Mid-Air Tactile Feedback Co-Located With Virtual Touchscreen Improves Dual-Task Performance

Georgios Korres, Said Chehabeddine, and Mohamad Eid

***Abstract*—The use of haptic technology has recently become essential in Human-Computer Interaction to improve performance and user experience. Mid-air tactile feedback co-located with virtual touchscreen displays have a great potential to improve the performance in dual-task situations, such as when using a phone while walking or driving. The purpose of this article is to investigate the effects of augmenting virtual touchscreen with mid-air tactile feedback to improve dual-task performance where the primary task is driving in a simulation environment and the secondary task involves interacting with a virtual touchscreen. Performance metrics included primary task performance in terms of velocity error, deviation from the middle of the road, number of collisions, and the number of off-road glances, secondary task performance including the interaction time and the reach time, and quality of user experience for perceived difficulty and satisfaction. Results demonstrate that adding mid-air tactile feedback to virtual touchscreen resulted in statistically significant improvement in the primary task performance (the average speed error, spatial deviation, and the number of off-road glances), the secondary task (reach time), and the perceived difficulty. These results provide a great motivation for augmenting virtual touchscreens with mid-air tactile feedback in dual-task human-computer interaction applications.**

***Index Terms*—Evaluation/methodology, mid-air tactile stimulation, psychology, user-centered design, virtual touchscreen.**

I. Introduction

Virtual touchscreen display utilizes a transmissive mirror to display a screen floating in front of the mirror (where the actual screen is behind the mirror) and a sensor to detect finger motion in order to control the screen interaction [1]. With an ever increasing complexity of in-vehicle infotainment systems, virtual touchscreen technologies have great potential to limit bio-mechanical interference, which is the action when the driver moves out of his/her natural driving position to reach for buttons, dials, and other car controls and thus reduces the driver's ability to control the car [2], [3]. Indeed, car manufacturers are exploring virtual touchscreen technology for their next generation cars (e.g. HoloActive Touch from BMW). However, one fundamental challenge in these technologies is the lack of tactile feedback when the user interacts with the screen.

Due to the fact that in-vehicle control involves performing dual-tasks (primary being driving and secondary being the interaction with the infotainment system), haptic feedback is well suited to reduce cognitive load [4], [5]. Previous studies showed that adding tactile feedback to a visual secondary task on a touchscreen significantly decreases distraction from a primary task (driving) [6]. Furthermore, studies in multitasking performance have utilized haptic sensation as an associative cue in order to improve the activation of a primary task [7]. When an associative cue and a primary task co-occur, a link establishes between the two that eventually activate the primary task following the presentation of the associative haptic cue [8]. For instance, Prewett and colleagues demonstrated that using vibrotactile cue as an alert message is more effective than using a visual cue when the primary task is visual [7]. Similarly, Lu *et al.* showed that interruption of a primary visual task with a secondary haptic task resulted in enhanced performance compared to when both primary and secondary tasks were visual [9]. This demonstrates the potential of tactile feedback in improving performance in dual-task situations.

Mid-air tactile stimulation technologies use three fundamentally different approaches: (1) Air-Jet [10], [11], (2) ultrasound [12], [13], and (3) laser [14]. Ultrasonic tactile stimulation seems the most studied approach due to its ability to generate relatively high-resolution tactile displays in 3D space [15]. Ultrasonic tactile stimulation involves using 2D array of ultrasound transducers to focus ultrasound beams in one or more focal points to produce localized acoustic pressure that human can feel [16]. Recent studies have explored co-located mid-air tactile-visual display technologies [17]–[19] in order to enhance interaction with virtual touchscreen technologies.

This study focuses on examining the effects of adding mid-air tactile feedback to a virtual touchscreen display in order to improve primary task (driving) and secondary task (interacting with the in-vehicle infotainment system) performance as well as quality of user experience. The remainder of the paper is organized as follows. Section II analyzes the related work for mid-air tactile feedback for in-vehicle dual-task control. Section III presents the experimental methods and materials. In section IV, the results are presented and thoroughly analyzed. Section V presents a general discussion about the results. Finally, section VI summarizes the findings and provides directions for future work.

