to rule out any impact of the sounds caused by the operation of the tactors, the participants wore ear plugs (Noise reduction: 29 dB) on top of which white noise was presented over headphones (Over-ear headphones: about 95 dB). For this pilot study, a short paper-and-pencil questionnaire with four items was devised which had to be completed after every trial (see Figure 4). Participants were asked to continue the tactile pattern and to indicate if the next vibration would be located closer to the wrist, the elbow or in no specific direction (Item 1). On a ten-point scale, participants rated if the sequence felt like one common, continuous event or like individual, separated events (Item 2), and to what extent did the sequence feel like a motion (Item 3) or a random pattern (Item 4).

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Item 1: Continue the pattern: In comparison to the last / third vibration, the next vibration would be ... [Mark one of the three possibilities]



Item 2: Did the three vibrations feel like one common, continuous event or like individual, separated events? [Ten-point scale]

Item 3: To what extent did the last sequence of vibrations feel like a motion pattern? [Ten-point scale]

Item 4: To what extent did the last sequence of vibrations feel like a random pattern? [Ten-point scale]

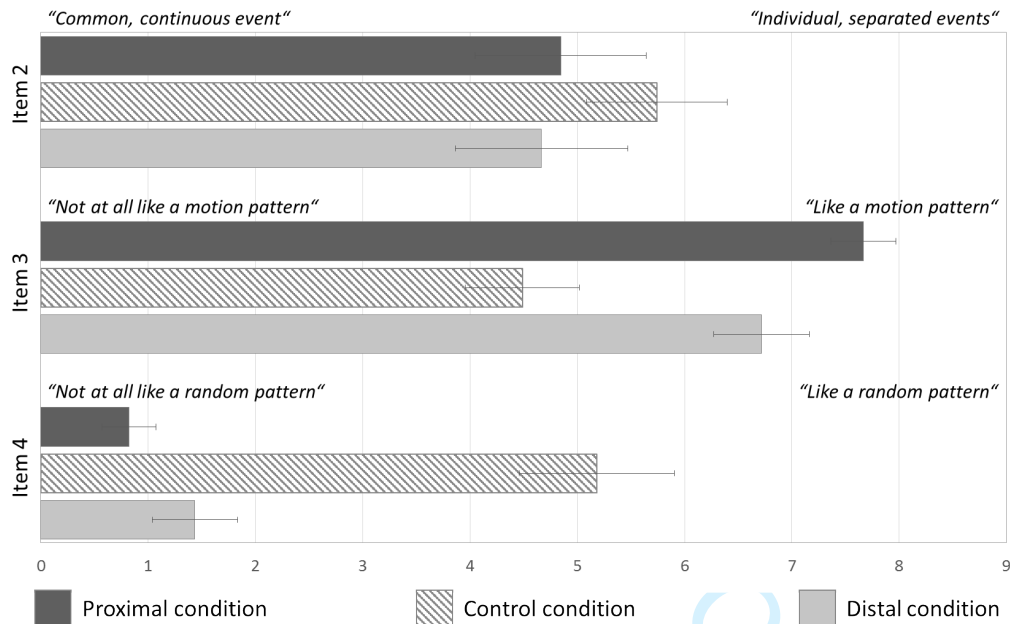


Figure 4: The four items and results of the questionnaire on the perception of the stimuli. The response frequency (Item 1) and mean rating (Items 2-4) are presented; Error bars depict the standard error of the means. The questionnaire was conducted in German, translation by the authors (see Appendix for the original wording).

Procedure

Each trial started with the visual presentation of a plus sign for 400 ms. Thereafter, three vibrotactile stimuli were presented successively for 250 ms each with an interstimulus-interval of 250 ms. Following the offset of the third vibration, the participants were asked to answer the

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four items of the questionnaire without time constraints. Then the experimenter started a new trial.

Three different conditions were presented, either one of two implied motion trials (in the distal or proximal direction), or a control trial (see Figure 1). For the implied motion trials, the vibrations were presented adjacent to each other in one single consistent direction. Therefore, these stimuli implied a motion from one tactor to the next along the participant's forearm. For 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, participants worked through nine trials (three per condition), for all trials, the target vibration was presented at tactor location C (central tactor location; see Figure 1).

