Introducing a New Haptic Illusion to Increase the Perceived Resolution of Tactile Displays

Rebekka Hoffmann[1,2], Manje A. B. Brinkhuis[1], Árni Kristjánsson[1] and Runar Unnthorsson[2]
[1]*Faculty of Psychology, University of Iceland, Sæmundargata 2, Reykjavik, Iceland*
[2]*Faculty of Industrial Engineering, Mechanical Engineering and Computer Science, University of Iceland, Sæmundargata 2, Reykjavik, Iceland*

Keywords: Haptic Illusion, Error of Localization, Tactile Spatial Acuity, Vibrotactile Resolution, Tactile Displays.

Abstract: Tactile high-resolution displays gained importance during the last decade due to their wide range of application areas. To maximize the throughput of information developers can be tempted to mount as many tactile actuators (tactors) as possible on a haptic device, thereby risking to overexert the user's sense of touch, and to critically decrease its usability. Studies therefore explore ways of increasing the perceived resolution of tactile displays by exploiting haptic illusions. We demonstrate a new spatiotemporal haptic illusion that has not been described in literature yet. We conducted an experiment, in which we manipulated the vibration intensity of two successive tactor activations, the direction of consecutive tactor activations (up, down) and inter-tactor distance (40, 20, or zero mm). Fourteen naive participants judged whether the second tactor activation was above or below the first activation. Our results suggest that varying the sequence of activations with different intensities leads to an error of localization. High intensity activations followed by low intensity activations resulted in an illusory downward movement, and vice versa. The haptic intensity-movement illusion provides a promising possibility to enhance the information conveyed in tactile displays, without increasing the tactor density at the cost of the product's usability, comfort and ergonomy.

1 INTRODUCTION

Tactile displays using vibrating motors (tactors) accompanied by effective haptic languages, are particularly powerful tools providing a great variety of application areas. Tactile high-resolution displays are an especially auspicious choice as hardware components for Sensory Substitution devices (SSDs), non-invasive human-machine interfaces that draw on the central nervous system by bypassing the impaired peripheral components (Kristjánsson et al., 2016; Reich et al., 2012). It is an exciting possibility to augment the sensory experiences of people, who have deficiencies in one sensory dimension, by conveying the missing information through an intact sense, like touch (Sorgini et al., 2018). For the 253 million people living with vision impairment (WHO, 2018), transforming visual into haptic information may constitute a vital alternative to costly invasive technologies (Striem-Amit et al., 2012), and research in the field of tactile displays to support visually impaired in orientation and mobility has gained impetus (Bach-y-Rita and Kercel, 2003; Cosgun et al., 2014; Kristjánsson et al., 2016). Within the Sound of Vision project, a multisensory SSD was developed for the blind that provides continuous, real-time haptic representations of the environment by means of a high-resolution tactile display (Hoffmann et al., 2018). Additionally to serving as visual aids, the development of devices transforming auditory information into tactile information aims to improve the life quality of hearing impaired by extracting features of speech in a sound-to-touch system (Novich and Eagleman, 2015), or enhancing experience of music perception (Jack et al., 2015; Nanayakkara et al., 2013). Moreover, beyond the use of tactile displays as SSDs, there are plenty of further areas of applications. For instance, vibrotactile arrays can support people with balance impairments by providing vibratory feedback (Wall and Weinberg, 2003), they can enhance the immersive experience in virtual environments for entertainment, or professional training (Faroque et al., 2015), and provide crucial means of

Hoffmann, R., Brinkhuis, M., Kristjánsson, Á. and Unnthorsson, R.
Introducing a New Haptic Illusion to Increase the Perceived Resolution of Tactile Displays.
DOI: 10.5220/0006899700450053
In *Proceedings of the 2nd International Conference on Computer-Human Interaction Research and Applications (CHIRA 2018)*, pages 45-53
ISBN: 978-989-758-328-5

communication and guidance for firemen, police and rescue teams in difficult environments, e.g. when navigating in dense smoke (Carton and Dunne, 2013).

Since, in all application contexts, highly complex information must be conveyed, a key consideration in the development of tactile displays is to find ways of maximizing the throughput of information. Regarding SSDs, the bypassed non-functional sense usually has a much higher resolution than the sense of touch: In order to convey speech information, bandwidths between 64 and 110 bits per second are required - a range of bandwidths that is not supported by the skin (Novich and Eagleman, 2015). Furthermore, music consists of highly complex compositions of auditory elements like rhythm, timbre and harmony, and when trying to transform these elements to tactile information, the original auditory information may extend beyond the tactile spectrum (Karam et al., 2009). Whereas audible vibrations span frequencies from 20 Hz up to 20 kHz, our tactile system can only detect vibrations ranging in frequency from 10 Hz and 1000 Hz (Nanayakkara et al., 2013). To convey the full visual experience would rely, similarly, on being able to convey information at a high resolution to encode the characteristics of a visual object (e.g. depth, brightness, colour, distance, direction, quantity, size and elevation), through tactile displays. Attempts to mimic the functioning of the human visual system through tactile stimulation, would be thwarted by the skin's limited processing capacity.