Manuscript received November 5, 2019; revised December 23, 2019; accepted January 29, 2020. Date of publication February 10, 2020; date of current version December 21, 2020. This paper was recommended for publication by Associate Editor V. Levesque and Editor-in-Chief Lynette Jones upon evaluation of the reviewers' comments. *(Corresponding author: Mohamad Eid.)*

The authors are with the Engineering Division, New York University Abu Dhabi, Abu Dhabi 129188, United Arab Emirates (e-mail: george.korres@nyu.edu; sc7388@nyu.edu; mohamad.eid@nyu.edu).

Digital Object Identifier 10.1109/TOH.2020.2972537

II. Related Work

Multimodal interaction for in-vehicle infotainment systems, such as audio, visual, and haptic media is well studied [20]. Previous studies demonstrated that visual-haptic combination significantly decreases distraction from the primary task of driving [6] and seems more effective during a task requiring a heavy cognitive load [21]. Therefore, this study focuses on visual-haptic interaction to improve dual-task performance.

There has been several studies on the incorporation of haptic interaction for driving assistance and warning, such as controlling car functions [22], maneuvering support and guidance [23], emergency warning [24], enhanced awareness of surroundings [25], preventing collisions [26], lane change guidance [27], and speed control [28]. These studies show that haptic interaction increases a driver's performance and safety [20].

Mid-air tactile feedback is also studied to enhance automotive user interfaces. Pitts *et al.* experimented to see if decreasing visual workload by adding a haptic element would enhance driving safety [29]. A primary task (driving) and a secondary task (touchscreen interaction) were examined. Participants were asked to perform touchscreen tasks while engaged in driving simulation. Results showed a reduction of task completion time and an improvement in user experience with mid-air tactile feedback. A recent study explored the use of mid-air tactile feedback, along with gesture control, to enhance automotive user interfaces [2]. The mid-air tactile interface was situated between the driver and passenger seat. The primary task was following a vehicle in the simulation environment, while the secondary task was interacting with the in-vehicle touchscreen. The study found that coupling gestures with mid-air tactile feedback reduce visual demand required to complete the secondary task. A similar study examined the impact of complementing gesture control of infotainment system with mid-air tactile feedback in a simulated driving environment [30]. Results demonstrated that mid-air tactile feedback decreased the eyes-off-the-road time (EORT) compared to visual feedback while not compromising driver performance. To the best of our knowledge, the effectiveness of co-located mid-air tactile feedback with virtual touchscreen in a dual-task driving simulation was never explored. The following hypotheses are examined in this study:

(i) Mid-air tactile feedback co-located with virtual touchscreen significantly improves the primary task performance compared to the condition when no tactile feedback is applied,

(ii) Mid-air tactile feedback co-located with a virtual touchscreen significantly improves the secondary task performance of interacting with the virtual touchscreen while driving as compared to no tactile feedback,

(iii) Mid-air tactile feedback co-located with virtual touchscreen improves the overall quality of user experience, in the form of user satisfaction and perceived difficulty, as compared to no tactile feedback.

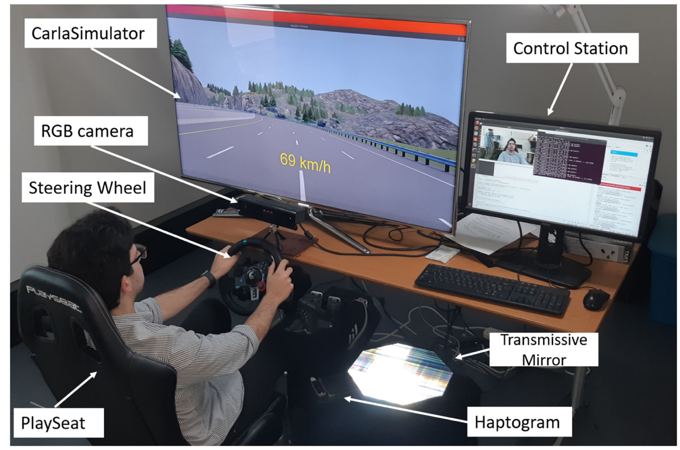

Fig. 1. Experimental setup.

