J Neurophysiol 122: 1810–1820, 2019.
First published August 21, 2019; doi:10.1152/jn.00125.2019.

RESEARCH ARTICLE | *Sensory Processing*

The intensity order illusion: temporal order of different vibrotactile intensity causes systematic localization errors

Rebekka Hoffmann,[1,2] Manje A. B. Brinkhuis,[1] Runar Unnthorsson,[2] and Árni Kristjánsson[1,3]
[1]*Faculty of Psychology, University of Iceland, Reykjavik, Iceland;* [2]*Faculty of Industrial Engineering, Mechanical Engineering and Computer Science, University of Iceland, Reykjavik, Iceland; and* [3]*School of Psychology, National Research University Higher School of Economics, Moscow, Russian Federation*

Submitted 20 February 2019; accepted in final form 14 August 2019

Hoffmann R, Brinkhuis MA, Unnthorsson R, Kristjánsson Á. The intensity order illusion: temporal order of different vibrotactile intensity causes systematic localization errors. *J Neurophysiol* 122: 1810–1820, 2019. First published August 21, 2019; doi:10.1152/jn.00125.2019.—Haptic illusions serve as important tools for studying neurocognitive processing of touch and can be utilized in practical contexts. We report a new spatiotemporal haptic illusion that involves mislocalization when the order of vibrotactile intensity is manipulated. We tested two types of motors mounted in a 4 × 4 array in the lower thoracic region. We created apparent movement with two successive vibrotactile stimulations of varying distance (40, 20, or 0 mm) and direction (up, down, or same) while changing the temporal order of stimulation intensity (strong-weak vs. weak-strong). Participants judged the perceived direction of movement in a 2-alternative forced-choice task. The results suggest that varying the temporal order of vibrotactile stimuli with different intensity leads to systematic localization errors: when a strong-intensity stimulus was followed by a weak-intensity stimulus, the probability that participants perceived a downward movement increased, and vice versa. The illusion is so strong that the order of the strength of stimulation determined perception even when the actual presentation movement was the opposite. We then verified this "intensity order illusion" using an open response format where observers judged the orientation of an imaginary line drawn between two sequential tactor activations. The intensity order illusion reveals a strong bias in vibrotactile perception that has strong implications for the design of haptic information systems.

NEW & NOTEWORTHY We report a new illusion involving mislocalization of stimulation when the order of vibrotactile intensity is manipulated. When a strong-intensity stimulus follows a weak-intensity stimulus, the probability that participants perceive an upward movement increases, and vice versa. The illusion is so strong that the order of the strength of stimulation determined perception even when the actual presentation movement was the opposite. This illusion is important for the design of vibrotactile stimulation displays.

apparent movement; haptic illusion; localization error; response bias; temporal order; vibrotactile intensity

INTRODUCTION

The tactile representation of our physical environment relies on the acuity of the tactile sensory system. Because of its relatively low receptor density (Bolanowski et al. 1994; Gardner and Martin 2013), tactile perception is prone to spatial imprecision. The tactile sensory system builds on prior knowledge to enhance perceptual resolution beyond the limits imposed by the imprecise sensory mechanisms (Adams et al. 2004; Knill and Richards 1996). Relying on prior knowledge, however, entails the cost that rare physical events violating expectations can be misperceived. Such illusions can reveal the brain's expectations regarding the world (Goldreich 2007).

The rate of discovery of new tactile and haptic illusions has increased in recent years (Hayward 2008, 2015; Lederman and Jones 2011), and there are interesting parallels between perceptual effects across senses (Konkle et al. 2009). Many well-known optical geometrical illusions have tactile counterparts such as the Delboeuf (Gentaz and Hatwell 2004), vertical-horizontal (Howell et al. 2013), Bourdon (Day 1990), Ebbinghaus (Ziat et al. 2014), Müller-Lyer (Millar and Al-Attar 2002), and Ponzo and Oppel-Kundt illusions (Suzuki and Arashida 1992). For tactile perception, there are characteristic spatiotemporal illusions related to underestimation of interstimulus distance and overestimation of interstimulus time (Goldreich 2007), such as the tau effect (Helson 1930; Lechelt and Borchert 1977), the kappa effect (Suto 1951), and the apparent haptic movement illusion (Carter et al. 2008; Sherrick and Rogers 1966). Spatiotemporal illusions involving errors of localization have also been found, such as the funneling illusion (Gardner and Spencer 1972; Rahal et al. 2009), where two adjacent simultaneous vibratory stimuli are perceived to originate from between the two tactors and sensory saltation (the "cutaneous rabbit") where a sequence of three taps to two skin sites, for example, evokes the perception of an object hopping along the skin (Flach and Haggard 2006; Geldard and Sherrick 1972). The cutaneous rabbit illusion has been tested with various manipulations (see Brooks and Trojan 2017 for review). The illusion generalizes across body parts and importantly for the current project occurs on the torso (Trojan et al. 2010) and also occurs for other stimulation types such as pain-inducing stimuli (Trojan et al. 2006). Notably, the illusion also seems to affect action (Trojan et al. 2010). In this context it is important to note that neural mechanisms involved in tactile perception are modulated by both temporal and spatial manipulations (Braun et al. 2000; Clark et al. 1988; Jung et al. 2012). All in all, these illusions reveal that processing of tactile

Address for reprint requests and other correspondence: Á. Kristjánsson, Faculty of Psychology, University of Iceland, Reykjavik, Iceland (e-mail: ak@hi.is).

stimulation shows large spatiotemporal interactions (Flach and Haggard 2006) and may involve spatiotemporal modulations of activity of the somatosensory cortex (Brooks and Trojan 2017; see Pei and Bensmaia 2014 for a review of tactile discrimination at the neural level).

In high-resolution tactile displays, complex information must be conveyed and localization errors must be taken into account during their design. For instance, when used as part of a sensory substitution device, the nonfunctional sense usually has a much higher resolution than the sense of touch. Conveying information about the nature of objects in the environment often requires information bandwidths that are not supported by the skin. Bandwidths between 64 and 110 bits, for example, are needed for speech perception, but such bandwidths are not supported by the skin (Novich and Eagleman 2015). Music consists of various elements, such as rhythm, timbre, harmony, etc., which exceed the capacity of tactile perception (Karam et al. 2009). Whereas audible vibrations of the air span frequencies from 20 Hz to 20 kHz, the frequency range of tactile vibration is only 10 Hz to 1,000 Hz (Nanayakkara et al. 2013). Developers of tactile devices may therefore be tempted to mount as many tactors as possible on a tactile device, risking overexertion of the tactile sense (see discussion in Kristjánsson et al. 2016; Dakopoulos and Bourbakis 2010). Some developers have used haptic illusions to create tactile displays with perceptually higher spatial resolution than indicated by the actual number of tactors mounted (Lederman and Jones 2011). By applying multiple "funneling" stimuli on the forearm while manipulating tactor intensity, Barghout et al. (2009) were able to create a continuous touch sensation. Investigating sensory saltation, Cholewiak and Collins (2000) placed a row of seven tactors at three body sites and activated them sequentially to draw a line on the skin, comparing two presentation modes: veridical, where each tactor was activated, and saltatory, where only the first, fourth, and seventh tactors were activated. Both resulted in clearly perceived lines at each body site.