Results and Discussion

When asked in which direction participants would continue the presented pattern, participants indicated to expect the pattern to continue in the implied direction (for both implied motion conditions, on average, 2.73 out of 3 times the participants would continue in the implied direction; see Item 1, Figure 4)³. When asked to what extent the sequence resembled a motion pattern (Item 3), the three different conditions were perceived differently. Overall, the implied motion conditions had a high resemblance to a motion pattern (7.19 on a scale from 0 to 9, Item 3). A one-factorial (implied proximal motion vs. implied distal motion vs. control condition) multivariate analysis of variances (MANOVA)⁴ with Pillai's trace as criterion revealed a significant main effect, $F(2, 11) = 19.73, p < .001, \eta_p^2 = .78$. Helmert contrasts revealed that the average of both implied motion sequence resembled more a motion pattern

³ For Item 1, two participants had to be excluded since they reported afterwards that they had not read the question properly and therefore answered wrongly.

⁴ 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 & Fidell, 2007).

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compared to the control pattern, $F(1, 12) = 15.60, p = .002, \eta_p^2 = .57$. Interestingly, the second contrast revealed that the implied motion sequence for the proximal direction resembled more a motion pattern than the implied motion stimulus in the distal direction condition, $F(1, 12) = 5.445, p = .038, \eta_p^2 = .31$. Similar results were obtained from Item 4. The MANOVA revealed a significant main effect, $F(2, 11) = 32.75, p < .001, \eta_p^2 = .86$, when asked to what extent the sequence resembled a random pattern. Once again, Helmert contrasts were conducted and revealed that the control sequence resembled more a random pattern in comparison with the average of both implied motion sequences, $F(1, 12) = 23.63, p < .001, \eta_p^2 = .66$. The second contrast between the two implied motion sequences was not significant, $F(1, 12) = 2.65, p = .130, \eta_p^2 = .18$. These results clearly indicate that the presented implied motion sequence is perceived to have more consistent motion characteristics than the control condition.

Experiment 1

In Experiment 1, participants were presented with a sequence of three vibrations at different locations on the forearm. The three vibrations either implied motion along the forearm in a consistent direction, or else they suggested a random pattern. A two-alternative forced choice task (2 AFC) was used to assess the perceived location. The participants' task was to indicate if they perceived the last vibration, the target vibration, as being located closer to the wrist or to the elbow. A forward shift in the proximal direction was measured as a higher percentage of elbow responses for the proximal direction condition as compared to the control condition. A forward shift for the distal direction condition was measured as a lower percentage of elbow responses for the distal implied motion condition as compared to the control condition. Based on the literature reviewed above, forward shifts for both directions were expected.

Methods

Localizing implied tactile motion stimuli

Participants

Based on the effect sizes of studies investigating the influence of (implied) motion on visual and auditory localization (Getzmann & Lewald, 2007, 2009; Cohen's d s ranging between 0.68 and 1.89), an effect of $dz = 0.7$ was used for sample size calculations. Those studies used an absolute judgment of the perceived last location (comparable to Experiment 2 of this study). Absolute judgment scores are known to elicit stronger forward shifts as compared to relative probe judgments (Kerzel, 2003; Kerzel & Gegenfurtner, 2003). In Experiment 1, a relative judgment score was used, the target vibration was judged in relation to a landmark (elbow / wrist). Therefore, the expected effect size was reduced to $dz = 0.5$ for Experiment 1. With $\alpha = .05$ and a power $(1-\beta) = .9$, we calculated a sample size of $N = 36$ using G*Power Version 3.1.9.2 (Faul, Erdfelder, Lang, & Buchner, 2007). The sample sizes were slightly increased ($N = 40$) to be able to exclude participants if needed.

The final sample consisted of 38 (22 female; 18-35 years; three left-handed) students from the University of Trier who took part in this study in return for course credit or a payment of 5€. All of the participants reported normal or corrected-to-normal vision and no sensory impairment on the forearm. The data from one participant was excluded due to a failure to comply with the task instructions. The data from another participant was excluded because he was aware of the purpose of the study.

Design

The experiments were designed with the three within-participants conditions of *direction* (proximal vs. distal), *experimental condition* (implied motion vs. control) and *target location* (central: 0 cm vs. outer: +/- 3.5 cm vs. outermost: +/- 7 cm). All of the analyses were computed with the frequency of elbow responses as the dependent variable.

Apparatus, Stimuli, & Procedure

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The apparatus, stimuli, and procedure were identical to the pilot study with the following exceptions. The volar side of the left forearm faced upwards (see Figure 3) and a black occluder covered the left forearm of the participants during the experiment. The trial procedure was identical to that of the pilot study with the difference that participants didn't answer a paper-and-pencil questionnaire. The participants had to indicate whether the last vibration in the sequence was perceived closer to the wrist or to the elbow with the help of the computer mouse. After a response had been recorded (or after 2000 ms had elapsed), the next trial started after an interval of 1000 ms.

