This article has been accepted for publication in IEEE Transactions on Haptics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TOH.2023.3304953

Between-Tactor Display Using Dynamic Tactile Stimuli for Directional Cueing in Vibrating Environments

Ryo Eguchi, *Member, IEEE*, David Vacek, Cole Godzinski, and Allison M. Okamura, *Fellow, IEEE*

***Abstract*—Torso-worn vibrotactile devices have been used in many studies on directional cueing and navigation in environments where visual feedback is limited. These devices aim to indicate directions with high resolution while using the smallest possible number of vibration motors (tactors). Resolution can be increased using between-tactor displays, but their performance in vibrating environments (e.g., a helicopter) are unknown. This study proposes a between-tactor display using dynamic stimuli and verifies its effectiveness when the user sits in a vibrating chair. We developed a waist belt device that displays 12 directions using 6 tactors. Static stimuli display virtual (between-tactor) locations by constantly vibrating two adjacent tactors equally, whereas dynamic stimuli move the virtual vibration position back and forth between tactors. We performed two studies in which participants felt tactile stimuli and used a joystick to move a cursor on a screen to a target in the perceived direction. Direction recognition accuracy and task completion time were measured under combined conditions of two belt orientations (tactor alignments), with and without chair vibration, and with and without audio white noise to mask tactor sound. In all conditions, dynamic stimuli increased recognition accuracy while maintaining task completion time compared to static stimuli.**

***Index Terms*—Vibrotactile feedback; Wearable devices; Haptic illusion**

I. INTRODUCTION

TACTILE cueing can present information to humans while leaving vision and auditory sensation available for interaction with the environment. Tactile feedback has been examined for use in navigating pilots of aerial vehicles in the heading direction [1], [2], as well as for people with visual impairments [3], [4]. Wearable devices often use vibration motors (tactors) to provide skin stimulation. Previous studies have developed such devices to provide vibrotactile stimuli to various body parts, including the hands [5], [6], arms [7], [8], neck [9], legs [10], [11], and torso [12]–[15]. The torso is advantageous because it has a large area of skin available, and torso displays leave the limbs to be free for interaction with the environment.

Many groups have developed torso-mounted devices with various alignments/numbers of tactors and displaying methods. 1-D [12], [14] and 2-D [13], [15] arrays have been examined. A 1-D array is effective for cueing and navigation of heading direction on a two-dimensional plane [14]. Up to twelve tactors have been examined by many groups (e.g., two and three [16], four [17], [18], six [19], [20], eight [4], [21], ten [22], and twelve [23], [24]). Cholewiak et al. [25] reported an average tactor localization accuracy of 74% using a 12-tactor belt and concluded that the number of tactors in one row around the torso must be no more than about eight tactors to achieve a high recognition accuracy. Previous devices have used continuous (always indicating the north) [3], [26], [27] or discrete (turning vibration on and off) [11], [21], [25] displays. Discrete displays are advantageous for long-term navigation because human sensitivity diminishes under continuous vibration [11].

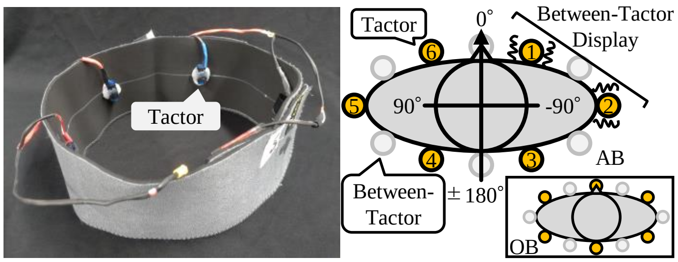
The long-term goal of our research is to design a garment with embedded tactors for navigation assistance or wayfinding. Thus, we aim to increase resolution by using virtual (between-tactor) vibrations to present 12 directions using only 6 tactors in terms of the wiring and cost. Previous studies created between-tactor displays by simultaneously vibrating two or more tactors [18], [25] or temporally modulating the vibration of two tactors [28]. Other groups proposed dynamic between-tactor stimuli using apparent tactile motion generated by sequential presentation of two tactile stimuli [11], [29], [30]. While some studies [30]–[32] showed better performance (faster response) using static stimuli compared to dynamic stimuli, others reported the opposite [33], [34]. Systems that present directions covering 360 degrees around the body (e.g., 12 directions) with a small number of tactors have not been investigated. In addition, vibrotactile stimuli may be masked by body vibrations (e.g., in a vibrating environment such as a helicopter cockpit) [35], [36]. Although Erp et al. [2] did a case study of tactile navigation in actual helicopter cockpit, they did not evaluate the recognition accuracy of directional indications and reaction time to static and dynamic stimuli.

We created a combination of static and dynamic vibrotactile stimuli that presents 12 directions using 6 tactors and quantitatively evaluate the recognition accuracy of those directional indications and their reaction time to the stimuli for a larger number of subjects in a vibrating environment.

This research was supported by an Overseas Research Fellowship from the Japan Society for the Promotion of Science (JSPS) and Small Business Innovation and Research (SBIR) grant W81XWH21C0051 through the Defense Health Agency and technical point of contact, Dr. Christopher Brill, through the Air Force Research Laboratory. The views expressed in this paper are those of the authors and do not reflect the official views or policy of the Department of Defense or its Components. Mention of any specific commercial products, process, or service does not constitute or imply its endorsement, recommendation, or favoring by the United States Government, Department of Defense, or Department of Air Force.