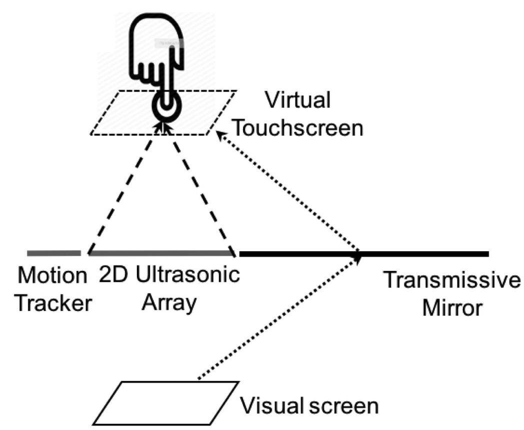

Fig. 2. Schematic diagram of the Haptogram system.

III. Methods and Materials

A. Experimental Setup

Fig. 1 shows the experimental setup used in this study. The setup is composed of the PLAYSEAT driving simulation seat, a Logitech G29 steering wheel and pedals, a 55 inch TV screen, a Kinect camera for head tracking and the Haptogram system [18] to provide co-located mid-air tactile-visual touchscreen interaction with the driver. The driving simulation is designed to create a realistic driving track seen on the large TV screen to allow participants to immerse themselves in the experience. The Kinect camera is used to track the head position/orientation while driving.

A schematic diagram of the Haptogram system is shown in Fig. 2. The Haptogram system consists of three components: mid-air virtual touchscreen display, a 2D array of ultrasound transducers for mid-air tactile display, and a hand/finger tracker [18]. The mid-air virtual touchscreen consists of a visual screen located underneath an Aerial Imaging (AI) mirror at 45° so a floating 2D image is displayed in mid-air on top of the screen. The ultrasound tactile display consists of a 10×10 2D array of ultrasound transducers. The hand tracking device is the commercially available LEAP motion sensor [2]. An open-source driving simulator named CARLA was used to implement

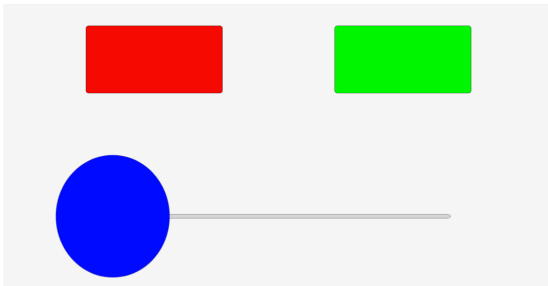

Fig. 3. Graphical user interface for the secondary task (red and green rectangles represent buttons and the blue circle represents a slider).

the driving simulation [31]. CARLA supports development, training, and validation of urban driving systems and is widely used in research to simulate realistic urban driving experience. A single-lane track is utilized in the simulation where the vehicle is controlled with automatic transmission.

B. Participants

A group of thirty subjects (13 females, average age of 20.6 years old) participated in this study, all of which are New York University Abu Dhabi students. The inclusion criterion for participants was an age range of 18-55 years old. The study was carried out with an approved protocol by New York University Abu Dhabi Institutional Review Board (FWA: #022-2019). Having a driving experience was not an inclusion criterion since the objective of this study was to examine the role of mid-air tactile feedback to improve dual-task performance of virtual touchscreen display where interacting with a touchscreen.