The experiment consisted of a total of 384 trials organized in two fully counterbalanced blocks. All of the five tactor locations were used as the endpoint of the sequence. In half of all trials, the sequence ended at the central tactor location (192 trials). Half of those trials were control trials (96 trials), the other half were implied motion trials, either in the proximal or distal direction (48 trials each). The remaining trials did not end at the central tactor location, with each of those four target end locations (two outer end locations, locations B and D; two outermost end location, locations A and E) being estimated equally often (24 trials in the implied motion and control conditions, respectively). The outer and outermost end locations were presented at a distance of 3.5 cm and 7 cm from the central location. Importantly, only for the central tactor location, did both motion direction conditions end at the same location, namely tactor location C (see Figure 1). Besides ending on the central tactor location, proximal direction trials also ended on the outer location B (stimulus sequence: D, C, B) or outermost location A (stimulus sequence: C, B, A). Similarly, distal direction trials ended on the outer location D (stimulus sequence: B, C, D) or outermost location E (stimulus sequence: C, D, E).

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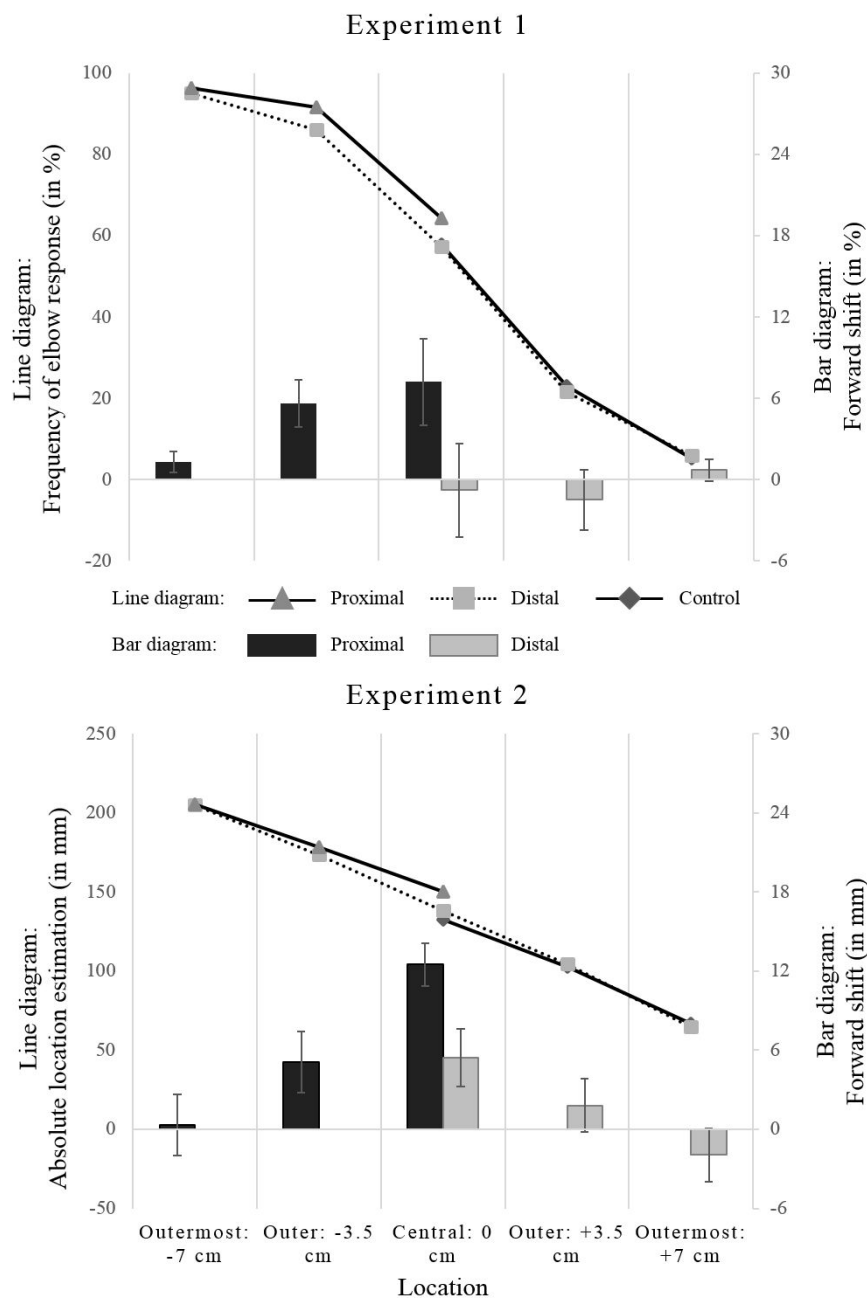