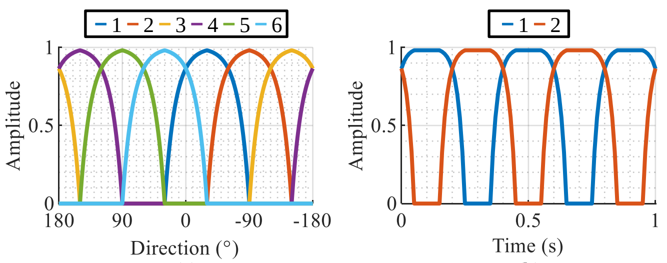
Ryo Eguchi, David Vacek, and Allison M. Okamura are with the Department of Mechanical Engineering, Stanford University, 424 Panama Mall, Stanford, CA 94305, USA (e-mail: eguchir;dvacek;aokamura@stanford.edu).

Cole Godzinski is with the Human Systems, Triton Systems, Inc., 330 Billerica Rd Suite 200, Chelmsford, MA 01824, USA (e-mail: cgodzinski@tritonsys.com).



(a) (b)

Fig. 1. (a) Belt with six tactors. (b) Top view of tactors and on-tactor/between-tactor directions for AB (Across Belly button) orientation. Inset shows the OB (On Belly button) alignment.



(a) (b)

Fig. 2. (a) Commanded vibration amplitudes as an exponential function of directional distance from target (AB orientation). (b) Amplitudes of two adjacent tactors are modulated over time for dynamic stimuli. The amplitudes of different tactors are represented by different colors.

We considered a helicopter because its vibration levels are very high compared to other vehicles (planes, trains, and cars) [37] and it requires 360-degree directional navigation with potentially poor visibility conditions (e.g., a dense fog).

II. Between-Tactor Display

A. Torso-Worn Tactile Belt

As shown in Fig. 1(a), six tactors were placed at equal intervals on an elastic belt. The belt is available in five sizes (their tactor intervals are from 12 to 17 cm). A microcontroller sends input voltage to each tactor as a PWM signal through a motor driver. As illustrated in Fig. 1(b), two belt orientations (AB: two tactors Across Belly button and OB: one tactor On Belly button) were examined in this study. The belt with both orientations presents 12 directions using 6 tactors. Directions on each tactor and between tactors are represented by vibrating a single tactor and two adjacent tactors, respectively. As shown in Fig. 2(a), the amplitude of tactor vibration is commanded as an exponential function of the angular distance from the target direction to the tactor direction and becomes zero at the direction of the neighboring tactor. This function ensures that vibrations of both tactors are sufficiently large to be perceived when the target is in between the two tactors.

B. Between-Tactor Display Algorithms

We compared static and dynamic stimuli for the between-tactor display. The static stimuli simultaneously vibrate the two tactors adjacent to the target direction with the same amplitude. The dynamic stimuli smoothly change the amplitude of two adjacent tactors to generate the sensation of moving vibration

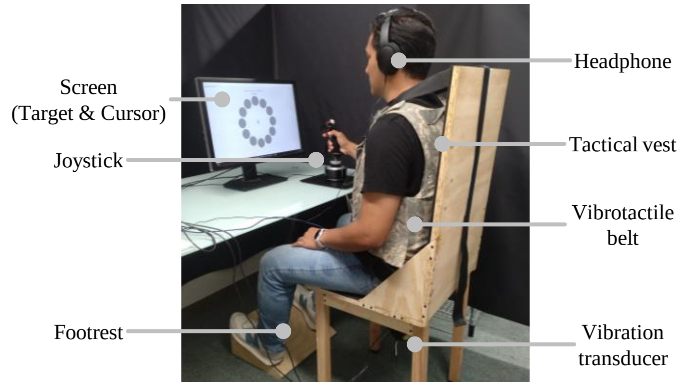


Fig. 3. Experiment setup. Participants wore the vibrotactile belt under a tactical vest and sat in a chair integrated with a strong vibration transducer. Using a joystick, users moved a cursor on a screen to indicate the perceived direction of the haptic cue. The headphones playing white noise were used only in Study II.

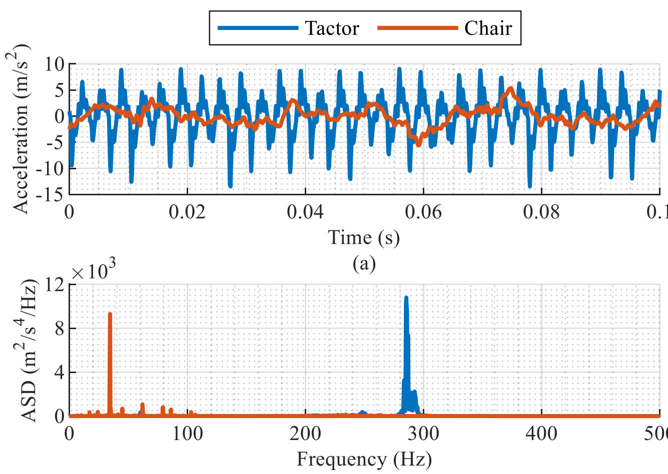


Fig. 4. (a) Time-series acceleration and (b) acceleration spectral density (ASD) for a tactor and the vibrating chair.

(e.g., illusory motion). As shown in Fig. 2(b), the duration for staying on each tactor and traveling between tactors were set to 100 ms (i.e., one cycle of the motion was 400 ms). We conducted a pilot study using the same tasks as the main studies and selected both temporal parameters through trial and error so that the users could recognize the dynamic stimuli and it did not significantly increase task completion time when compared to static stimuli. We also referred to a previous study [12], which reported that users improved tactor localization performance when both parameters were more than 100 ms. We displayed each direction using at most two adjacent tactors because this leaves other tactors free for other potential purposes, such as alerting about obstacles approaching in other directions. We aimed to investigate whether dynamic stimuli improve directional display compared to static stimuli in noisy vibrating environments. We conducted two studies as described in the following sections.