In the attempt to convey as much information as possible, developers may be tempted to mount as many tactors as possible on a tactile device, which may overexert their user's sense of touch. Therefore, an important body of research focusses on determining vibrotactile spatial acuity, meaning the minimal possible spacing between tactors on a given body site before their loci become indistinguishable (Jóhannesson et al., 2017; Jones and Sofia, 2012; Van Erp, 2005). However, to simply mount the highest density of tactors on a device, even if correctly considering the tactile spatial acuity, still involves practical drawbacks from a usability point of view. If users are to be expected to use a particular device, a plethora of requirements need to be considered, e.g. portability, comfort, accessibility of interface, and appearance (Kristjánsson et al., 2016). Every additional tactor entails the use of more cables, bigger control units, increased weight, size and bulkiness of the device, and increased heat and noise emissions, as well as increased production costs. These implications critically decrease practical and ergonomic functioning (Dakopoulos and Bourbakis, 2010) of the device, leading to a trade-off between accuracy and usability, varying the number of tactors.

Another important body of research therefore explores innovative ways of increasing the amount of information that can be conveyed through vibrotactile signals, e.g. by exploiting haptic illusions. In the past decade, the rate of discovery of new tactile and haptic illusions has increased greatly, indicating growing interest in the subject (Hayward, 2015; Lederman and Jones, 2011). Haptic illusions arise when the interpretation of an object through the sense of touch does not correspond to the physical stimulus. Beyond well-known tactile illusions with optical geometrical counterparts (Gentaz and Hatwell, 2004; Ziat et al., 2014), tactile perception is subject to characteristic spatiotemporal illusions related to the underestimation of inter-stimulus distance and overestimation of inter-stimulus time, e.g. the tau and kappa effect, or apparent movement illusion (Carter et al. 2008; Lechelt and Borchert, 1977). Once understood, especially the spatiotemporal illusions that involve an error of localization, like the funneling illusion and the sensory saltation illusion, could be exploited to increase the perceived resolution of tactile displays. The funneling illusion (Gardner and Spencer, 1972) occurs when two adjacently located vibratory stimuli are presented simultaneously and, instead of being perceived separately, the associated sensation is perceived to originate from between the two tactors. Barghout and colleagues (2009) applied multiple "funneling" stimuli on the forearm and were able to create a continuous touch sensation by manipulating the tactor intensities. They thereby established an additional information channel and increased the spatial resolution of vibrotactile perception. Further, Cholewiak and Collins (2000) explored the sensory saltation illusion (also called the cutaneous rabbit, Geldard and Sherrick, 1972), which is evoked by tapping two or more separate regions of the skin in rapid succession. Tapping, for instance, wrist and elbow creates a sensation of sequential taps hopping up the arm from wrist to elbow, although there is no physical stimulus between the two actual stimulus locations. 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* mode, where only the first, fourth, and seventh tactor were activated. They found that that the saltatory mode produced equivalent sensations to the veridical mode, and that both resulted in clearly perceived lines at each body site. These results promote the possibility of omitting tactors by exploiting haptic illusions like sensory saltation.

In the current paper, we introduce a new haptic illusion, for which manipulation of vibratory intensity (frequency, acceleration) of a sequence of vibrotactile stimuli leads to an error of location. The illusion was discovered during the Sound of Vision project (Hoffmann et al., 2018), and, to the best of our knowledge, has not been described in the literature yet. 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 2nd stimulus is erroneously perceived to be below the 1st stimulation location (in vertical plane). The same seems to apply vice versa, with a more intense 2nd vibratory stimulation being erroneously perceived to be located above the first stimulation. Importantly, the described haptic intensity-movement illusion could be exploited to increase the perceived resolution of haptic products. This is a promising option to increase the amount of information that can be conveyed in high-resolution tactile displays, instead of increasing the density of tactors and thereby lowering the product's usability, comfortability and ergonomy. In what follows we describe an experiment that we conducted to demonstrate illusory movement caused by vibratory intensity-changes, by assessing the participant's responses while systematically manipulating the intensity of vibratory tactor stimulations.

2 METHOD

2.1 Participants

Fourteen students at the University of Iceland (7 females, 21-28 years, *M* = 23.79, *SD* = 1.89), participated. They were naive about the purpose of the study, and gave written informed consent before the experiment started. The experiments were approved by the appropriate ethics committee and conformed to the Declaration of Helsinki.