Figure 5: Plot of the data from Experiment 1 (upper panel) and Experiment 2 (lower panel) as a function of location (x-axis). Line diagram: Mean scores of the frequency of elbow response (Experiment 1) and absolute location estimation (Experiment 2) for the control as well as both implied motion conditions. Bar diagram: The forward shift, the difference between the implied motion and control score, as a function of direction. Positive values represent an overestimation in implied motion direction. Error bars represent standard errors.

Data Analysis

Those trials in which the participants did not respond in the 2000 ms response window (1.01% of the trials) were excluded. We analyzed the frequency of elbow responses with

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generalized linear mixed effect models (GLMM) in R (packages “lme4”, Bates, Mächler, Bolker, & Walker, 2015; R Core Team, 2018), accounting for the two-alternative forced choice task by using the binomial-logit function. For each direction of implied motion, we fitted four models to the data (see Table 1). The simplest model explains the data only with an intercept (Model 1, intercept only). For the next three models, we successively added an additional fixed effect. For Model 2, the continuous predictor *location* was added to Model 1 (ranging from 0 to +7 in the distal direction condition, ranging from 0 to -7 in the proximal direction condition). For Model 3, the previous Model 2 was extended to include the categorical predictor *experimental condition* (implied motion vs. control). For Model 4, the previous Model 3 was extended to include the interaction between the two predictors (full model; Model 4). We compared each model with its previous model in order to probe if the addition of the fixed effect resulted in a significantly better model fit. The best fitting model was determined by the last model which explained the data significantly better. All models treated the intercept of individual participants as random effects⁵. The raw data, diagrams depicting single participant data with model fitting curves for each participant as well as the R-script are available for open access (Merz, Meyerhoff, Spence, & Frings, 2018).

Results

The visual impression of a forward shift in the proximal direction condition was confirmed by the GLMM analysis. The model with the predictors of location as well as experimental condition was the most appropriate (Model 3; Table 1, I). In other words, a location closer to the elbow (more negative values) resulted in a higher frequency of elbow responses in the proximal direction condition. Importantly, a forward shift was found, the

⁵ Reanalyzing the models with the intercept as well as the slopes of the two predictor variables of location and condition of individual participants as well as their interaction treated as random effects identified the same best fitting models.

Localizing implied tactile motion stimuli

implied motion condition resulted in a higher frequency of elbow responses as compared to the control condition. In contrast, for the distal direction condition, no forward shift was found. The most appropriate model to explain the distal data was Model 2 (Table 1, II), which only incorporated the predictor location. Models with more predictors did not lead to a significantly better fit of the data (see Table 1, sections I & II).

Table 1
Results of the GLMM analysis of Experiment 1 and of the LMM analysis of Experiment 2. The best fitting model per analysis is presented in bold.

Model (Random Intercept)	df	Estimate*	AIC	Test	χ^2	p
<i>I. Results of the GLMM analysis (logit) of the 2 AFC task in Experiment 1: Implied motion in proximal direction</i>						
1. Intercept	2	0.341	10010.8			
2. Intercept + 1 predictor (Location)	3	-0.447	8546.4	1 vs. 2	1466.4	< .001***
3. Intercept + 2 predictors (Location + Exp. Condition)	4	0.384	8502.2	2 vs. 3	46.2	< .001***
4. Full model (2 predictors and their interaction)	5		8503.5	3 vs. 4	0.7	.409
<i>II. Results of the GLMM analysis (logit) of the 2 AFC task in Experiment 1: Implied motion in distal direction</i>						
1. Intercept	2	0.332	11689.8			
2. Intercept + 1 predictor (Location)	3	-0.485	9461.6	1 vs. 2	2230.3	< .001***
3. Intercept + 2 predictors (Location + Exp. Condition)	4		9463.1	2 vs. 3	0.5	.474
4. Full model (2 predictors and their interaction)	5		9465.0	3 vs. 4	0.1	.760
<i>III. Results of the LMM analysis of the absolute location judgement in Experiment 2: Implied motion in proximal direction</i>						
1. Intercept	3	138.02	23581.4			
2. Intercept + 1 predictor (Location)	4	-9.65	21731.4	1 vs. 2	1852	< .001***
3. Intercept + 2 predictors (Location + Exp. Condition)	5	12.34	21688.8	2 vs. 3	44.6	< .001***
4. Full model (2 predictors and their interaction)	6	1.79	21664.0	3 vs. 4	26.9	< .001***
<i>IV. Results of the LMM analysis of the absolute location judgement in Experiment 2: Implied motion in distal direction</i>						
1. Intercept	3	138.28	24094.2			
2. Intercept + 1 predictor (Location)	4	-10.33	22311.2	1 vs. 2	1785	< .001***
3. Intercept + 2 predictors (Location + Exp. Condition)	5	-4.96	22310.3	2 vs. 3	2.8	.092
4. Full model (2 predictors and their interaction)	6	0.97	22306.3	3 vs. 4	6.0	.013*