It is important to note that although the above discussion makes it clear that many tactile illusions exist, less is known about vibrotactile stimulation, which is increasingly being used in various applications, and understanding its properties is therefore of high importance. In this article we report a new spatiotemporal haptic illusion from vibrotactile stimulation that we have chosen to call the "intensity order illusion." The illusion involves intensity-driven mislocalization of the presented stimuli that should be taken into account during the design of vibrotactile displays but could also be used for increasing their efficiency: when a vibratory stimulus of high intensity is followed by a second vibratory stimulus of lower intensity at the same location, the location of the second stimulus seems to be erroneously perceived below the first stimulation location. The reverse also occurs, where a more intense second vibratory stimulation is erroneously perceived above a lower intensity initial stimulation.

METHODS

Experiment 1

In *experiment 1* we created apparent movement with two successive vibrotactile stimulations of varying distance and direction while changing the temporal order of vibratory stimulation intensity (strong-weak vs. weak-strong), asking participants to indicate the perceived direction of movement. Our experiments are part of the development of a sensory substitution device (SSD) that is discussed in other publications (e.g., Hoffmann et al. 2018; Jóhannesson et al. 2016; Kristjánsson et al. 2016; see www.soundofvision.net), which also explains why we used different tactor types. This, however, only adds to the generalizability of the results. Another consideration was that we wanted to ensure that our SSD would allow the hands to be free, and we therefore used passive areas of the body as stimulation sites.

Participants. Sixteen students at the University of Iceland [all naive, 7 women, age: 21–34 yr (mean = 24.4 yr, SD = 3.1 yr)] participated after signing informed consent. The experiment was approved by the National Bioethical Committee of Iceland (VSN-15-107) and conformed to the Declaration of Helsinki.

Apparatus. A custom-built plastic frame (containing an electronics board, battery, and charger circuit) was used as a base for the 4×4 array of tactors, mounted on a 15-cm-thick foam layer. We created custom software with PsychoPy (Peirce 2009) for tactor control. We tested two tactors: cylindrical eccentric rotating mass (ERM) motors (case diameter: 9 mm, length: 25 mm; model no. 307-103, Precision Microdrives) (Precision Microdrives 2018a) that create vibration normal to the skin's surface (NERMs). They were mounted with an inter-tactor distance of 20 mm (measured center to center, c/c). They were run at two different intensities, either strong (4 V, 270 Hz, 180 mA, 9 G) or weak (1.2 V, 100 Hz, 35 mA, 1.7 G). Second, we tested coin cell-shaped ERM motors (case diameter: 8 mm, height: 3 mm, comparable to model no. 308-100, Precision Microdrives) (Precision Microdrives 2018b). They create vibration parallel to the skin's surface (PERMs). They were placed at inter-tactor distances of 10 mm c/c. The tactors were mounted as shown in Fig. 1, *A* and *B*. The PERMs require a higher difference in intensity between the strong and the weak conditions and were run at 4-V direct current (DC; 230 Hz, 90 mA, 1.0 G) and 2.8-V DC (170 Hz, 67 mA, 0.6 G). For the NERMs, the intensity varied by a difference (Δ) of 170 Hz (7.3 G), whereas it was substantially smaller for the PERMs, Δ60 Hz (0.4 G). We should note that for both tactor types, frequency and amplitude are inextricably linked and cannot be manipulated independently. One mounting base at a time containing either the NERMs or the PERMs was placed in the lower thoracic region (see Fig. 1*C*) stimulating areas of hairy skin.

Stimuli. One trial consisted of a pair of successive tactor activations along the vertical axis (the second activation was above, below, or in the same location as the first). Either the first tactor activation was strong and the second weak, or the first activation weak and the second strong. Interstimulus distance (ISD) varied in five conditions: the second tactor activation was one or two tactors below or above the first, or the same tactor could be activated twice (as shown in Fig. 2). Since the PERMs were closer to one another than the NERMs, actual ISDs were 40 and 20 mm for the NERMs and 20 and 10 mm for the PERMs. Since successive tactor activations at two locations tend to induce an apparent movement (Sherrick and Rogers 1966), we jointly refer to the distance and direction conditions as "movement." The tactors were turned on for 200 ms with an interstimulus interval (ISI) of 50 ms and an intertrial interval (ITI) of 1,500 ms (responses exceeding the ITI were not included in the analyses). Participants performed 800 trials (400 trials for each tactor, counterbalanced across participants). There were 40 trials in each condition for each tactor, presented in random order, following a 100-trial training session.

Procedure. Participants wore a top made of sheer fabric to prevent vibrations from being absorbed by thick fabric. Participants sat in front of a computer screen and keyboard in a quiet room and were outfitted with headphones, and one mounting structure at a time was strapped around the participants waist and placed centrally so that the spine was placed at the middle of the tactor array. The back was chosen because we wanted to avoid using active body parts such as the hands, for example. Participants were naive about the full set of movement conditions and were not informed that the same tactor was

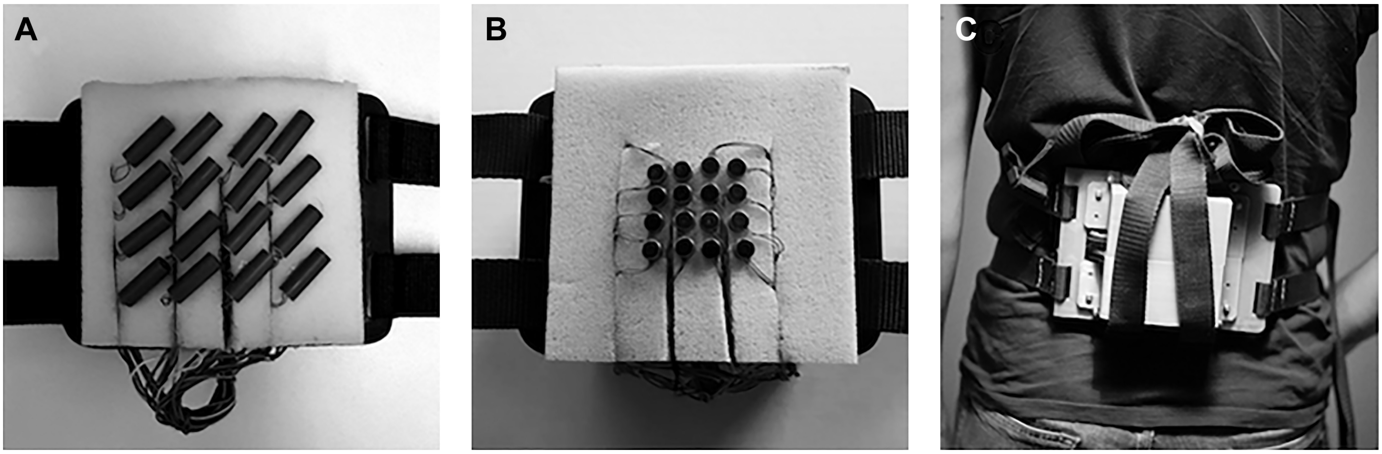

Fig. 1. Apparatus for *experiment 1*. Two tactor types were tested. *A*: mounting base with a 4 × 4 array of normally rotating eccentric rotating mass (ERM) motors (NERMs) placed at 20-mm center-to-center (c/c) distance. *B*: mounting base with a 4 × 4 array of parallel rotating ERM motors (PERMs) placed at 10-mm c/c distance. *C*: one mounting base at a time was strapped around the participant's waist so that the array rested in the lower thoracic region.