2.2 Apparatus

An array of 4 x 4 tactors was glued to a 15 cm thick layer of foam, as shown in Figure 1, whereby the central part of the device consisted of 4 additional cm of foam to ensure good fit in the spine area. The foam was mounted on a plastic frame containing the electronics board, battery and charger circuit, and was equipped with straps to be fastened around the participant's waist, with the tactor array placed on the lower back. We created custom software, written in Python, and making use of the Psychopy library (Peirce, 2009) for stimulus presentation. The tactors were Eccentric Rotating Mass (ERM) motors, covered in a plastic shell (diameter: 9 mm, length: 25 mm, Precision Microdrives, 2018; model #307-103), and were controlled with a simple Darlington driver. Based on previous work determining vibrotactile spatial acuity (Jóhannesson et al., 2017), the ERMs were placed as close as physically possible, at an inter-tactor distance of 20 mm, measured from center-to-center (c/c). The tactors were run at two intensities, either at high intensity (4 V), with 230 Hz vibration frequency (100 mA, 7 G), or at low intensity (1 V), with 90 Hz vibration frequency (30 mA, 1G).

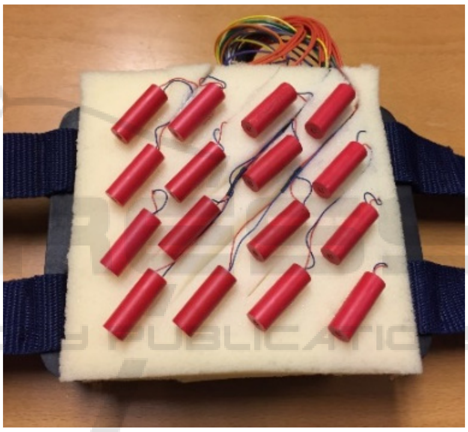

Figure 1: Array of 4 x 4 Eccentric Rotating Mass motors mounted 20 mm (centre-to-centre) apart from each other on a frame with foam, to be placed centrally at the participant's lower backs.

2.3 Stimulus

Each trial consisted of a pair of successive tactor activations. The tactors were activated along the vertical axis, meaning that the 2nd tactor activation within each trial was either above, below or the at the same location as the 1st tactor activation. Within each trial, the intensity of tactor activation was systematically varied in two conditions, with either the 1st activation being strong (230 Hz, 7 G) and the 2nd being weak (90 Hz, 1G), aiming to induce a perceived shift of localization downwards, or vice versa, with the 1st activation being weak and the 2nd being strong, aiming to induce a perceived shift of localization upwards. Additionally, the inter-tactor distance was systematically varied across trials, in five conditions: The 2nd tactor activation was either 40 mm (c/c) below the 1st (with one inactive tactor in between) or the 2nd tactor activation was 20 mm (c/c) below the 1st (adjacent tactors). The same approach was applied for the upwards direction, with 40 and 20 mm (c/c) inter-tactor distance. Finally, the fifth condition consisted of the same tactor being activated twice. On each trial (in all conditions), the tactors were turned on for 200 ms with an inter-stimulus interval of 50 ms, and an inter-trial interval of 1500 ms.

Overall, the experiment consisted of 400 trials, and every condition was assessed by 40 trials in random order. The experiment was divided into four blocks of 100 trials each, whereby the location of the 1st tactor, the distance to the 2nd tactor, the direction of intensity-change, and whether the 2nd tactor was above, below or the same as the 1st tactor, were randomized and equally balanced within one block.

2.4 Procedure

Participants were requested to wear a sheer shirt to avoid the vibrations of the tactors being absorbed by thick fabric. After signing the informed consent, participants took seat in front of a computer screen in a quiet room. They were outfitted with headphones and the tactor array, which was placed centrally in the participant's lower back. Subsequently, participants received task instructions. Importantly, all participants were naive about the full set of inter-tactor-distance conditions and not informed about the possibility that the same tactor might be activated twice. In a two-alternative forced choice task (2AFC), participants were asked to judge whether they perceived the 2nd tactor activation to be located above or below the 1st activation by pressing the up and down arrow keys on a standard keyboard, respectively. Further, participants were encouraged to close their eyes to avoid visual distraction, and they wore headphones playing white noise to mask the sound of the tactors to avoid that it would serve as an auditory cue. After a short training session of 100 trials, the experiment started and took about 15 minutes to complete. There was a break after each completed block, where participants could decide individually when to proceed. All in all, the procedure took about half an hour.