*The estimated value equals the unstandardized estimate for the (1) intercept, (2) the predictor location, (3) the predictor experimental condition, and (4) the interaction between location and experimental condition in the best fitting model.

In order to compare the two direction conditions directly, we analyzed the central target location separately. A forward shift, that is, a significant difference between the control and implied motion condition, was found for the proximal, $t(37) = 2.27, p = .029, d = 0.37$, but not for the distal direction condition, $t(37) = -0.23, p = .819$. This result fits with the GLMM analysis.

Discussion

Localizing implied tactile motion stimuli

In Experiment 1, the participants had to judge whether the last of three sequentially-presented vibrations was perceived closer to the wrist or to the elbow. Our results show a significant forward shift for an implied motion sequence in the proximal direction was obtained. That is, participants perceived the target location as being misplaced further along its trajectory as compared to the control sequence. Notice that this is the first time that a purely tactile forward shift resulting from implied motion has been evidenced.

In contrast to our expectations, no forward shift in implied motion direction was found for the distal sequence. One possibility – which we confirm in Experiment 2 - is that the effect in the distal direction is smaller and thus not appropriately captured by the binominal dependent variable. Therefore, we conceptually replicated and reinvestigated the pattern of results of Experiment 1 with a continuous dependent variable in Experiment 2.

Experiment 2

In Experiment 2, the participants were once again presented with a sequence of three vibrations at different locations on the forearm which either implied a motion in a single consistent direction or did not. Participants indicated the target location on a ruler attached to their forearm. A 250 mm ruler was attached on top of the arm bandage, but on the dorsal side of the forearm (see Figure 3). On this ruler, starting with 0 mm at the wrist and ending with 250 mm at the elbow, the participants had to indicate the location of the target vibration. Note that this changes our dependent variable from a relative to an absolute score (each answer indicates the absolute location estimation of the perceived target location).

Methods

Participants

Localizing implied tactile motion stimuli

As stated above, based on the effect sizes of studies investigating the influence of (implied) motion on visual and auditory localization (Getzmann & Lewald, 2007, 2009; Cohen's d s ranging between 0.68 and 1.89), an effect of $d_z = 0.7$ was used for sample size calculations. With $\alpha = .05$ and a power of $(1-\beta) = .9$, we calculated a sample size of $N = 19$ using G*Power Version 3.1.9.2 (Faul et al., 2007). The sample size was slightly increased ($N = 21$) to be able to exclude participants if needed. Twenty-one new students (14 female, 20-35 years, one left-handed) from the University of Trier took part in this study in return for course credit or a payment of 8 €. All of the participants reported normal or corrected-to-normal vision and no sensory impairment on the forearm.

Design, Apparatus, Stimuli, and Procedure

The design, apparatus, stimuli, and procedure were identical to Experiment 1 with the following exceptions. The occluder was omitted so that participants were able to see the outline of their forearm. Instead, a 250 mm ruler with 0 mm at the wrist and 250 mm at the elbow was attached to the top of the arm bandage. The ruler was attached to the dorsal side of the forearm which faced-upward in this experiment (see Figure 3). The participants were instructed to indicate the location of the last vibration by pointing with their right index finger at the corresponding location on the ruler. The experimenter (who was unaware of the presented sequence) sat next to the participant in order to note the indicated location. The experimenter initiated a new trial when the indicated location was noted and the participant as well as the experimenter were ready.

All of the participants completed 192 experimental trials preceded by eight practice trials. Every location was targeted equally often (16 trials in the implied motion and control conditions, respectively), except for the central location which served as a target in the proximal

Localizing implied tactile motion stimuli

as well as the distal direction condition (16 trials each and corresponding 32 control trials). The participants were allowed to pause after every 24 trials.