C. Experimental Procedure

The experimental study involved participants completing multiple rounds in which they performed two tasks: (1) a primary task of completing a track while maintaining a constant speed of 80 km/h (the speed was displayed on the screen, giving participants continuous visual feedback about their current speed), (2) perform two secondary tasks of interacting with the virtual touchscreen, with or without tactile feedback. The secondary task involves interaction with a virtual touchscreen having two buttons (colored in red and green) and a slider (blue circle), as shown in Fig. 3. The user was prompted to click the red or green button in one task and strike the slider from one side to the other for the other task. Upon clicking the button, its color brightness was reduced by 50% to provide the user with visual feedback about the click event. As for the slider, the circular tick mark movement along the sliding direction was the only visual feedback provided. Note that the same visual feedback is provided for the two conditions of the secondary task (with or without tactile feedback).

The tactile feedback was provided at the tip of the index finger in the form of a focal point of acoustic pressure with a diameter of approximately 10 mm, force intensity of 2.49 mN, and a vibration frequency of 250 Hz. The ultrasonic array provides a single on-off tactile feedback whenever a button is clicked. As for the slider, a continuous and moving tactile feedback is

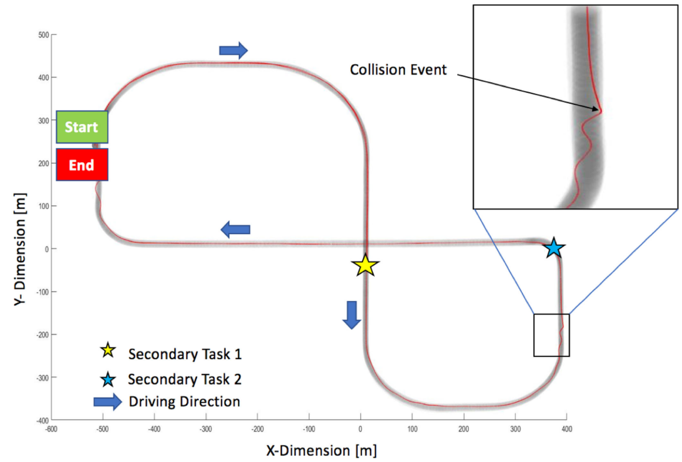

Fig. 4. A sample run of the driving track. Secondary task 1 involves swiping the slider whereas the secondary task 2 involves clicking the button (with or without tactile feedback). A single-lane road is utilized where a collision event is recorded upon contact between the car and the roadsides.

provided as the user's finger strikes along the sliding direction. Participants received auditory instructions on when they need to perform the secondary task (randomized along the driving task).

The study's procedure was as follows: After signing a consent form, participants were asked to sit in the car seat, which was adjusted to their height if needed. The Kinect camera was placed in front of them to record head movements and perform head calibration. Participants had to look at all four corners of the screen while slowly rotating their heads. They were then given two driving training sessions and shown how to accelerate, reverse, brake, and turn the wheel for 10 minutes. The last calibration step undertaken consisted of familiarizing participants with the Haptogram system (took around 10 minutes).

After completing the training, four runs were launched during which drivers were asked to perform two secondary tasks per track while driving (a sample driving run is shown in Fig. 4). The secondary task could be sliding the blue circle or pressing either the red or green buttons, with the first prompt and second prompt being unique. For each of these four runs, tactile feedback when performing the secondary task was either activated (T_ON) or deactivated (T_OFF). There were two main patterns run: T_ON, T_OFF, T_OFF, T_ON and T_OFF, T_ON, T_ON, T_OFF, with half of the participants doing one and the other half doing the other. After completing the four runs, participants completed an exit survey and were given a food voucher as compensation.

Data was collected using the Haptogram system, the Kinect camera, and the driving simulator. The driving simulator provided the timestamp, steering axis, coordinates of the car at a particular time, velocity, duration of collisions, and the task prompts. The Haptogram system gave the GUI data file which contains two variables labeled timestamp and task. Time is only recorded when the Leap Motion hand tracker is activated (when the subject's hand is in the workspace of the hand tracking device). The Kinect camera provided translations and rotations of head movements at every timestamp.