sometimes activated twice. In a 2-alternative forced-choice task, participants were simply instructed to judge immediately after each stimulus pair (within the 1,500-ms ITI) whether the second tactor activation was above or below the first one and to indicate this by pressing the up or down arrow keys on the keyboard. Rain noise was played through headphones during the whole experiment to mask the tactor sounds. Participants could take short breaks after each completed block. The procedure took about an hour.

Statistical analyses. If strong vibrotactile stimulation followed by weak stimulation induces an apparent downward movement, the probability of "up" responses should decrease, and vice versa for weak stimulation followed by strong stimulation. The apparent movement should also occur, even if the second stimulation is in the same location as the first.

To assess effects of tactor type, intensity order, and actual movement (up, down, or same) on the probability of up responses, we fitted mixed-effects binomial logistic regression models (Hartzel et al. 2001; Hosmer et al. 2013) in R, using the glmer function as part of the lme4 package in R (Bates et al. 2015). We used the Gauss-Hermite quadrature method to approximate true likelihood when estimating parameters in the models, with an adaptive algorithm of 10 integration points to increase estimation accuracy (Pinheiro and Chao 2006). To account for the variance of responses across subjects, the subject ID was added to each model as a random factor. We performed stepwise model selection, comparing parameters with the parameters of the same model plus one additional fixed predictor. Chi-square distributed likelihood ratio tests were performed to assess whether additional predictors significantly improved the fit. The parameters of the relevant models (with fixed predictors) are reported, with regression coefficients, effect direction, and confidence intervals [significance of predictors was assessed with Wald (1943) statistics]. Additionally, we report Bayes factors (BF) based on the Bayesian information criterion (BIC; Dienes 2014; Wagenmakers 2007).

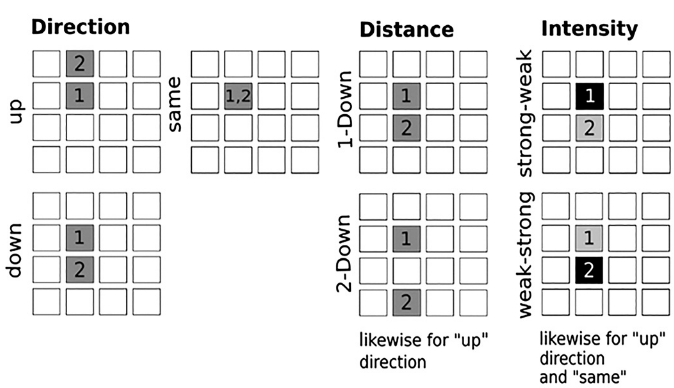

Fig. 2. Example stimuli for *experiment 1*. The squares represent the 4 × 4 tactor array, and the marked fields represent the tactors activated in the sequence indicated by the numbers. One trial consisted of 2 successive vibrotactile stimulations, which varied in direction, distance, and intensity change as shown. All conditions were randomized and counterbalanced within each trial block.

Experiment 2

The mislocalization from the intensity order illusion for which we found evidence in *experiment 1* may partly reflect a bias for responding "up" when vibrational intensity increases or "down" when it decreases. We therefore developed an alternative paradigm to further validate the illusion. In *experiment 2*, participants were asked to indicate orientation, defined as the angle between two sequential tactor activations. Additionally, we increased the number of possible stimulation locations.

Participants. Sixteen new naive participants from the University of Iceland participated (7 women, age: 19–45 yr, mean = 28.2 yr, SD = 4.6 yr), providing written informed consent. The data from one participant who reported discomfort were excluded. The experiment was approved by the National Bioethical Committee of Iceland (VSN-15-107) and conformed to the Declaration of Helsinki.

Apparatus. The apparatus was similar to that used in *experiment 1*, except that only the NERMs were used. The number of tactors, however, was increased to 25 in a 5 × 5 array. On half the trials, the device was rotated by 90° to counterbalance the orientation of the diagonally placed motors across experiment runs (Fig. 3).

Stimuli. Each trial consisted of a pair of successive tactor activations, where the central tactor of the array vibrated first and a randomly chosen tactor within the array vibrated second. This setup resulted in 25 possible presentation pairs, where the two subsequent activations within a trial had a certain orientation and distance. The tactors were turned on for 200 ms with an ISI of 50 ms and ITIs that varied randomly between 1,100 and 1,700 ms. Participants used the mouse to indicate the orientation of the two subsequent stimulations. A clock hand arrow appeared in the direction of the mouse pointer following an initial mouse click. After the arrow was freely adjusted (without a time limit), the final position was confirmed with a second mouse click (as illustrated on the response screen in Fig. 3). The position of the arrow then remained fixed for 1 s and turned gray, showing the confirmed response to the participant. As in *experiment 1*, either the first tactor activation was strong and the second weak, or vice versa. The experiment consisted of 1,000 trials, with 20 repeti-