Data Analysis

We analyzed the absolute location estimation with linear mixed effect models (LMM) in R. As in Experiment 1, we fitted four models to the data of each direction condition (see Table 1). All models treated the intercept of individual participants as random effects⁶. The raw data, diagrams depicting single participant data with model fitting curves for each participant as well as the R-script are available for open access (Merz, Meyerhoff, Spence, & Frings, 2018).

Results

For both motion direction conditions, a forward shift at the central location, which decreases toward the outer locations, is indicated by Figure 5. The LMM analysis supports this description (see Table 1, sections III & IV). For both motion directions, the data is best explained with the full model (Model 4), which incorporated the fixed effects of location, experimental condition as well as their interaction. As expected, the location of the target vibration influenced the location estimation, a target vibration closer to the elbow was perceived as closer to the elbow. Importantly, for both motion directions, the difference between the implied motion and control condition, the forward shift, was strongest at the central location and decreased toward the outermost location (see Figure 5, bar diagram). In the proximal direction condition, the implied motion trials were perceived closer to the elbow than the control trials. In the distal direction condition, this was reversed, the implied motion trials were

⁶ Reanalyzing the models with the intercept as well as the slopes of the two predictor variables of location and condition of individual participants as well as their interaction treated as random effects identified the same best fitting models.

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perceived closer to the wrist than the control trials, as expected by the forward shift. For both motion conditions, this difference decreased toward the outermost locations.

In order to compare the magnitude of the forward shift in the two direction conditions, we analyzed the central target location separately. A significant difference between the implied motion and control condition, a forward shift, was observed for the proximal, $t(20) = 5.36, p < .001, d = 1.17$, as well as the distal direction condition, $t(20) = 2.51, p = .021, d = 0.55$. For both direction conditions, the central target location was misperceived further along its trajectory as compared to the control condition. The magnitude difference between the forward shifts for the two direction conditions (7.1 mm) was also significant, $t(20) = 2.89; p = .009; d = 0.63$, indicating a stronger forward shift for the proximal direction compared to the distal direction.

Discussion

In Experiment 2, the participants indicated the target location on a ruler attached to their forearm. A strong forward shift at the central target location for approaching stimuli moving in the proximal direction was documented. This replicates the main finding of Experiment 1 and the influence of implied motion on tactile localization. Furthermore, a forward shift for the distal direction was also found, underlining the importance of implied motion in tactile localization in general. The effect of implied motion on the localization of tactile stimuli was the same for the two directions, with stronger forward shifts for the proximal direction. For both direction conditions, the strength of the forward shift was strongest at the central target location and decreased to the outer and outermost target locations. This result fits with the change of spatial uncertainty along the forearm (Cholewiak & Collins, 2003), which will be discussed in more detail in the General Discussion section.

General Discussion

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In two experiments, we investigated the influence of implied motion on tactile localization. To investigate the effect of implied motion on tactile localization, a control condition was conducted. Systematic differences between the control and the implied motion conditions can only be attributable to the dynamic property of the motion in a single consistent direction. Using two different experimental approaches, a systematic forward shift was observed in the tactile modality for the first time. Participants perceive the last location of a dynamic stimulus to be further along its trajectory. These results stand in line with studies using visual or auditory targets (see Hubbard, 2005, 2014).

As one important influencing factor, the direction of implied motion was systematically investigated throughout our study. A stronger forward shift for targets heading in the proximal direction was found. An implied motion stimulus in the proximal direction approaches the elbow but further heads toward the participant's egocentre at the upper body and the head. We perceive the self at this area of our body (Alsmith & Longo, 2014; Limanowski & Hecht, 2011; Starmans & Bloom, 2012). Furthermore, in their review of the graphesthesia task, Arnold, Spence, and Auvray (2017) identified an overall predominance of the head-centred-perspective in the interpretation of ambiguous tactile stimuli presented to the skin surface. Therefore, we argue that the stimuli in our study approach to and recede from our self (i.e. the head/torso). Looking at the forward shift for approaching and receding stimuli in the visual modality, differing results have been obtained (Hubbard, 1996; Nagai et al., 2002). As already mentioned in the Introduction, no differences or even greater forward shifts for receding targets (Hubbard, 1996, Experiment 1) were found. This stands in contrast to stronger forward biases for approaching stimuli in the tactile modality, indicating modality-specific differences in the perception of (implied) motion in depth.