III. Study I: Effects of Vibration Location

AND ENVIRONMENTAL VIBRATION

A. Study Design

An experimental setup is shown in Fig. 3. The system included the vibrotactile belt, a laptop PC, a screen, and a joystick, and run at 100 Hz. The screen displayed gray targets in 6 or 12 directions equally distributed on a circle. The users wore the belt and a heavy tactical vest (to simulate military flight conditions) and sat in a chair. The chair was vibrated using a large transducer (ButtKicker Concert, Westerville, OH, US) on full power to produce environmental vibrations. Vibrations of tactors and chair were recorded using an accelerometer (Kistler 8614A, Winterthur, CH) at 10,000 Hz, and their root-mean-square (RMS) acceleration levels and power spectrum were analyzed using MATLAB (MathWorks, Natick, MA, US).

As shown in Fig. 4, RMS accelerations and the main frequency component of our vibrating chair were 1.81 $\mathrm{m/s^2}$ and 40 Hz, which are close to the vibration parameters noted in [37] and [38]. Leatherwood et al. [38] examined RMS acceleration levels of various helicopters and reported that the levels are up to 1.4 $\mathrm{m/s^2}$. Delcor et al. [37] reported acceleration levels in the majority of helicopters having three blades is usually less than 2 $\mathrm{m/s^2}$. They also mentioned that the helicopter's structure is such that some frequencies are filtered and the most important excitation occurs at the blade passing frequency, which varies between 15 and 30 Hz depending on the helicopter model. Due to limitations of the Buttkicker actuator used to vibrate the chair, the main frequency component of our vibrating chair was slightly higher than desired. On the other hand, the acceleration levels and frequency of the tactors in the belt were 3.97 $\mathrm{m/s^2}$ and 280 Hz. We selected a tactor vibration of 280 Hz because it was the natural frequency for the eccentric mass motors available for the study and close to the frequency used by Cholewiak et al. [25], which reported the localization accuracy of 92% using a belt with eight tactors vibrating at 250 Hz. Thus, there were differences in both vibration amplitude and frequency between vibrating environment and tactor.

In the study, participants were presented with 6 on-tactor and 6 between-tactor directions (real and virtual targets) by static and dynamic stimuli from the belt. Participants moved a cursor from the center of the screen to the perceived direction of the tactile cue using the joystick, and pressed the trigger when they reached the gray target corresponding to their choice of direction. The skill level required for the study was low, and participants practiced indicating directions with the joystick to familiarize them with the study task. We measured accuracy of the selected target direction and the task completion time, measured as the duration from commanding the stimuli to clicking the trigger on the target. We investigated the effects of number of targets (6 vs. 12) and types of stimuli for between-tactor display (static vs. dynamic) under two belt orientations (AB vs. OB) and with vs. without chair vibration. Participants completed 12 sessions using different combinations of the conditions A–C and 3 sessions of condition D, where the conditions were as follows.

- A: Two belt orientations (AB vs. OB)
- B: 6 on-tactor targets or 12 targets with static or dynamic between-tactor stimuli (6 vs. 12-S vs. 12-D)
- C: On or Off chair vibration (NoVib vs. Vib)
- D: Visual cues (no haptics) for 6 target directions with two alignments and 12 targets (6-AB vs. 6-OB vs. 12)

In condition D (using vision instead of haptics), the target was indicated on the screen by changing color (from gray to blue) instead of using tactor vibration. The goal of this visual condition was to measure a baseline task completion time (the duration from receiving stimuli to clicking targets). All possible types of target alignment were used: 6 targets with AB alignment, 6 targets with OB alignment, and all 12 targets. To determine the order of sessions, conditions A and D were pseudo-randomized and then condition B was pseudo-randomized within each value of the A condition. The chair vibration (C) was switched on/off in alternate sessions because of the limited continuous operating time of the transducer mounted on the chair. In each session, each target direction was presented for five trials and their order was pseudo-randomized.

Twenty-nine student participants (12 male, 27.7$\pm$10.5 yrs, 168.4$\pm$10.7 cm, 67.7$\pm$15.6 kg) were recruited for the experiment. We did not expect a large difference between our participants and expert helicopter pilots because both groups needed to become familiar with the haptic belt and indicating a perceived direction via the joystick. The study was approved by Stanford University (IRB-62374) and all participants provided informed consent prior to the experiment. Participants took breaks between sessions and the study took about 1.5 hours in total.

B. Results

Recognition accuracy and task completion time were averaged for each target direction for all participants, and the results are shown in Fig. 5. Accuracy was lower for targets further away from the belly button and spine (called anchor points in [25]). Completion time was longer on virtual (between-tactor) targets compared to real (on-tactor) targets. Performances averaged over all target directions and box plots indicating the median and lower and higher quartiles are shown in Fig. 6. These results show that both accuracy and completion time were better for 6 targets compared to 12 targets; performances for 6 targets were similar to the vision condition. Dynamic stimuli (12-D) resulted in higher accuracy than static stimuli (12-S). We did not observe normality of data for both recognition accuracy and task completion time using a Lilliefors test. Thus, we did a Kruskal-Wallis test and multiple comparisons test with Bonferroni method, which can be applied for non-parametric statistics. Fig. 7 shows the results of statistical analysis comparing static and dynamic stimuli under the other three conditions. Asterisks describe significant differences ($*$: $p < 0.05$, $**$: $p < 0.01$, and $***$: $p < 0.001$). 12-D accuracy was significantly higher than 12-S on both real and virtual targets, under both NoVib and Vib conditions, and AB and OB belt orientations ($p < 0.01$). Completion time was significantly shorter for real targets compared to virtual targets ($p < 0.001$). There was no significant difference in accuracy or time between AB and OB.