D. Analysis Metrics

The different metrics used for the analysis of the data set and their associated definitions are as follows:

- *Average Speed Error:* The error of the average speed of a round relative to the 80 km/h target.
- *Speed Variation:* The root mean square error of the speeds from 80 km/h per round.
- *Spatial Deviation:* The root mean square error from the recorded reference path (middle of the road).
- *Number of Collisions:* A collision is recorded when the car crashes into the road side barriers. In order to ignore constant collisions the collision counter was set inactive while a continuous collision was detected.
- *Number of Off-road Glances:* An off-road glance is detected when the time duration when a participant head orientation (indicating looking outside the screen) exceeds a threshold of 360 ms [32].
- *Task Reach Time:* The total time that took the participants to activate the secondary task from the time they were instructed from the driving simulator.
- *Task Interaction time:* The total time that each participant interacted with a secondary task (button or slider) from its first activation.
- *Task Difficulty:* Participants rated the difficulty of the task using a five-point Likert scale.
- *User Satisfaction:* User satisfaction is also evaluated using a five-point Likert scale.

Since the data for all the evaluation metrics did not follow a normal distribution (Kolmogorov-Smirnov normality test), the Wilcoxon signed-rank test was used for statistical analysis for the primary task performance and quality of experience rating. Furthermore, since the Wilcoxon signed-rank test gives a P value only and provides no straightforward estimate of the magnitude of the effect, the η^2 effect size test was utilized to estimate the magnitude of the significance. The secondary task metrics were analyzed using the Mann-Whitney U test since several data points were missing due to several incomplete secondary tasks.

IV. Results

A. Primary Task Performance

The performance of the primary task (driving) is evaluated using the average speed error and its variation, the spatial deviation, the number of collisions, and the number of off-road glances (distraction).

The average speed error, calculated as the average speed minus the reference speed (80 km/h), is shown in Fig. 5. The difference in the means for the average speed error between the two conditions (“Tactile On” and “Tactile Off”) was found to be statistically significant **($p < 0.01$)**, with the “Tactile On” condition having less error. The magnitude of this significance was found to be high with $\eta^2 = 0.22$.

In order to evaluate the driving stability, the Root Mean Square Error (RMSE) for the total speed variation as well as the spatial deviations were analyzed. As for the average speed

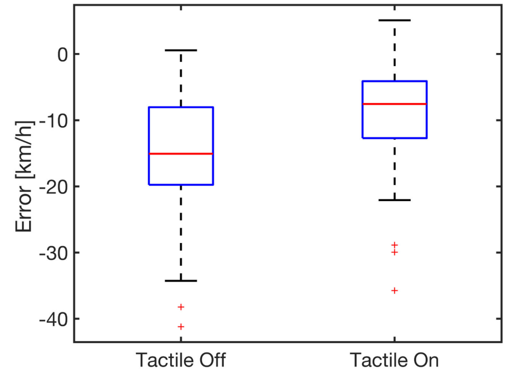

Fig. 5. Average speed error for the “Tactile Off” and “Tactile On” conditions.

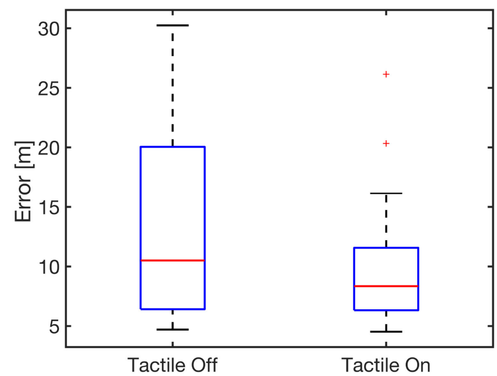

Fig. 6. Error for the car deviation from the middle of the road for both the “Tactile Off” and “Tactile On” conditions.

error, the difference was found to be statistically significant **($p < 0.01$)**, with the “Tactile On” condition having lower variations (high significance with $\eta^2 = 0.21$). Furthermore, the spatial deviation from the middle of the road was statistically smaller for the “Tactile On” condition compared to the “Tactile Off” condition **($p < 0.01$)**, as shown in Fig. 6. Furthermore, the deviation significance was found to be high ($\eta^2 = 0.13$).