Besides the representational momentum literature, there is plenty of evidence for differences between approaching and receding stimuli. For example, looming / approaching

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stimuli have been shown to elicit stronger psychophysiological (Bach, Neuhoﬀ, Perrig, & Seifritz, 2009; Bach et al., 2007) as well as emotional (Bach et al., 2009; Schiff, Caviness, & Gibson, 1962) responses. Approaching (in comparison to receding) stimuli are perceived as lasting longer (Grassi & Pavan, 2012; Kline & Reed, 2013) and as changing more in terms of their loudness (Neuhoﬀ, 1998, 2001). Such differences are often explained by the differing importance of approaching and receding stimuli for survival. According to the argument that is often made in the literature, approaching stimuli need to be attended to so that an appropriate action can be initiated (such as stepping out of the way if a car is rapidly approaching; Spence, Lee, & Van der Stoep, 2017). Therefore, according to researchers, participants err on the “side of safety” (Neuhoﬀ, 2001, p. 88). This is evidenced, for example, by the underestimation of time of arrival judgments for approaching auditory stimuli (Rosenblum, Wuestefeld, & Saldana, 1993; Schiff & Oblak, 1990). Further, approaching stimuli tend to be mislocalized and perceived as being closer to the observer’s body than are receding stimuli of the same objective distance from the observer (Neuhoﬀ, 2001; Neuhoﬀ, Planisek, & Seifritz, 2009). The error on the side of safety might help to generate responses faster and might increase the chance to be able to respond (if necessary) to the approaching stimulus (see Neuhoﬀ, 2018, for a recent review of the looming literature). Interestingly, both Guski (1992) and Popper and Fay (1997) have attributed a warning function to the auditory system. The auditory system might be helpful in directing an observer’s visual resources toward the event or to initiate a fast response (turn around; jump out of the way) if necessary. Similar functions might underlie the tactile system, thus providing “quick and dirty” information erring on the side of safety.

With the reported experiments here, it is not possible to differentiate between approaching / receding stimuli in a spatiotopic and a somatotopic frame of reference. Participants extended their arms and placed them on the desk (see Figure 2), but never changed the position of their arms. Therefore, an experiment in which diﬀerent arm positions were used

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(e.g., bending the arm at the elbow so that the hand is directed toward the upper body / head, e.g. Gallace, Soto-Faraco, Dalton, Kreukniet, & Spence, 2008; Pritchett, Carnevale, & Harris, 2012) can distinguish between the two spaces of references. Alternatively, the self, located at the upper body / torso, might be interpreted as a landmark. Previous research (Hubbard & Ruppel, 1999) indicates that objects moving toward a landmark undergo landmark attraction, which adds to the representational momentum effect and therefore increases the forward shift.⁷

In this study, an influence of spatial uncertainty on the forward shift was documented. The strength of the forward shift was strongest at the central tactor location and decreased to the outer and outermost tactor locations (Experiment 1 – proximal direction condition; Experiment 2 – proximal and distal direction condition). This is in line with differences in the localization performance along the forearm (Cholewiak & Collins, 2003). The overall localization performance increases from the central to the outermost target location along the forearm. An increase in spatial acuity leads to a decrease in the magnitude of the forward shift. These results are in line with previous findings reported in the visual and auditory modality (Fu et al., 2002; Schmiedchen et al., 2013) and findings with the flash-lag effect (Kanai et al., 2004). Spatial acuity increases from the central to the outermost location, but the stimuli also approach the boundary of the experimental set-up at these extreme locations, which was also found to decrease the forward shift (Hubbard & Motes, 2005).

To date, a few studies already exist investigating the tactile localization of moving stimuli. Due to different foci, and therefore crucial differences in their experimental set-up, it is difficult to draw any conclusion from these studies to the current study. The studies by Seizova-Cajic, Taylor and colleagues (Nguyen, Taylor, Brooks, & Seizova-Cajic, 2016; Seizova-Cajic & Taylor, 2014) used moving tactile brushing stimuli along the forearm and

⁷ We thank an anonymous reviewer for bringing this potential explanation to our attention.