This article has been accepted for publication in IEEE Transactions on Haptics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TOH.2023.3304953

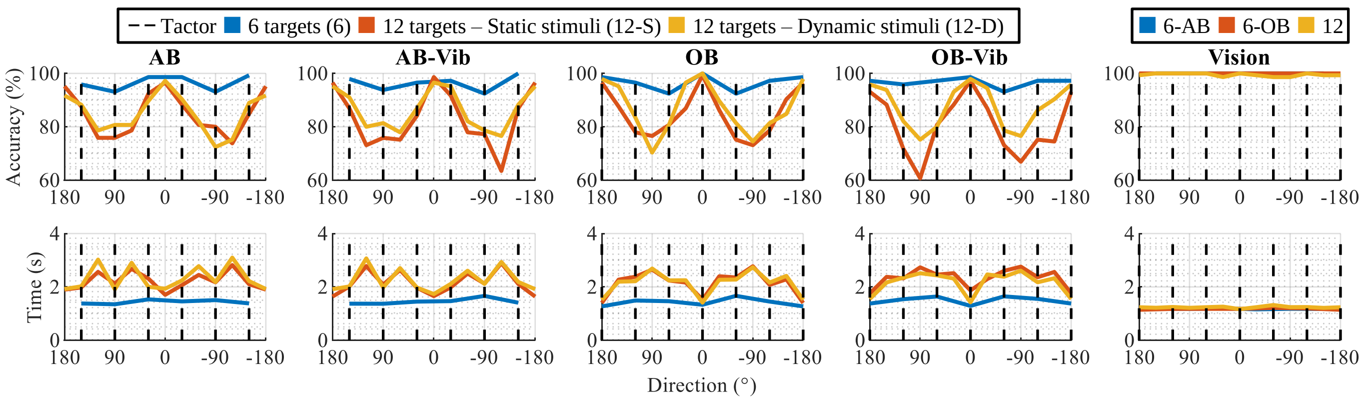


Fig. 5. Results of Study I, averaged for each target direction under AB and OB belt orientations with/without chair vibration.

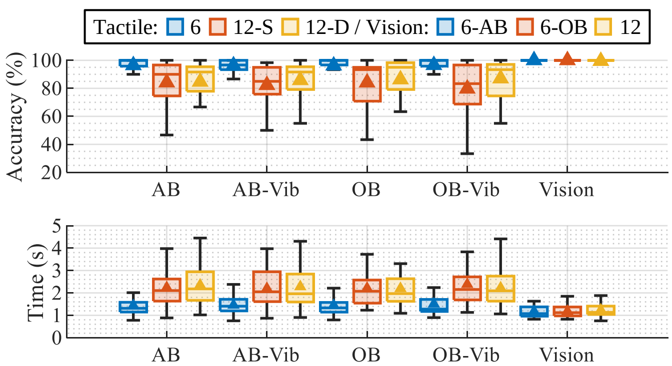


Fig. 6. Recognition accuracy and task completion time averaged over all target directions for AB and OB belt orientations with/without chair vibration for Study I.

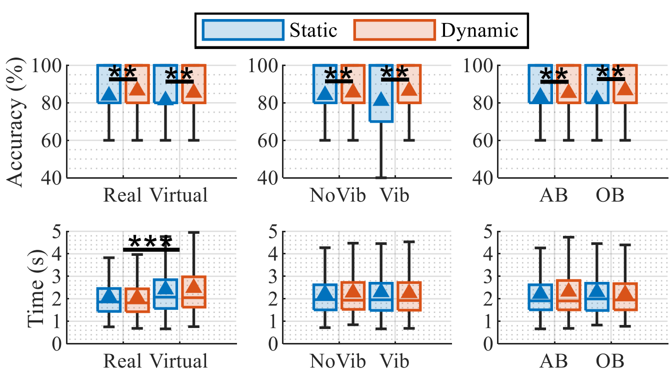


Fig. 7. Results of statistical analysis (Bonferroni's multiple comparisons test) comparing various conditions under static and dynamic stimuli for Study I.

There were two possible confounds in Study I. First, the better performance of 12-D compared to 12-S might have been due to participants hearing the vibration sounds of the tactors. Thus, we designed a follow-on study (Study II) to test whether the vibration sounds had an effect. Second, because we changed the belt orientation halfway through the experiment, participants had to re-map the relationship between tactor location and target direction. Because there was no significant difference between the AB and OB tactor alignments in Study I, we used only the AB alignment in Study II. This eliminated the need for participants to re-learn mappings and allowed us to study learning curves.

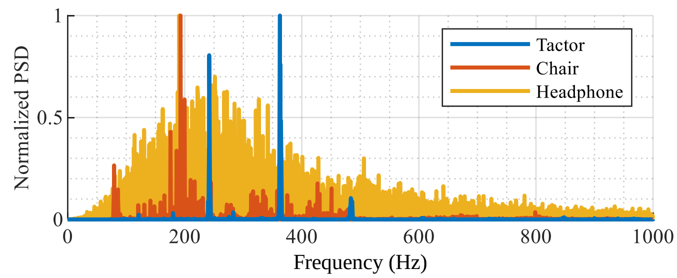


Fig. 8. Normalized power spectrum density (PSD) of vibration sound for a tactor, the vibrating chair, and white noise played through the headphones.