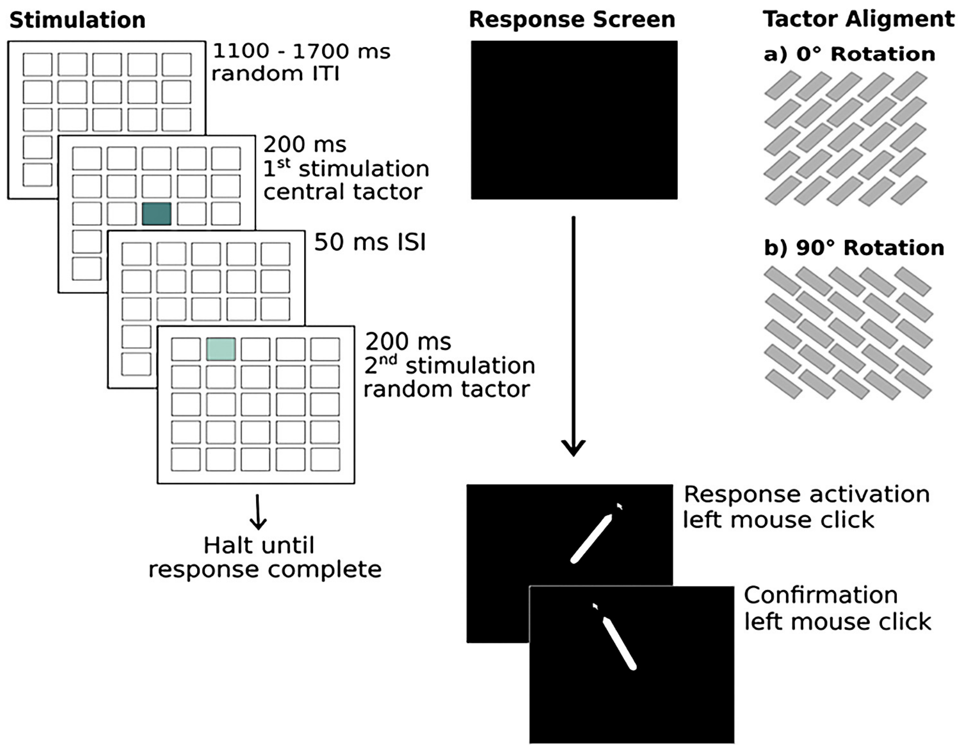

Fig. 3. Stimuli and response interface for *experiment 2*. The first of 2 successive vibrotactile stimulations was located at the center of the array and the second in a random location while the intensity of the 2 stimuli within a pair was either strong-weak or weak-strong. Participants indicated the perceived orientation of the stimulations by adjusting a line on the screen. Half of the experiment was conducted with the same tactor alignment as in *experiment 1* (*a*: 0° device rotation), and the other half with horizontally mirrored tactor alignment (*b*: 90°device rotation). ISI, interstimulus interval; ITI, intertrial interval.

tions of each condition, split evenly between two sessions conducted a few days apart. One session was subdivided into four blocks (125 trials) with breaks in between. The device was either mounted at an angle of 0° during the first two blocks and changed to an angle of 90° in the latter two blocks, or vice versa (counterbalanced). Within each two blocks with the same tactor alignment, the location of the second tactor activation and the temporal order of intensity were randomized so that each direction and distance would be presented equally often within the intensity order conditions.

Procedure. As in *experiment 1*, testing was divided into two identical sessions, which were conducted a few days apart, following 10 practice trials before the first session. The mounting structure was strapped around the participants' waist (0° or 90° rotation, and which orientation was tested first was counterbalanced), with the tactors placed on the lower back centered on the spine, stimulating an area of hairy skin. Participants were informed that the first vibrotactile stimulation would be located in the center of the array, followed by a second stimulation in any other location, but not that the same tactor could be activated twice. They were asked to indicate the direction of a line between the first and second stimulation by adjusting a line on the screen (see description in the stimuli section above and in Fig. 3). Each session took ~50–60 min. Otherwise, methods were identical to *experiment 1*.

Statistical analysis. We calculated the response errors on the basis of difference between the actual presentation direction (in degrees) and the response clock hand angle (in degrees). The presentation orientation and distance for each tactor was determined on the basis of its position relative to the central tactor (measured c/c), as shown in Fig. 4. In the right half of the circle an upward bias (+) was indicated by an overestimation of the angle of the two tactor activations, whereas in the left half of the circle an upward bias was indicated by an underestimation of this angle. The response errors were therefore multiplied by −1 for the left semicircle. Trials with vertical presentation orientation (90° and 270°) and with the same tactor activated twice were excluded because deviations in responses from the presented orientation could not be interpreted as either upward or downward with the current response method. To assess the effect of presentation orientation, distance, tactor alignment, and intensity order, linear mixed models were fitted in R using the lme4 package (Bates et al. 2015; response error as a dependent variable and participant as a random factor). We performed stepwise model selection using chi-square distributed likelihood ratio tests to assess whether the additionally included predictor improved the model fit (see *experiment 1*).

RESULTS

Experiment 1

When both tactor type and intensity order were included in the same model, there was a significant interaction between tactor type and the effect of intensity order [$\chi^2(6) = 97.17$,

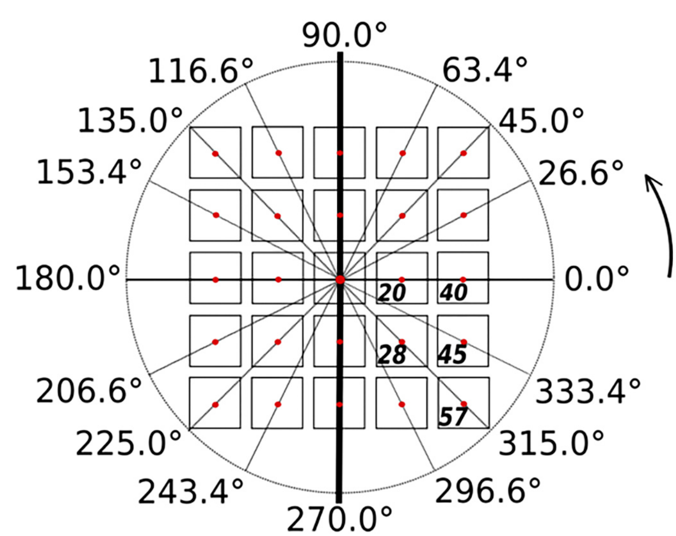

Fig. 4. Possible presentation orientations (in degrees) and distances (in mm; bold italic) for each of the tactors in the 5 × 5 array, resulting in 25 overall orientation and distance conditions. The 5 possible distances are shown in *bottom right* quadrant.