2.5 Statistical Analysis

In order to demonstrate the proposed haptic illusion of an apparent shift of location induced by an intensity-change of tactor activation (downwards in case of strong-to-weak, and upwards in case of weak-to-strong), the trials in which the same tactor was activated twice without the participants being aware of it, were of particular interest for the analysis. If the responses were independent of the intensity-change, in both conditions, the participant's responses would be random and the proportion of up/down responses would therefore be equally distributed at chance level (0.5). If the intensity-change, however, induced an apparent movement, the probability of participants responding with up in the strong-weak condition may be attenuated and, likewise, the probability of responding up in the weak-strong condition may increase. Furthermore, the effect of illusionary movement caused by the intensity-change may be most pronounced when the inter-tactor distance is zero, whereas increasing inter-tactor distance could increase discriminability when judging the direction of activations, minimizing the illusory effect.

One sample, one sided t-tests were conducted in R (R Project for statistical computing) to assess if the participant's responses for the same tactor activation differed significantly from chance level (0.5). Further, a repeated measures ANOVA was conducted to assess the main overall effects of inter-tactor distance, presentation direction, intensity-change direction (strong-to-weak, weak-to-strong), as well as possible interactions. *Generalized eta squared statistics* (η_G^2) were calculated with R ezANOVA function and are reported as recommended for within-subject designs (Olejnik and Algina, 2003). Pairwise post-hoc comparisons were conducted (Tukey's HSD adjusted) to assess whether the two conditions of intensity-change (strong-to-weak vs. weak-to-strong) differed for the same tactor activation, the close inter-tactor distances (20 mm c/c) as well as for the far inter-tactor distances (40 mm c/c), for up and down presentation direction, respectively.

3 RESULTS

Figure 2 reports the ratio of up-responses as a function of intensity-change condition, and distance between the two stimuli. While Panel A shows the two distance conditions, where the 2nd tactor activation was below the first, Panel B shows the condition, in which the same tactor was activated twice, and Panel C plots the two distance conditions, in which the 2nd activation was above the first.

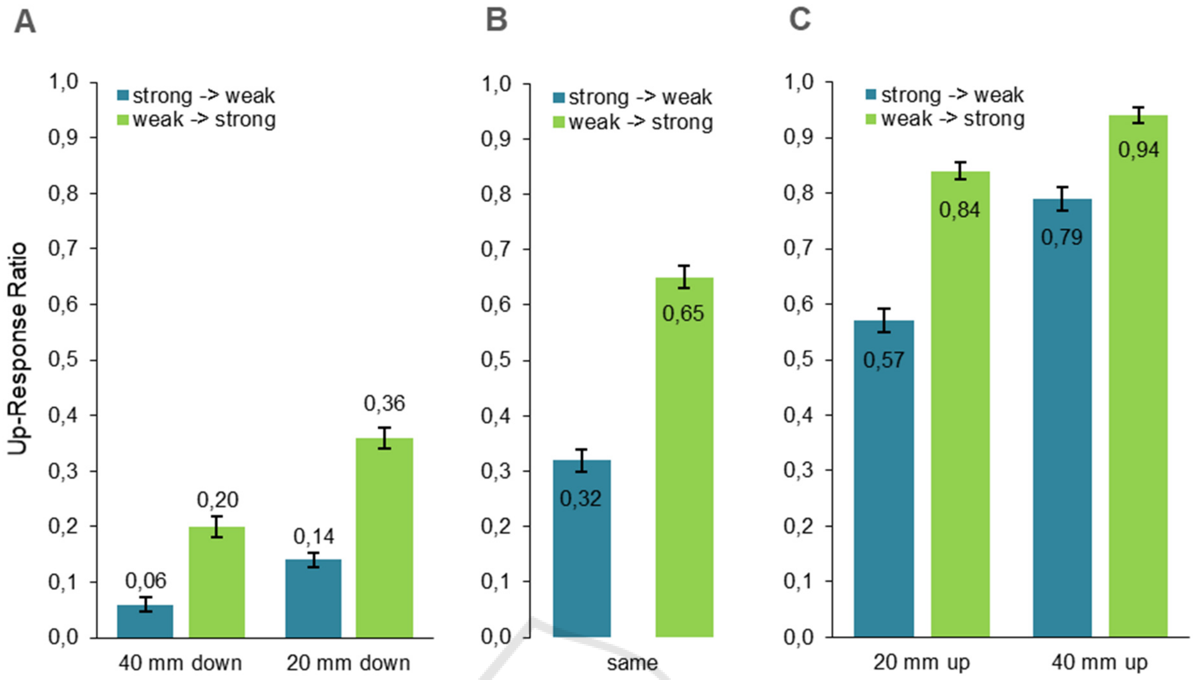

Figure 2: Panel A shows the ratio of up-responses as a function of intensity-change, and inter-tactor distance between the two successively activated tactors for the condition, in which the second tactor activation was below the first. Panel B shows the ratio of up-responses for the condition, in which the same tactor was activated twice, and Panel C shows the same for the two distance conditions, in which the second tactor activation was above the 1st. Error bars represent the standard error of the mean (SEM).