IV. Study II: Auditory Effects and Learning Curves

A. Study Design

The setup shown in Fig. 3 was also used for this study. The users wore headphones (Bose QuietComfort, Framingham, MA, US) playing white noise with sufficient volume to mask the sound of the tactors. The vibration sounds of the tactor and chair were recorded using a USB microphone (Snowball, Blue Microphones, Westlake Village, CA, US) and their power spectrum were analyzed using FFT together with noise sound data played by the headphones. The results of normalized power are shown in Fig. 8. The result shows that the tactor sound had a higher frequency compared to the chair, and headphone sound covers both frequency bands of tactor and chair so the headphone can drown out other sounds by adjusting its amplitude (volume).

This study investigated effects of vibration environment and sound masking using headphones on between-tactor display performance. Participants completed 12 sessions combining the conditions A–C and 3 sessions of condition D, where the conditions were as follows.

A: With or Without Headphone (NoHP vs. HP)
B: 6 targets or 12 targets with static or dynamic stimuli (6 vs. 12-S vs. 12-D)
C: On or Off chair vibration (NoVib vs. Vib)
D: Vision with 6 tactors with AB alignment (executed twice) or 12 tactors (6-AB vs. 6-AB vs. 12)

Similar to Study I, the order of conditions A and D were pseudo-randomized and then condition B was pseudo-randomized within each value of condition A. The chair

This article has been accepted for publication in IEEE Transactions on Haptics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TOH.2023.3304953

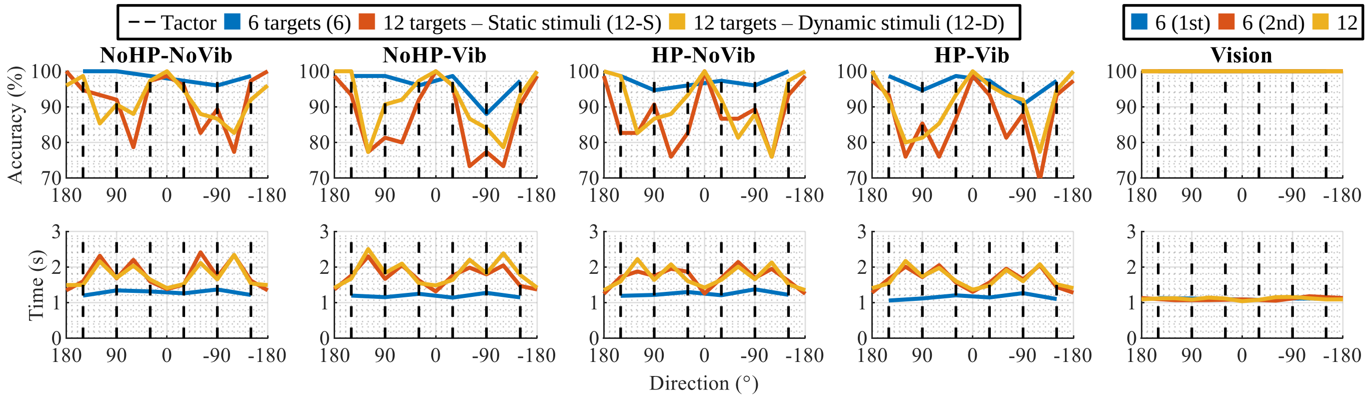


Fig. 9. Results for Study II, averaged for each target direction for conditions with/without headphone and with/without chair vibration.

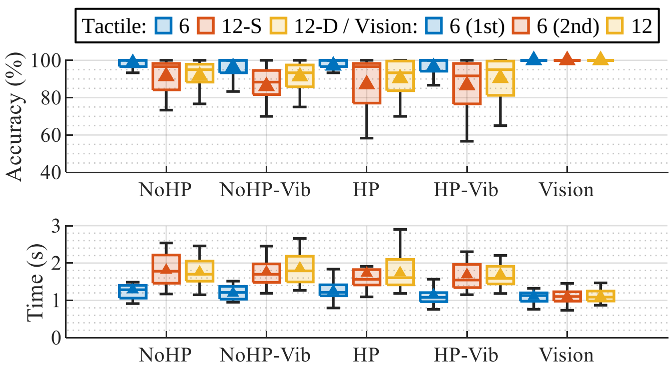


Fig. 10. Recognition accuracy and task completion time averaged over all target directions for conditions with/without headphone and chair vibration for Study II.

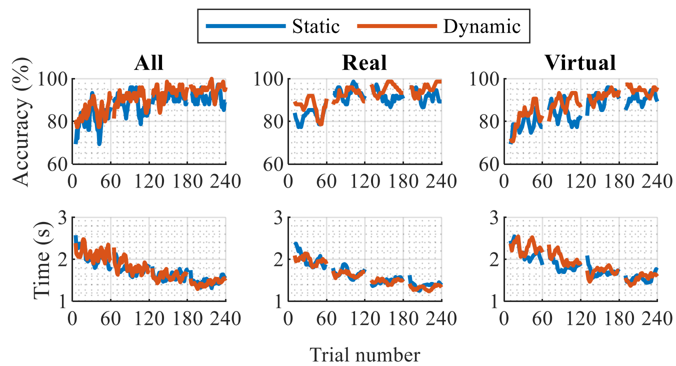


Fig. 12. Learning curves of recognition accuracy and time for Study II. Results are means of moving average of five trials for all participants in 12 sessions combining conditions A–C.