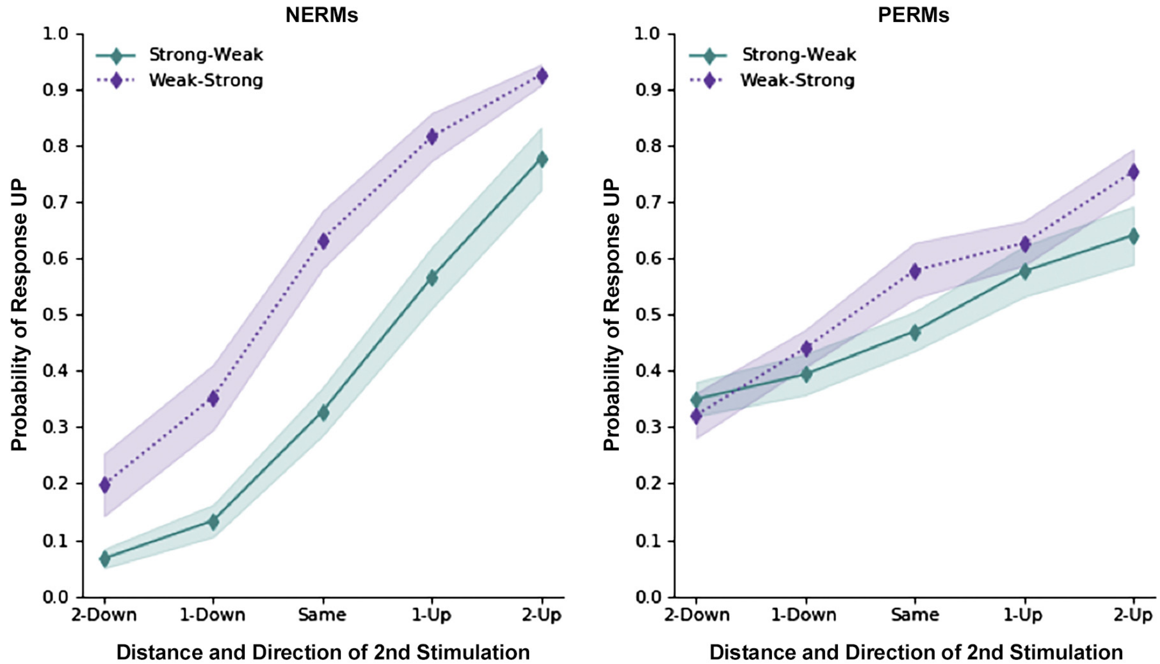

Fig. 5. Results of *experiment 1* for normally rotating eccentric rotating mass (ERM) motors (NERMs; *left*) and parallel rotating ERM motors (PERMs; *right*). For each tactor type, the graphs show the probability of participants responding "up" as a function of the 5 movement conditions and how the response ratio is influenced by the intensity change conditions (strong followed by weak vs. weak followed by strong). Symbols represent means, and error ranges are SE.

$P < 0.001$, BF = 1.1061×10^{19}]. This indicates that the order of intensity affects each tactor type differently, so we report results for each tactor type separately.

NERMs. When the same NERM tactor was activated twice, participant's responses were strongly influenced by the temporal order of vibration intensity, as shown in Fig. 5. If the first stimulus was strong and was followed by a weak stimulus, the probability of participants responding "up" was 0.33, significantly below chance [$t(16) = -4.03$, $P < 0.001$], showing a higher probability of a perceived downward movement. Conversely, if the first stimulus was weak and was followed by a strong one, the probability of participants responding "up" was 0.63, significantly above chance level [$t(16) = 2.59$, $P = 0.01$].

The NERM parameters are shown in Table 1. Including the fixed predictors of movement [M1: $\chi^2(3) = 2018.75$, $P < 0.001$] and intensity order direction [M2: $\chi^2(4) = 430.07$, $P < 0.001$] resulted in significantly improved model fits, suggesting that the responses were influenced by the temporal order of vibration intensity. The strong effect of intensity order is supported by a very strong Bayes factor: the observed results are 3.0488×10^{91} more likely to be observed under the extended model (M2). Tukey's honestly significant difference (HSD)-adjusted, pairwise post hoc comparisons (following a repeated-measures ANOVA) revealed significant differences in the probability of an up response for 1-up and 1-down ($P < 0.05$), but not for the larger movements (2-up and 2-down, all $P > 0.05$).

PERMs. The temporal order of vibration intensity had a smaller effect for the PERMs than for the NERMs (as shown in Fig. 5). If strong intensity was followed by weak intensity, the probability of participants responding up was close to chance (0.47), and if weak intensity was followed by strong intensity, the probability of participants responding up was 0.58. The accuracy rate was lower with the PERMs than with the NERMs (0.63). The M1 [$\chi^2(3) = 437.20$, $P < 0.001$] and M2 models [$\chi^2(4) = 24.06$, $P < 0.001$] were significantly better than M0, and M2 was better than M1 (BF = 2100.65), as shown in Table 2. Tukey's HSD-adjusted, pairwise post hoc comparisons (following a repeated-measures ANOVA) revealed no significant differences in the up-response probability for any of the movements (all $P > 0.05$).

Experiment 2

We excluded 306 trials (2.55%) where the response error crossed the central vertical axis relative to the presented direc-

Table 1. *Results for NERMs, comparing model 1 (including movement) and model 2 (including movement and intensity order)*

	Model 1				*Model 2*			
	Coefficient [CI]	SE	*z*	*P*	Coefficient [CI]	SE	*z*	*P*
Intercept	−0.117 [−0.35, 0.12]	0.12	−0.89	<0.05	0.516 [0.26, 0.76]	0.13	3.89	<0.001
Movement	0.964 [0.91, 1.01]	0.03	38.10	<0.001	1.05 [0.99, 1.10]	0.03	38.32	<0.001
Intensity order					−1.30 [−1.43, −1.17]	0.07	−19.79	<0.001
BIC	6,750.4				6,332.0			

Both models for the normally rotating eccentric rotating mass motors (NERMs) involve subjects as random effect, and the model parameter estimates are based on adaptive Gauss-Hermite quadrature with 10 integration points. Reported are the regression coefficients with associated confidence intervals (CI), standard errors (SE), Wald statistics (*z* and *P* values), and the model fit index Bayesian information criterion (BIC) for each model.

Table 2. *Results for PERMs, comparing model 1 (including movement) and model 2 (including movement and intensity order)*

	Model 1				*Model 2*			
	Coefficient [CI]	SE	*z*	*P*	Coefficient [CI]	SE	*z*	*P*
Intercept	0.059 [−0.21, 0.33]	0.14	0.424	<0.50	0.190 [−0.09, 0.47]	0.14	1.34	<0.05
Movement	0.399 [0.36, 0.44]	0.02	20.22	<0.001	0.401 [0.36, 0.44]	0.02	20.26	<0.001
Intensity order					−0.262 [−0.37, −0.16]	0.05	−4.90	<0.001
BIC	8,127.4				8,112.1			

Both models for the parallel rotating eccentric rotating mass motors (PERMs) take subjects as random effect into account, and the model parameter estimates are based on adaptive Gauss-Hermite quadrature with 10 integration points. Reported are the regression coefficients with associated confidence intervals (CI), standard errors (SE), Wald statistics (*z* and *P* values), and the model fit index Bayesian information criterion (BIC) for each model.

tion, making it impossible to assess vertical bias. We also excluded nine trials with invalid responses.

In the strong-weak condition, participants underestimated the orientation of the second stimulation, with an average response error of M = −17.22° (SD = 52.47°). In the weak-strong condition, the average response error was M = −10.37° (SD = 36.22°), indicating that participants judged the second stimulation to be on average 6.85° higher than in the strong-weak condition. Figure 6 shows normal distribution curves fitted to the density of averaged response errors.

For the vertical presentation orientation, response accuracy substantially increased for both vertical orientations compared with the adjacent lateral presentation directions, with small response errors at 90° of −6.01° and −4.21° for the weak-strong and strong-weak conditions, respectively. Conversely, at 270°, participants responded with very high accuracy, with response errors of 2.71° for the weak-strong and 0.98° for the strong-weak condition.

A model that included a fixed predictor for presentation orientation in degrees (M1) yielded a significantly improved fit [$\chi^2(4) = 615.02$, $P < 0.001$, BF = 5.339×10^{131}] over the baseline model (M0). Adding a second fixed predictor for distance (M2) improved the model fit significantly [$\chi^2(5) = 6.47$, $P < 0.05$]; however, the Bayes factor of 0.055 indicates that M1, without distance as factor, is more strongly supported by the data. Including a third predictor for the alignment of the tactors (M2) did not significantly improve the model fit [$\chi^2(4) = 0.514$, $P = 0.474$], suggesting that the tactor alignment had no influence on the responses. Adding intensity order (M3) to the model significantly improved the fit ($X^2(6) = 77.64$, $P < 0.001$, BF: 6.448×10^{14}), indicating that the response errors were significantly influenced by the temporal order of vibration intensity. Table 3 shows the parameters for M3.