Figure 2 indicates that the ratio of up-responses within each presentation condition is substantially influenced by the sequence of intensity changes of the vibratory stimuli, which was confirmed by the statistical analysis. Besides the significant main effect of presentation direction and distance ($F(4,52) = 100.10$, $p < .001$, $\eta_G^2 = .72$), we found a highly significant main effect of intensity-change direction on the up-response ratio with a large effect size ($F(1,13) = 13.35$, $p < .003$, $\eta_G^2 = .31$).

In detail, for the trials in which the same tactor was activated twice, participants did not respond randomly but were influenced by the intensity-change direction. If the first stimulation was of high vibratory intensity followed by a low intensity stimulation, participants appeared to perceive the 2nd stimulus to be below the first and responded up significantly below chance level ($t(13) = -3.95$, $p > .001$). Likewise, in case the first stimulus was of low intensity followed by a high intensity stimulus, participants tended to erroneously perceive the 2nd stimulus above the first, and responded up significantly above chance level ($t(13) = 2.81$, $p = .007$).

Furthermore, there was a significant interaction between the two main effects of presentation direction/distance and the intensity-change direction ($F(4, 52) = 8.26$, $p < .001$, $\eta_G^2 = .05$), meaning that varying the direction of intensity-change within each stimulus pair affected the ratio of up-responses differently, depending on the presentation direction and distance. The pairwise comparisons indicate that the influence of intensity-change was strongest when the same tactor was activated twice, with a difference in the up-response ratios of -0.34 (95% CI: -.55 to -.12) between the strong-to-weak and weak-to-strong condition, which was significant ($p > .001$). The influence of intensity-change was lower but significant when the 2nd tactor activation was close (20 mm c/c) to the 1st, for both up (-0.27, 95% CI: -.48 to .06, $p = .003$) and down (-0.24, 95% CI: -.46 to -.03, $p = .016$) presentation directions. At the furthest inter-tactor distance of 40 mm (c/c), the influence of intensity-change on the up-response ratio was, even though still noticeable as a trend, not significant anymore, neither for the up (-0.15, 95%: CI: -.37 - .07, $p = .44$) nor for the down (-0.13, 95% CI: -.35 - .08, $p = .56$) presentation directions.

4 DISCUSSION

To demonstrate a spatiotemporal haptic illusion that could be exploited for increasing the perceived spatial acuity of tactile displays, we systematically manipulated the sequence of vibration intensity of two successive tactor activations. Our results indicate that varying the sequence of stimuli with different vibratory intensities (frequency and acceleration) causes an error of localization. When the same tactor was activated twice without the participants being aware of it, they did not respond randomly. Our results show that when a vibratory stimulus of high intensity was followed by a stimulus of low intensity, participants appeared to perceive the 2nd vibration to be located below the first, even though there was no actual change of location. Further, our results suggest the same effect for the opposite direction: presenting a vibratory stimulus of low intensity followed by high intensity at the same location provokes a perceived upwards movement. The effect of illusionary movement was still apparent in ambivalent situations, when two adjacent tactors of close inter-tactor distance were successively activated (20 mm c/c), but decreased with increasing inter-tactor distance (40 mm c/c).

Even though, to the best of our knowledge, this haptic illusion has not been described in the literature yet, there is a body of research on multisensory correspondences that provides a theoretical foundation for explaining possible underlying mechanisms. In general, cross-modal correspondences refer to universally experienced associations between apparently haphazard stimuli across different senses (Spence, 2011). In the intensity-movement illusion, high vibratory frequency (and acceleration) in tactile stimulation appears to be associated with elevation, whereby low vibratory frequency (and acceleration) appear to be associated with being located below. Interestingly, there is a commonly studied and robust audio-visual cross-modal correspondence between high and low pitch (auditory frequencies) as being associated with high and low visual elevations, respectively (e.g. Jamal et al., 2017). Additionally, a large amount of research suggests similarity correspondences between audio frequencies (high pitch vs. low pitch) and the visual features of size, colour, brightness and form (e.g. Gallace and Spence, 2006; Melara, 1989). Further, the occurrence of synesthetic visuo-haptic interactions have been documented, with participants preferentially matching black and white squares with low-frequency and high-frequency vibrotactile stimuli, respectively (Martino and Marks, 2000). Besides these intensely studied vision based correspondences, research further suggests a strong cross-modal audio-haptic connection (Nava et al., 2016; Wilson et al., 2010). It is therefore not surprising that Occelli et al. (2009) demonstrated a multisensory correspondence between the pitch of a tone and the elevation of tactually stimulated locations. Summing up, these cross-modal associations found for all senses (visuo-auditory, visuo-haptic, audio-haptic) linking high frequencies (of haptic vibration or auditory pitch) to elevation (spatially on skin, or visually) and opposite, could be the underlying mechanism for the described haptic illusion of perceiving an illusory downward movement when vibratory frequency changes from high to low (and vice versa). In general, such haptic illusions are worth studying, since they provide a powerful tool to gain insight into the limits of haptic perception (Lederman and Jones, 2011). Tactile representation of our physical environment relies on the acuity of the tactile sensory system. Due to the low receptor density, tactile perception is prone to spatial imprecision (Jóhannesson et al., 2017), and the tactile sensory system builds on prior knowledge and multisensory correspondences to enhance perceptual resolution beyond the limits set by sensorineural imprecision (Adams et al., 2004). Such correspondences usually occur between stimulus properties that are correlated in nature, and therefore 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, comes at the cost that rare physical events violating the expectation, as artificially recreated in our experiment, are misperceived.