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participants judged the last location where they perceived the brush. The authors focused on the effects of a gap in the tactile stimulation (10 out of 20 cm of skin was not contacted by the brush due to an occluder) and if this gap could be overcome by manipulating the space-time continuum. For this, the tactile stimulation was irregular and not continuous, therefore it is difficult to compare any results with the current study. Trojan et al. (2010) investigated the perceived location of all three tactile stimuli in a reduced rabbit / saltation illusion design. Hereby, the first two stimuli were presented to the same location (stimulus onset asynchrony: 1020 ms), the third using different stimulus onset asynchronies (20 – 1020 ms) 10.5 cm apart. Overall, the third (last) tactile stimuli was misperceived toward the location of the first two stimuli (indicating a backward shift; see Figures 3 & 4 in their paper). Interestingly, the participants were asked to indicate the location of a single tactile stimulus (see Figure 2, location 8 in their paper) and this showed a similar mislocalization. Since these two mislocalizations were never compared, it is difficult to draw a conclusion if in fact a forward, backward, or no shift would be found with the cutaneous rabbit / saltation illusion.

Whitsel et al. (1986) were interested in the perceived length of a motion stimulus for differing velocities and showed that the perceived length decreases with an increase in velocity. In one of the experiments (Experiment 1), participants judged the perceived start- and endpoint of a motion stimulus in a single consistent direction (experimental stimulus) in comparison to the start- and endpoint of another motion stimulus in a single consistent direction (control stimulus). The control stimulus was also a motion stimulus in one single direction, so no control condition without a motion in a single consistent direction exists. Therefore, no conclusion about the existence of a forward / backward-shift in the tactile modality can be drawn from this study. In contrast, in this study, we used a control condition without motion in a consistent direction by presenting the first two vibrations at random locations. Therefore, the control as well as the implied motion stimuli inherited motion characteristics (as evidenced in the Pilot

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study). Crucially, the implied motion trials indicated a motion in a single consistent direction with a consistent speed while the control trials did not. This difference resulted in the occurrence of the forward shift. Nevertheless, location estimation of a single, stationary vibration could be used in prospective research. We would not expect any difference between the control condition of the present study and a stationary control.

The notion of where we localize dynamic tactile sensations applied to the skin surface is also relevant in applied contexts. To unload and support the visual sensory system during difficult and attention-demanding tasks (e.g., driving a car in rush hour traffic), the focus was turned to the auditory and especially the tactile modality to present supporting information (e.g., warning signals, Ho, Gray, & Spence, 2014; Meng, Gray, Ho, Ahtamad, & Spence, 2015; Meng, Ho, Gray, & Spence, 2015). Interestingly, recent studies found that auditory as well as tactile looming / approaching warning signals decrease braking response times (Gray, 2011; Ho, Spence, & Gray, 2013; Meng, Gray, et al., 2015; Meng, Ho, et al., 2015). This can be explained in terms of people erring on the side of safety to be able to initiate fast responses. Combining the existing knowledge about dynamic stimuli and their perception will lead to further developments and improvement in tactile interface design and hopefully to a safer environment for all people.

Conclusions

The present study provides the first demonstration of the influence of implied motion on the localization of sequences of spatially-distributed vibrotactile stimuli. Comparable to the localization of dynamic events in the visual and auditory modalities, a dynamic tactile event is mislocated further along its trajectory. The present data suggest that motion patterns approaching people's egocentre are perceived further along their trajectory as compared to

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receding motion patterns. The results would appear to stand in contrast to the localization of approaching and receding stimuli in the visual modality. We speculate that this may be an adaptive mechanism to be able to attend and respond to approaching stimuli quickly. Further, the spatial uncertainty influences the forward shift. With increasing spatial acuity to localize the target stimulus, the influence of implied motion on tactile localization decreases.

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For Review Only

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Appendix

Pilot Study – Original German wording:

Item 1: Setze das Muster fort: Im Vergleich zur letzten / dritten Vibration, wäre die nächste Vibration... [*mark one of the three possibilities*] (a) ...näher am Handgelenk, (b) ...näher am Ellenbogen, (c)...in keiner bestimmten Richtung/weiß nicht.

Item 2: Haben sich die drei Vibrationen wie ein gemeinsames, durchgängiges Event oder wie einzelne, separate und nicht zusammengehörige Events angefühlt? [*Ten-point scale, ranging from*] gemeinsames, durchgängiges Event [*to*] einzelne, separate Events.

Item 3: In wie weit hat sich die letzte Vibrationsabfolge als ein Bewegungsmuster angefühlt? [*Ten-point scale, ranging from*] Überhaupt nicht wie ein Bewegungsmuster [*to*] wie ein Bewegungsmuster.

Item 4: In wie weit hat sich die letzte Vibrationsabfolge als ein Zufallsmuster angefühlt? [*Ten-point scale, ranging from*] Überhaupt nicht wie ein Zufallsmuster [*to*] wie ein Zufallsmuster.