Figure 7 shows that the effect of intensity order varied by presentation orientation and was stronger for the upper half than for the lower half of presented orientations. In the upper half of the stimulus presentations, the effect could have been mainly driven by a decreased accuracy (or increased uncertainty) in the strong-weak condition causing a bias toward the horizontal midline. Note that such a bias to the central midline in the upper semicircle results in an downward bias that would mask the illusion but that the same bias to the central midline would result in an upward bias in the lower semicircle. There was, however, no such difference in the lower half of the stimulus display. In fact, in the lower half of the display, the weak effect of intensity suggests a general upward bias consistent with the effects of the illusion. The results therefore suggest that the effects of stimulus intensity are twofold. First, an interaction between intensity-driven uncertainty induces a bias toward the

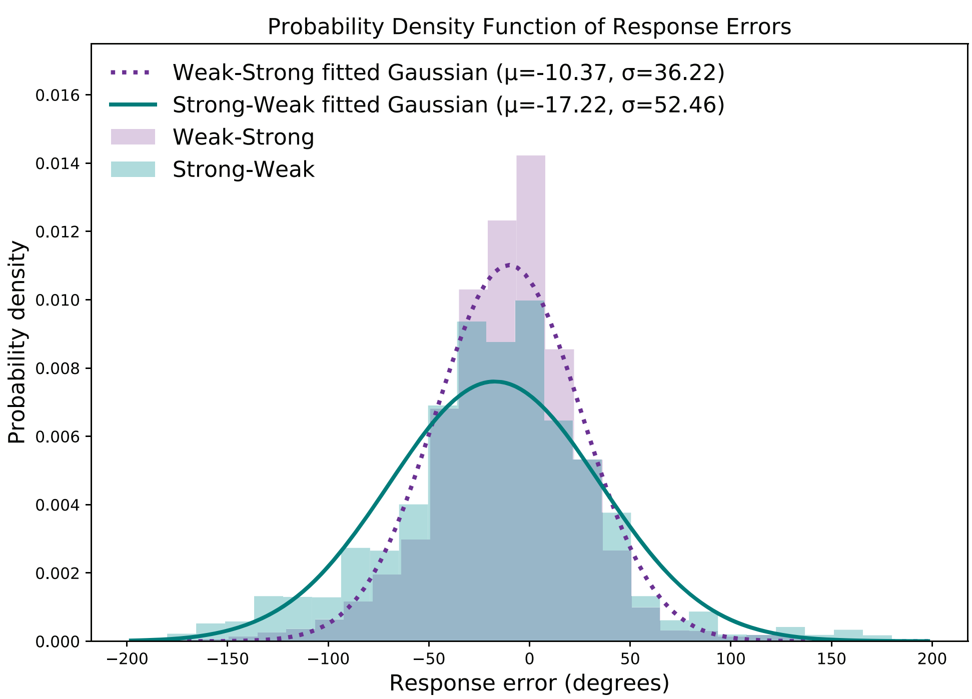

Fig. 6. Normal distributions fitted to the density histograms of response errors for each of the two intensity order conditions (strong-weak and weak-strong). Fit results are means (μ) and standard deviation (σ).

Table 3. *Parameters for model 3 (including presentation orientation, interstimulus distance, and intensity order as fixed predictors)*

	Coefficient	CI	SE	*t*	*P*
Intercept	−28.660	[−35.34, −21.98]	3.408	−8.409	<0.001
Presentation orientation	0.091	[0.08, 0.10]	0.004	24.467	<0.001
Interstimulus distance	0.086	[0.02, 0.15]	0.034	2.549	0.023
Intensity order	−6.849	[−8.37, −5.33]	0.776	−8.825	<0.001

Model 3 takes subjects as random effect. Reported are the regression coefficients with associated confidence intervals (CI), standard errors (SE), and *t* statistics (*t* and *P* values) for each fixed predictor.

horizontal midline. Second, the weak-strong condition induced a general upward bias. To account for these two influences of intensity changes, we created a model that includes an interaction term between intensity and presented orientation and a term for the overall effect of intensity on perceived orientation. The model that included a general effect of intensity fitted the data significantly better than a model that only included the interaction term [$\chi^2(6) = 69.63$, $P < 0.001$, BF = 1.181×10^{13}].

To illustrate that error distributions were skewed toward the horizontal axis, reflecting what might be called a central response bias, we selected lateral orientations that were closest to the vertical axis, as depicted in Fig. 8. Specifically, we selected tactors at angles 63.4° and 116.6° to select orientations that were in the upper half of the tactor grid, and tactors at angles 243.4° and 296.6° for orientations that were in the lower half of the tactor grid. The skewness of the error distributions for these directions, which approached straight up and straight down, shows that participants more often overestimated the orientation when the second tactor activation was in the lower half of the tactor grid and more often underestimated the direction height when the second tactor activation was in the upper half of the tactor grid.

DISCUSSION

Experiment 1

Experiment 1 showed that varying the intensity of two successive vibrotactile stimuli led to errors of localization, where strong stimulation followed by weak stimulation caused a downward bias, whereas weak stimulation followed by strong stimulation caused an upward bias. Most interestingly, the intensity order illusion even occurred when the actual presentation movement was opposite to the apparent movement induced by the intensity change.

Even though this intensity order illusion occurred for both tactor types, the results were less clear for the PERMs. First, the PERMs were mounted at a 10-mm smaller inter-tactor distance and operate at a lower vibrational intensity, which yields lower response accuracy (Hoffmann et al. 2018; Jóhannesson et al. 2017). Accuracy was also lower for the PERMs,