Besides serving as a tool for studying cognitive processes, the haptic intensity-movement illusion could be applied practically to increase the perceived resolution of haptic products, as has been shown for other haptic illusions (Barghout et al., 2009; Cholewiak and Collins, 2000). This is a promising option to increase the amount of information that can be conveyed in high-resolution tactile displays, while avoiding the trade-off of lowering the product's usability, comfort and ergonomy by increasing the density of tactors. Furthermore, to exploit tactile illusions may yield benefits beyond usability related aspects, by possibly bypassing the anatomical and morphological changes of the skin in old age. This aspect is especially relevant since the majority of the target group for SSDs, a key application area of high-resolution haptic displays, is of older age. According to the WHO (2018), for instance, 81% of people who suffer from vision impairment are older than 50 years. It has been shown that spatial tactile acuity substantially decreases with age (Stevens and Patterson, 1995), resulting in less accurate tactile information conveyance when using tactile devices. Although a causal link between impaired tactile acuity in old age and receptor loss remains controversial (Dinse et al., 2006), a lower density of mechanoreceptors in the skin (Bruce, 1980), and slower conduction velocities of peripheral nerves (Peters, 2002) have been documented. The intensity-movement illusion demonstrated in this study might help circumventing these morphological limitations by increasing perceived tactile spatial acuity. Moreover, while haptic illusions can be affected by aging, as shown by Ballesteros et al. (2012), the current perceptual effects may rely on neurological mechanisms that are unrelated to morphological limitations. However, since the result of our study bases on a sample of adolescents, with ages ranging from 21 to 28 (M = 23.79), we are cautious to generalize to other ages. Further studies should therefore explore the effect of age on the intensity-movement illusion, to investigate its applicability in SSDs for different age groups.

It is important to note that the described intensity-movement illusion needs further empirical exploration in order to investigate how robustly it can be replicated across various conditions and experimental setups, and which factors act in a facilitating or inhibiting way.

Since the current results are limited to the back area, future studies should examine if the haptic illusion extends to other body sites, like abdomen, arms, legs, or face. It is of particular interest to explore how the direction of “upward/downward” in the vertical plane relates to other body parts that require a more specific definition of direction (e.g. arms and legs), as the understanding of up or down depends on their position. Specifically, following the neurologic classification system for body directions (proximal vs. distal, medial vs. lateral), “upwards” relates to “proximal” (towards the brain, e.g. from wrist towards elbow), and “downward” relates to “distal” (away from the brain). Such an approach may yield valuable information on how the haptic illusion relates to body position.

Finally, future studies should further assess the effects of using different tactor types, and spatiotemporal parameters, like inter-stimulus-interval, stimulus duration and inter-stimulus distance, on the occurrence of the illusion. We will conduct follow up experiments to specify the frequency range in which the illusion can be reliably demonstrated, and at which frequency differences the illusion is most likely to occur.

REFERENCES

Adams, W. J., Graf, E. W., Ernst, M. O., 2004. Experience can change the 'light-from-above' prior. In *Nature neuroscience, 7*(10), 1057-1058.

Bach-y-Rita, P., W. Kercel, S., 2003. Sensory substitution and the human-machine interface. In *Trends in Cognitive Sciences, 7*(12), 541–546.

Ballesteros, S., Mayas, J., Reales, J. M., Heller, M., 2012. The Effect of Age on the Haptic Horizontal–Vertical Curvature Illusion With Raised-Line Shapes. In *Developmental Neuropsychology, 37*(8), 653-667.