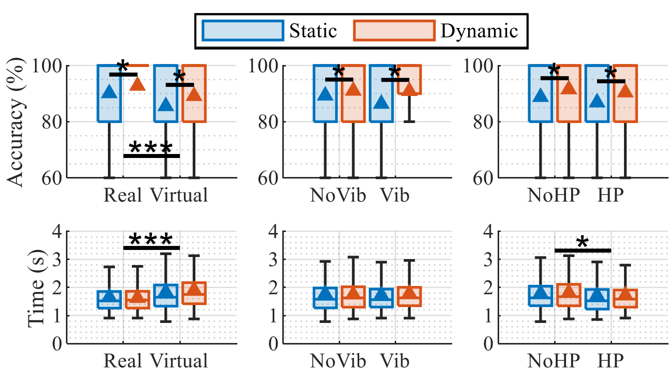


Fig. 11. Results of statistical analysis comparing various conditions under static and dynamic stimuli for Study II.

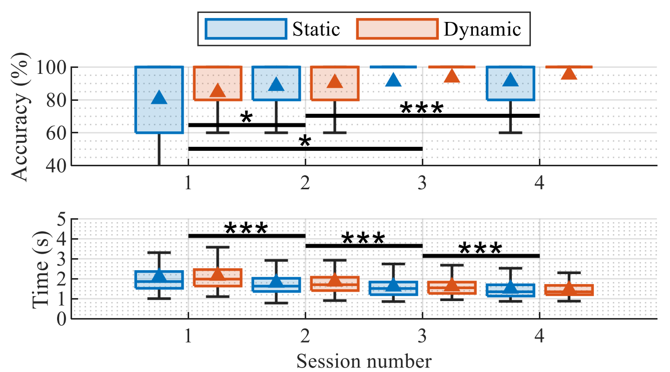


Fig. 13. Results of statistical analysis comparing mean results of four sessions for Study II.

vibration (C) was switched on/off in alternate sessions. In each session, each direction was presented for five trials, and their order was pseudo-randomized. Fifteen student participants (7 male, 24.3±3.9 yrs, 1.71±0.11 m, 67.1±14.3 kg) recruited for this study. The study was approved by Stanford University (IRB-62374) and all participants provided informed consent prior to the experiment. Participants took breaks between sessions and the study took about 1.5 hours in total.

B. Results

Recognition accuracy and task completion time were averaged for each target direction for all participants, and the results are shown in Fig. 9. Results averaged over all target directions and box plots indicating the median and lower and higher quartiles are shown in Fig. 10. The results show the same performance trends as Study I for comparisons between 6 and 12 targets, 12-S and 12-D, anchor points and other points, and real and virtual targets. As in Study I, we did not observe normality of data for both recognition accuracy and task completion time using a Lilliefors test. Thus, we did a Kruskal-Wallis test and multiple comparisons test with the Bonferroni method. Fig. 11 shows results of statistical analysis comparing static and dynamic stimuli under other three conditions. Asterisks describe significant differences ($*$: $p < 0.05$, $**$: $p < 0.01$, and $***$: $p < 0.001$). The following three results are the same with Study I; (i) both accuracy and time were significantly improved in 6 targets compared to 12 targets, (ii) 12-D significantly improved accuracy on both real and virtual targets and under both NoVib and Vib conditions compared to 12-S ($p < 0.05$), (iii) both accuracy and time were significantly improved on real targets compared to virtual targets ($p < 0.001$). In addition to the above, the results show that 12-D improved accuracy compared to 12-S under both NoHP and HP conditions ($p < 0.05$), and noise from headphone (HP) significantly shortened time ($p < 0.05$).

The moving average of five trials averaged for all participants are shown in Fig. 12. Learning curves were found in both time and accuracy. Mean of 12-S and 12-D according to the number of session and results of statistical analysis are shown in Fig. 13. Significant improvements were found between sessions 1–2 ($p < 0.001$), 1–3 ($p < 0.001$), and 2–4 ($p < 0.05$) for accuracy and between sessions 1–2 ($p <$0.001), 2–3 ($p <$0.001), and 3–4 ($p < 0.05$) for time. 12-D slightly improved accuracy compared to 12-S in each session ($p = 0.075$).

V. Discussion

A vibrotactile belt with 6 tactors spread equally around the torso successfully displayed 12 target directions using a combination of on-tactor and between-tactor directions by using static and dynamic stimuli.

For Study I, Fig. 5 shows that performance decreased as directions were far from anchor points as previous works reported [25], [39]. Fig. 5 and 6 show that performance of 12 targets including real and virtual targets were decreased compared to 6 targets. This can be due to task complexity and difficulty in perceiving in-between targets. Fig. 7 shows that dynamic stimuli significantly improved accuracy (about 3%) compared to static stimuli regardless of real/virtual targets, environments with/without chair vibration, and AB/OB belt orientations while not prolonging task completion time.

For Study II, Figs. 9 and 10 show the same trends as Study I, and Fig. 11 shows that dynamic stimuli improved accuracy (about 3%) compared to static stimuli regardless of noise sound from headphone. These results indicate that dynamic stimuli is robust against noisy environments such as chair vibration and noise masking tactor sound, and its better performance compared to static stimuli was not due to auditory feedback. Task completion time was significantly shortened under noise sound (headphone condition). This suggests that the single mode (only vibrotactile) feedback might enhance response to the stimuli compared to multi-modal cueing including auditory feedback. While we cannot be certain of the reason, it may be due to the fact that single mode (only tactile) feedback reduces sensory information; the combination of auditory and tactile feedback may take longer time for the user to integrate in order to perceive the direction. Yang et al. [40] proposed a system notifying timing of cross-lane-turning to vehicle drivers and examined reaction time for combination of haptic and auditory cueing. They observed that the reaction time did not reduce significantly when using both the haptic and auditory feedback compared to only haptic feedback. This result suggests that the combination of haptic and auditory feedback does not shorten reaction time and there is rather a possibility that the combination prolongs time in more complicated tasks (e.g., choosing direction).