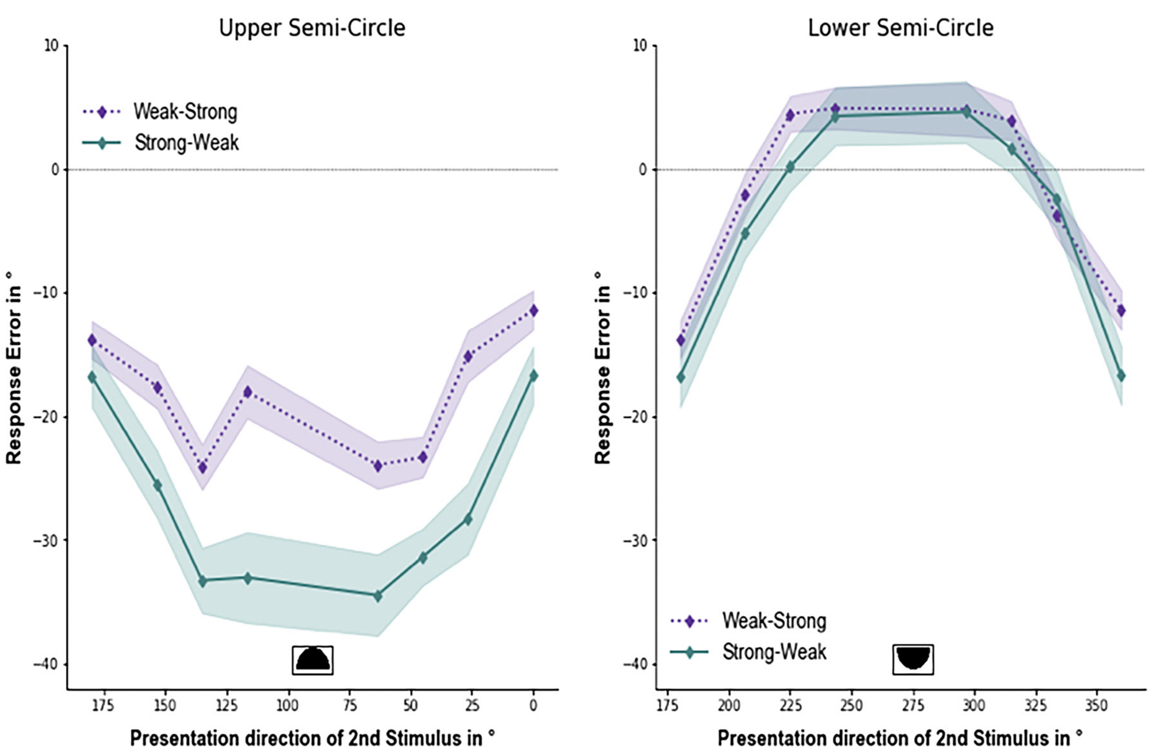

Fig. 7. Average response error (in degrees) as a deviation from the presentation orientation for each of the 2 intensity order conditions (strong-weak vs. weak-strong). Responses are plotted for all lateral presentation orientations from left to right (excluding vertical of 90° and 270°) and split into upper and lower semicircles (symbols above *x*-axis). Negative response errors represent an underestimation of the second stimulus location, whereas positive response errors represent an overestimation of the same. Symbols represent means, and error ranges are SE.

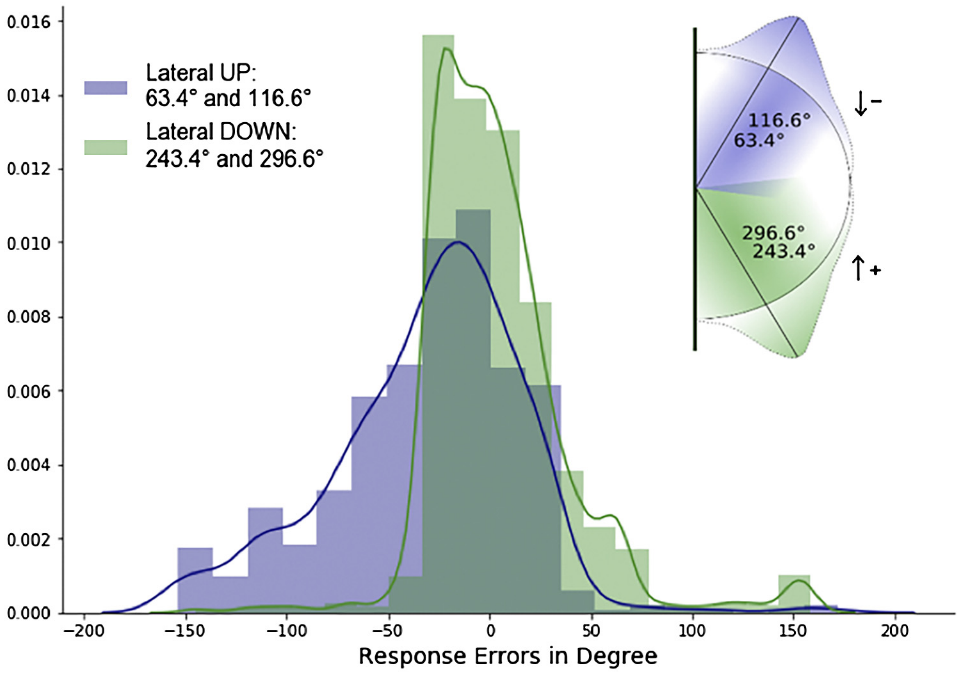

Fig. 8. Average density distributions of response errors for 2 presentation orientations. The temporal order of vibratory intensity is merged, and data are collapsed over the vertical axis. Errors are shown for the 2 lateral presentation orientations closest to the vertical axis for either up (63.4° and 116.6°) or down (243.4° and 296.6°) responses. Importantly, trials where the responses crossed the vertical axis are included. The skewed distributions illustrate that participants showed a response bias away from the vertical axis, toward the horizontal axis. Specifically, the orientation for the up responses (blue) was generally biased downward, and the orientation for down responses (green) was generally biased upward. *Inset* illustrates these distributions around their polar coordinates to give an idea about how the responses were distributed spatially. Arrows in *inset* denote direction of the bias.

which may reflect overall difficulties with differentiating between directions as Fig. 5 suggests. The PERMs may yield a weaker intensity effect because of the smaller difference (Δ) in stimulation intensity (see METHODS). We therefore focus on the NERMs in *experiment 2*.

Experiment 2

Strong vibrotactile stimulation followed by weak stimulation led to a downward shift of perceived stimulation orientation, and weak stimulation followed by strong stimulation led to an upward shift of perceived stimulation orientation, consistent with *experiment 1*. In addition to a substantial overall downward bias in *experiment 2*, the intensity order effect varied greatly by presentation orientation, resulting in different patterns above and below the horizontal midline of the stimulation area.

The results further show that participants were able to reliably tell the two general lateral directions apart (only 2.55% errors). Conversely, the low precision of responses (reflected in high standard deviations, 36°–52°) indicates that participants had difficulty determining the exact position of the second stimulation within the right and left halves of the tactor array. Participants accurately classified the side of lateral stimulation (left vs. right) but were not able to precisely identify the orientation within either the left or the right side. The results further suggest that within the left (or right) side, participants showed a response bias toward the center (the horizontal axes within each side), where the probability that participants underestimated or overestimated the orientation on the left or right depended on whether the second tactor was presented in the upper or lower half of the grid. As Fig. 8 shows, when the second stimulation was in the upper half of the tactor grid, participants were more likely to underestimate the vertical direction of the two tactor activations, whereas when the second stimulation was in the lower half of the tactor grid, participants were more likely to overestimate the vertical direction of the tactor activations. This central bias could underlie the U-shape of the response errors in Fig. 6: the strongest central bias occurs closest to the vertical axis and decreases toward the horizontal axis.