Barghout, A., Cha, J., Saddik, A. El, Kammerl, J., Steinbach, E., 2009. Spatial resolution of vibrotactile perception on the human forearm when exploiting funneling illusion. In *Haptic Audio visual Environments and Games*. IEEE.

Bruce, M. F., 1980. The relation of tactile thresholds to histology in the fingers of elderly people. In *Journal of Neurology, Neurosurgery & Psychiatry, 43*(8), 730–734.

Carter, O., Konkle, T., Wang, Q., Hayward, V., Moore, C., 2008. Tactile Rivalry Demonstrated with an Ambiguous Apparent-Motion Quartet. In *Current Biology, 18*(14), 1050–1054.

Carton, A., Dunne, L. E., 2013. Tactile distance feedback for firefighters. In *Proceedings of the 4th Augmented Human International Conference*. ACM.

Cholewiak, R. W., Collins, A. A., 2000. The generation of vibrotactile patterns on a linear array: Influences of body site, time, and presentation mode. *Perception and Psychophysics, 62*(6), 1220–1235.

Cosgun, A., Sisbot, E. A., Christensen, H. I., 2014. Guidance for human navigation using a vibrotactile belt interface and robot-like motion planning. In *Proceedings of the International Conference on Robotics and Automation*. IEEE.

Dakopoulos, D., Bourbakis, N. G., 2010. Wearable obstacle avoidance electronic travel aids for blind: A survey. In *Transactions on Systems, Man and Cybernetics, Applications and Reviews, 40*(1), 25–35. IEEE.

Dinse, H. R., Kleibel, N., Kalisch, T., Ragert et al., 2006. Tactile coactivation resets age□related decline of human tactile discrimination. *Annals of Neurology, 60*(1), 88-94.

Faroque, S., Horan, B., Adam, H., Pangestu, M., Thomas, S., 2015. Haptic Virtual Reality Training Environment for Micro-Robotic Cell Injection. In H. K. et Al. (Ed.), *Haptic Interaction*, *277*, 245–249. Springer. Tokyo.

Gallace, A. and Spence, C., 2006. Multisensory synesthetic interactions in the speeded classification of visual size. In *Perception & Psychophysics*, *68*(7), 1191-1203.

Gardner, E. P., Spencer, W. A., 1972. Sensory Funneling. I. Psychophysical Observations of Human Subjects and Responses of Cutaneous in Mechanoreceptive Afferents in the Cat to Patterned Skin Stimuli. In *Journal of Neurophysiology, 35*(6), 925–953.

Geldard, F. A., Sherrick, C. E., 1972. The Cutaneous “Rabbit”: A Perceptual Illusion. In *Science, 178*(4057), 178–179.

Gentaz, E., Hatwell, Y., 2004. Geometrical haptic illusions: The role of exploration in the Müller-Lyer, vertical-horizontal, and Delboeuf illusions. In *Psychonomic Bulletin and Review, 11*(1), 31–40.

Hayward, V., 2015. Tactile illusions. In *Scholarpedia, 10*(3), 8245.

Hoffmann, R., Spagnol, S., Kristjánsson, Á., Unnthorsson, R., 2018. Evaluation of an Audio-Haptic Sensory Substitution Device for Enhancing Spatial Awareness for the Visually Impaired. In *Optometry and Vision Science, Assistive Technology in Vision Impairment.* In publication, accepted: 16 July, 2018.

Jack, R., McPherson, A., Stockman, T., 2015. Designing Tactile Musical Devices with and for Deaf Users: a Case Study. In *Proceedings of the International Conference on the Multimedia Experience of Music*, 3-25.

Jamal, Y., Lacey, S., Nygaard, L., Sathian, K., 2017. Interactions between Auditory Elevation, Auditory Pitch and Visual Elevation during Multisensory Perception. In *Multisensory Research, 30*(3–5), 287–306.

Jóhannesson, Ó. I., Hoffmann, R., Valgeirsdóttir, V. V., Unnþórsson, R., et al., 2017. Relative vibrotactile spatial acuity of the torso. In *Experimental Brain Research, 235*(11), 3505–3515.

Karam, M., Nespoli, G., Russo, F., Fels, D. I., 2009. Modelling perceptual elements of music in a vibrotactile display for deaf users: A field study. In *Second International Conferences on Advances in Computer-Human Interactions*. IEEE.

Kristjánsson, Á., Moldoveanu, A., Jóhannesson, Ó. I., Balan, O. et al., 2016. Designing sensory-substitution devices: Principles, pitfalls and potential. In *Restorative Neurology and Neuroscience, 34*(5), 769–787.