Figs. 12 and 13 show that both accuracy and time improved as the number of sessions increased, and the learning curves did not all reach a plateau. These results indicate that a 12-target display might be as accurate as a 6-target display if a user undergoes sufficient training. Higher accuracy of dynamic stimuli compared to static stimuli in all sessions show that the dynamic stimuli can enhance accuracy while maintaining time.

Under all conditions of both studies, dynamic stimuli showed about 3% improvement of recognition accuracy compared to static stimuli. A previous study [12] reported that localization performance increases when Burst Duration (BD, defined as the time between the onset and the end of a burst) and Stimulus Onset Asynchrony (SOA, defined as the time between the onsets of two bursts) increase. The dynamic stimuli had a BD of 100 ms and an SOA of 100 ms in our study. Increasing these parameters could increase accuracy but lengthen completion time.

A previous study [36] reported that tactile vibration stimuli are masked by similar frequencies. Meanwhile, the results indicate that tactile cueing was not masked in our case, where there were differences in both vibration amplitude and frequency between vibrating environment and tactor. Future research will examine what frequency and amplitude of tactor vibration is the lowest perceivable. These are helpful for examining effective settings for tactile helicopter pilot navigation. In future work, we will also examine different combinations of BD and SOA for dynamic stimuli to improve recognition accuracy while maintaining task completion time. We will also enhance resolution of displayed direction by spatio-temporal information augmentation, such as changing the BD between adjacent tactors for displaying quartile directions. These methods will be validated in environments with vibration and noise. In addition, after refining the approach and integrating it with a flight simulator, we plan to test this direction feedback approach with expert pilots.

References

[1] L. Lutnyk, D. Rudi, E. Meier, P. Kiefer, and M. Raubal, “Flybrate: Evaluating vibrotactile cues for simulated flight,” *International Journal of Human–Computer Interaction*, pp. 1–18, 2022.

[2] J. B. V. Erp, H. A. V. Veen, C. Jansen, and T. Dobbins, “Waypoint navigation with a vibrotactile waist belt,” *ACM Transactions on Applied Perception*, vol. 2, no. 2, pp. 106–117, 2005.

[3] S. M. Kärcher, S. Fenzlaff, D. Hartmann, S. K. Nagel, and P. König, “Sensory augmentation for the blind,” *Frontiers in Human Neuroscience*, vol. 6, p. 37, 2012.

[4] J. V. Durá-Gil, B. Bazuelo-Ruiz, D. Moro-Pérez, and F. Mollà-Domenech, “Analysis of different vibration patterns to guide blind people,” *PeerJ*, vol. 5, p. e3082, 2017.

[5] M. Sun, W. He, L. Zhang, P. Wang, S. Wang, and X. Bai, “Haptic compass: Active vibrotactile feedback of physical object for path guidance,” in *IEEE Conference on Virtual Reality and 3D User Interfaces*, 2019, pp. 1171–1172.

[6] B. Hans and L. Moccozet, “Vibrotactile feedback models to explore virtual reality without going round in circles,” in *25th International Conference Information Visualisation*, 2021, pp. 137–142.

[7] S. Panëels, M. Anastassova, S. Strachan, S. P. Van, S. Sivacoumarane, and C. Bolzmacher, “What's around me? Multi-actuator haptic feedback on the wrist,” in *World Haptics Conference*, 2013, pp. 407–412.

[8] M. Ogrinc, I. Farkhatdinov, R. Walker, and E. Burdet, "Sensory integration of apparent motion speed and vibration magnitude," *IEEE Transactions on Haptics*, vol. 11, no. 3, pp. 455–463, 2018.

[9] S. Schaack, G. Chernyshov, K. Ragozin, B. Tag, R. Peiris, and K. Kunze, "Haptic collar: Vibrotactile feedback around the neck for guidance applications," in *Proceedings of the 10th Augmented Human International Conference*, 2019, pp. 1–4.

[10] Y. Salzer, T. Oron-Gilad, A. Ronen, and Y. Parmet, "Vibrotactile "on-thigh" alerting system in the cockpit," *Human Factors*, vol. 53, no. 2, pp. 118–131, 2011.

[11] Z. Liao, J. V. S. Luces, and Y. Hirata, "Human navigation using phantom tactile sensation based vibrotactile feedback," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 5732–5739, 2020.

[12] J. van Erp, "Vibrotactile spatial acuity on the torso: effects of location and timing parameters," in *World Haptics Conference*, 2005, pp. 80–85.

[13] L. A. Jones, B. Lockyer, and E. Piateski, "Tactile display and vibrotactile pattern recognition on the torso," *Advanced Robotics*, vol. 20, no. 12, pp. 1359–1374, 2006.

[14] L. A. Jones and K. Ray, "Localization and pattern recognition with tactile displays," in *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2008, pp. 33–39.

[15] B. Wahn and P. König, "Vision and haptics share spatial attentional resources and visuotactile integration is not affected by high attentional load," *Multisensory Research*, vol. 28, no. 3-4, pp. 371–392, 2015.

[16] Y. Salzer, T. Oron-Gilad, and A. Henik, "Evaluation of the attention network test using vibrotactile stimulations," *Behavior Research Methods*, vol. 47, no. 2, pp. 395–408, 2015.