Note also that uncertainty in the responses increased when the intensity of the second stimulation was weak, because the standard deviations were higher for strong-weak activations (SD = 52.47) than weak-strong activations (SD = 36.22). The central response bias caused by uncertainty and the effect of intensity order seemed to amplify each other in the upper semicircle: the strong-weak condition yielded higher uncertainty and accordingly showed a bias toward the horizontal axis, in the same direction as the proposed intensity order illusion. Conversely, the weak-strong condition yielded more precise answers, and therefore decreased the central downward bias, again consistent with the illusion effect. The upper semicircle alone, therefore, does not show distinct effects of an upward bias caused by intensity. Instead, the difference between the two intensity conditions may be caused by lower accuracy in the strong-weak condition. Note, however, that in the lower semicircle, a central response bias would have consequences that are opposite to those effects in the upper semicircle. Specifically, in the strong-weak condition, a relatively inaccurate response would lead to a bias toward the horizontal midline, an upward bias, relative to the responses in the weak-strong condition. In other words, the results should be mirrored for the lower semicircle, with the strong-weak condition showing a stronger upward bias than the weak-strong condition. Yet, the results for the lower semicircle are the opposite, indicating a general upward bias (i.e., in both semicircles) in the responses during weak-strong trials, relative to the strong-weak condition, on top of a bias to the horizontal midline. Moreover, the intensity change effect is still significant in the lower semicircle, even though it is partly masked by the opposite uncertainty response bias.

General Discussion

Varying the vibrational intensity of two successive stimulations yields a systematic localization error. When the second stimulation is stronger than the first, observers tend to report that it is located above the actual presentation direction, and when weak stimulation follows strong stimulation, observers tend to report that the stimulation was below the actual stimulation. This illusion can be so strong that participants perceive a movement in accordance with the intensity change, even though the actual presentation order is the opposite. Furthermore, the illusion was strong even when it was masked by the uncertainty response bias for directions within the lower semicircle in *experiment 2*. There was also a strong overall downward bias in the responses, especially in *experiment 2*.

Even though we found no descriptions of this haptic illusion in the literature, a body of research on multisensory correspondence provides a theoretical framework for possible underlying mechanisms. There are universally experienced associations between apparently haphazard stimuli across different senses (Spence 2011). In the intensity order illusion, high vibratory stimulation appears to be associated with "up," but low vibratory stimulation appears to be associated with "down."

For example, auditory pitch (frequency) is associated with visuospatial height (Evans and Treisman 2010; Jamal et al. 2017). Analogous with the proposed spatiotemporal haptic intensity illusion, varying the frequency of an incidental sound induces corresponding visual illusory upward or downward movement for a stationary light (Miller et al. 1958). Additionally, a large amount of research suggests correspondences between audio frequencies (pitch) and visual size (Parise and Spence 2008), sharpness (Walker et al. 2010), and brightness and color (Ward et al. 2006). Also, synesthetic visuo-haptic interactions have been documented, with participants preferentially matching black and white squares with low- and high-frequency vibrotactile stimuli, respectively (Martino and Marks 2000). There are also studies suggesting strong audio-haptic connections (Nava et al. 2016; Wilson et al. 2010). In Occelli et al. (2009), participants made speeded discrimination responses to unimodal auditory (low-vs. high-frequency sounds) or vibrotactile stimuli (presented to the index finger, upper location vs. the thumb, lower location). Performance was better in the compatible condition, supporting the cross-modal association between the relative frequency of a sound and the relative elevation of a tactile stimulus (Occelli et al. 2009).

Melara and Marks (1990) found a significant congruency effect when participants performed a speeded discrimination task with the visually presented syllables "HI" and "LO" and high- and low-frequency tones. The strong frequency effect found in *experiment 1* may therefore reflect comparable mechanisms for haptic frequency (see Occelli et al. 2009). Overall, the various cross-modal associations found for all senses, consistently linking frequencies (of haptic vibration or auditory pitch) to elevation (spatially on the skin, or visuospatial height), could underlie the intensity order illusion reported here.

Cross-modal correspondences tend to occur between stimulus properties that are correlated in nature and seem likely to be learned (Spence 2011). Parise et al. (2014), for instance, found clear mappings between frequency and elevation in auditory scene statistics with high-pitched sounds tending to emanate from high locations and low-pitched sounds from low locations. Cross-modal correspondences serve to increase the efficiency of information processing and support the integration of sensory data into meaningful representations (Spence 2011). Relying on these heuristics, however, can come at the cost that rare physical events violating the expectation, as artificially recreated in our experiment, are misperceived.

Future Work

For the tactor types we used, both frequency and amplitude are inextricably linked, so adjusting one parameter changes the other. No clear conclusions can therefore be drawn about whether frequency or amplitude (or both combined) cause the intensity order illusion. These parameters should therefore be manipulated and disentangled in future to assess their independent contribution, with tactors that allow independent control of frequency and amplitude (e.g., linear resonant actuators).

The results of *experiment 2* suggest that the central tactor column running along the spine affects performance differently than peripheral columns. Subsequent experiments could therefore assess possible changes in responses when the tactor array is placed in the periphery of the spine without crossing it. Also of interest will be to assess whether the intensity order illusion can be induced on other body parts, such as abdomen, limbs, or face, and if there is a difference between glabrous or hairy skin areas (as tested in the present work). During investigation of the limbs, determining how the direction of "up/down" in the vertical plane, as tested here, translates to these areas, since the interpretation of directions changes depending on how they are positioned in relation to the torso. It appears likely that the interpretation of direction follows the neurological classification system for body directions (toward vs. away from the brain), where "up" corresponds to "proximal" (e.g., from elbow toward shoulder) and "downward" corresponds to "distal" (e.g., from knee to foot). Other unanswered questions involve the general downward bias that we found. For example, assessing whether it reflects a response bias or a perceptual one, and how it relates to findings for other sensory systems, would be of interest. Studies of visual perception have, for instance, shown up vs. down asymmetries, with a preference for upward stimulus motion (Seya et al. 2015; van den Berg and Collewijn 1988).

Although the current results provide strong verification of the intensity order illusion, further empirical investigations and replications across various conditions and experimental setups are required to determine which factors facilitate or inhibit the illusion and the optimal temporal parameters for robustly inducing the illusion. The effects of interstimulus interval and stimulus duration, which have been found to influence other haptic illusions, such as the cutaneous rabbit (Brooks and Trojan 2017; Trojan et al. 2010), should be investigated. It is also important to determine the optimal frequency range for the illusion. Eventually, the results of these studies could serve as a basis for increasing the effectiveness and ergonomy of haptic wearables. With appropriate spatiotemporal activation sequences, the perceived resolution of haptic displays could be increased, as has been demonstrated for other haptic illusions involving localization error (Barghout et al. 2009; Cholewiak and Collins 2000).

GRANTS

The research was funded by the European Union Horizon 2020 Research and Innovation Program (643636).

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

R.H., M.A.B., R.U., and A.K. conceived and designed research; R.H. performed experiments; R.H. and M.A.B. analyzed data; R.H., M.A.B., R.U., and A.K. interpreted results of experiments; R.H. and M.A.B. prepared figures; R.H. drafted manuscript; R.H., M.A.B., R.U., and A.K. edited and revised manuscript; R.H., M.A.B., R.U., and A.K. approved final version of manuscript.

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