Lechelt, E. C., Borchert, R., 1977. The interdependence of time and space in somesthesis: The Tau effect reexamined. In *Bulletin of the Psychonomic Society, 10*(3), 191–193.

Lederman, S. J., Jones, L. A., 2011. Tactile and Haptic Illusions. In *IEEE Transactions on Haptics, 4*(4), 273–294.

Mahzoun, E. E., 2013. *Good Vibrations : A vibrotactile aid toward music sensation aiming at helping deaf people*. Blekinge Institute of Technology.

Martino, G. Marks, L. E., 2000. Cross-modal interaction between vision and touch: the role of synesthetic correspondence. In *Perception, 29*, 745–754.

Melara, R. D., 1989. Dimensional interaction between color and pitch. In *Journal of Experimental Psychology: Human Perception and Performance, 15*(1), 69.

Nanayakkara, S. C., Wyse, L., Ong, S. H., Taylor, E. A., 2013. Enhancing musical experience for the hearing-impaired using visual and haptic displays. *Human-Computer Interaction, 28*(2), 115–160.

Nava, E., Grassi, M., Turati, C., 2016. Audio-visual, visuo-tactile and audio-tactile correspondences in pre-schoolers. In *Multisensory Research, 29*(1–3), 93–111.

Novich, S. D., Eagleman, D. M., 2015. Using space and time to encode vibrotactile information: toward an estimate of the skin’s achievable throughput. In *Experimental Brain Research, 233*(10), 2777–2788.

Occelli, V., Spence, C., Zampini, M., 2009. Compatibility effects between sound frequency and tactile elevation. In *NeuroReport, 20*(8), 793–797.

Olejnik, S., Algina, J., 2003. Generalized Eta and Omega Squared Statistics: Measures of Effect Size for Some Common Research Designs. In *Psychological Methods, 8*(4), 434–447.

Peirce, J. W., 2009. Generating stimuli for neuroscience using PsychoPy. In *Frontiers in neuroinformatics*, 2-10.

Peters, A., 2002. The effects of normal aging on myelin and nerve fibers: a review. In *Journal of neurocytology, 31(8-9)*, 581–593.

Precision Micordrives, 2018. *ERM Vibration Motor*. https://www.precisionmicrodrives.com/product/307-103-9mm-vibration-motor-25mm-type. Accessed 02.05.2018.

Reich, L., Maidenbaum, S., Amedi, A., 2012. The brain as a flexible task machine: Implications for visual rehabilitation using noninvasive vs. invasive approaches. In *Current Opinion in Neurology, 25*(1), 86–95.

Jones, L. A., Sofia, K., 2012. Measuring surface wave propagation during vibrotactile stimulation. In *Haptics Symposium*. IEEE.

Sorgini, F., Caliò, R., Carrozza, M. C., Oddo, C. M., 2018. Haptic-assistive technologies for audition and vision sensory disabilities. In *Disability and Rehabilitation: Assistive Technology, 13*(4), 394-421.

Spence, C., 2011. Crossmodal correspondences: A tutorial review. In *Attention, Perception, and Psychophysics, 73*(4), 971–995.

Stevens, J. C., Patterson, M. Q., 1995. Dimensions of spatial acuity in the touch sense: Changes over the life span. *Somatosensory & motor research*, *12(1)*, 29-47.

Striem-Amit, E., Bubic, A., Amedi, A., 2012. Neurophysiological Mechanisms Underlying Plastic Changes and Rehabilitation following Sensory Loss in Blindness and Deafness. In Murray, M., MT W. (Eds.), *The Neural Bases of Multisensory Processes*, 395–422. CRC Press/Taylor and Francis.

Van Erp, J. B. F., 2005. Vibrotactile spatial acuity on the torso: Effects of location and timing parameters. *1st Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE.

Wall, C., Weinberg, M. S., 2003. Vibrotactile Display of Body Tilt Reduces Sway in Vestibulopathic Subjects. *IEEE Engineering in Medicine and Biology Magazine, 22*(2), 84–90.

WHO, 2018. *World Health Organization Media Centre - Visual impairment and blindness*. Available at: http://www.who.int/mediacentre/factsheets/fs282/en/. Accessed 02.05.2018.

Wilson, E. C., Reed, C. M., Braida, L. D., 2010. Integration of auditory and vibrotactile stimuli: Effects of frequency. In *The Journal of the Acoustical Society of America, 127*(5), 3044–3059.

Yau, J. M., Olenczak, J. B., Dammann, J. F., Bensmaia, S. J., 2009. Temporal Frequency Channels Are Linked across Audition and Touch. In *Current Biology, 19*(7), 561–566.

Ziat, M., Smith, E., Brown, C., et al., 2014. Ebbinghaus illusion in the tactile modality. *Haptics Symposium*. IEEE.