[17] L. E. Grierson, J. Zelek, and H. Carnahan, "The application of a tactile way-finding belt to facilitate navigation in older persons," *Ageing International*, vol. 34, no. 4, pp. 203–215, 2009.

[18] G. Paolocci, T. L. Baldi, L. Sampieri, and D. Prattichizzo, "Design and comparison of haptic policies for human guidance," in *IEEE Haptics Symposium*, 2022, pp. 1–8.

[19] B.-C. Lee, A. Ho, B. J. Martin, and K. H. Sienko, "Effects of co-vibrotactile stimulations around the torso on non-volitional postural responses," in *Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2012, pp. 6149–6152.

[20] B. J. Martin, B.-C. Lee, and K. H. Sienko, "A cutaneous positioning system," *Experimental Brain Research*, vol. 233, no. 4, pp. 1237–1245, 2015.

[21] E. Faugloire and L. Lejeune, "Evaluation of heading performance with vibrotactile guidance: The benefits of information–movement coupling compared with spatial language." *Journal of Experimental Psychology: Applied*, vol. 20, no. 4, p. 397, 2014.

[22] Q. Ouyang, J. Wu, Z. Shao, and D. Chen, "A vibrotactile belt to display precise directional information for visually impaired," *IEICE Electronics Express*, vol. 15, no. 20, pp. 1–11, 2018.

[23] F. Hao and A.-g. Song, "Design of a wearable vibrotactile display waist belt," in *IEEE 8th World Congress on Intelligent Control and Automation*, 2010, pp. 5014–5017.

[24] J. Yu, M. Reyes Adame, and K. Möller, "A vibrotactile assistive system for directional navigation," *Biomedical Engineering/Biomedizinische Technik*, vol. 58, no. SI-1-Track-P, p. 000010151520134395, 2013.

[25] R. W. Cholewiak, J. C. Brill, and A. Schwab, "Vibrotactile localization on the abdomen: Effects of place and space," *Perception & psychophysics*, vol. 66, no. 6, pp. 970–987, 2004.

[26] S. M. Weisberg, D. Badgio, and A. Chatterjee, "Feel the way with a vibrotactile compass: Does a navigational aid aid navigation?" *Journal of Experimental Psychology: Learning, Memory, and Cognition*, vol. 44, no. 5, p. 667, 2018.

[27] C. Brandebusemeyer, A. R. Luther, S. U. König, P. König, and S. M. Kärcher, "Impact of a vibrotactile belt on emotionally challenging everyday situations of the blind," *Sensors*, vol. 21, no. 21, p. 7384, 2021.

[28] R. Kessler, M. Bach, and S. P. Heinrich, "Two-tactor vibrotactile navigation information for the blind: Directional resolution and intuitive interpretation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 25, no. 3, pp. 279–286, 2017.

[29] L. Vargas, H. H. Huang, Y. Zhu, and X. Hu, "Static and dynamic proprioceptive recognition through vibrotactile stimulation," *Journal of Neural Engineering*, vol. 18, no. 4, p. 046093, 2021.

[30] Z. Xiong and X. Huang, "Comparison of the static and dynamic vibrotactile interactive perception of walking navigation assistants for limited vision people," *IEEE Access*, vol. 10, pp. 42 261–42 267, 2022.

[31] S. M. Petermeijer, J. C. F. de Winter, and K. J. Bengler, "Vibrotactile displays: A survey with a view on highly automated driving," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 4, pp. 897–907, 2016.

[32] S. M. Petermeijer, S. Cieler, and J. C. De Winter, "Comparing spatially static and dynamic vibrotactile take-over requests in the driver seat," *Accident Analysis & Prevention*, vol. 99, pp. 218–227, 2017.

[33] C. Ho, R. Gray, and C. Spence, "Reorienting driver attention with dynamic tactile cues," *IEEE Transactions on Haptics*, vol. 7, no. 1, pp. 86–94, 2014.

[34] F. Meng, R. Gray, C. Ho, M. Ahtamad, and C. Spence, "Dynamic vibrotactile signals for forward collision avoidance warning systems," *Human Factors*, vol. 57, no. 2, pp. 329–346, 2015.

[35] P. Kowalski and J. Zając, "Research on simultaneous impact of hand–arm and whole-body vibration," *International Journal of Occupational Safety and Ergonomics*, vol. 18, no. 1, pp. 59–66, 2012.

[36] M. Morioka and M. J. Griffin, "Masking of thresholds for the perception of fore-and-aft vibration of seat backrests," *Applied Ergonomics*, vol. 50, pp. 200–206, 2015.

[37] L. Delcor, E. Parizet, J. Ganivet-Ouzeneau, and J. Caillet, "Perceived discomfort for typical helicopter vertical sine vibrations for seated participants," *Journal of Low Frequency Noise, Vibration and Active Control*, vol. 40, no. 3, pp. 1661–1667, 2021.

[38] J. D. Leatherwood, S. A. Clevenson, and D. D. Hollenbaugh, "Evaluation of ride quality prediction methods for helicopter interior noise and vibration environments. nasa tp-2261," AVSCOM TR 84-D-2, Tech. Rep., 1984.

[39] J. B. Van Erp, "Presenting directions with a vibrotactile torso display," *Ergonomics*, vol. 48, no. 3, pp. 302–313, 2005.

[40] B. Yang, T. Obana, Z. Wang, T. Kaizuka, T. Sugimachi, T. Sakurai, T. Maki, and K. Nakano, "Evaluations of different human machine interfaces for presenting right-turn timing at intersections," *International Journal of Intelligent Transportation Systems Research*, vol. 19, pp. 71–82, 2021.