Attention is evaluated based on the number of collisions and the number of off-road glances. As for the number of collisions, the difference between the “Tactile On” and “Tactile Off” conditions was found to be statistically significant **($p < 0.05$)**. Furthermore, the difference in the number of off-road glances between the “Tactile On” and “Tactile Off” conditions was found to be statistically significant **($p < 0.01$)**, with “Tactile On” condition showing smaller distraction. The significance of these differences were found to be high with $\eta^2 = 0.20$ for the number of collisions and $\eta^2 = 0.25$ for the off-road glances. These results demonstrate that tactile feedback enhanced attention to the primary task of driving.

B. Secondary Task Performance

The performance of the secondary task is evaluated based on the reach time and the interaction time, with the task interaction time evaluated separately for the button and the slider tasks. As mentioned in the previous section the samples were found to not be from normal distributions; however, unlike the

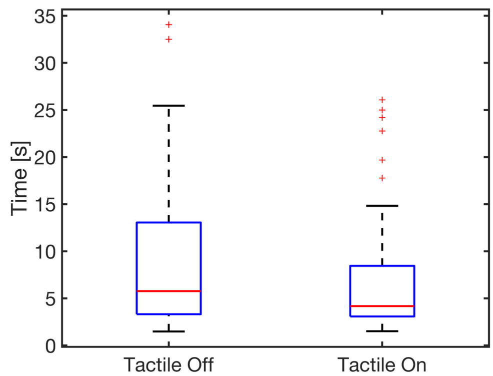

Fig. 7. Reach time for the "Tactile Off" and "Tactile On" conditions.

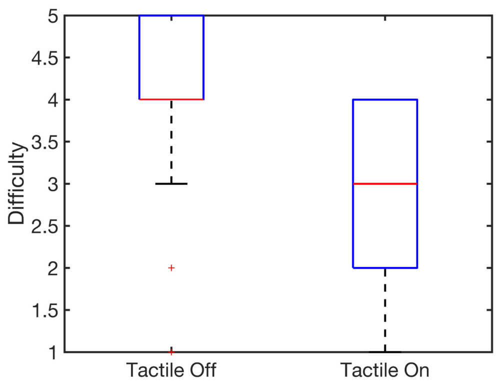

Fig. 8. The perceived difficulty level for the "Tactile Off" and "Tactile On" conditions.

primary task, the secondary task samples are not paired due to the sizable failure rate, at about 33% (a failure is reported when the participant misses clicking the button or fail to complete the sliding task). Consequently, the secondary task was analyzed using the Mann-Whitney U test due to several data points missing.

The average reach time for the buttons and slider were compared between the "Tactile On" and "Tactile Off" conditions. Results showed that the difference was found to be statistically significant **($p < 0.05$)**, with the "Tactile On" condition having a shorter reach (Fig. 7). Furthermore, the magnitude of this significance was low ($\eta^2 = 0.01$).

The difference in the amount of time spent interacting with a button between the two conditions was found to be statistically insignificant (interaction involves a single click). On the other hand, the difference in the interaction time for the slider was found to be statistically significant **($p < 0.05$)**, with the "Tactile On" condition spending less time interacting with the slider. It seems that the tactile sensation provided the expected feedback about the movement.

C. *Quality of Experience*

The exit survey included questions about the difficulty of the dual-task in the two conditions "Tactile Off" and "Tactile On" as well as user satisfaction. As shown in Fig. 8, the difficulty of completing the dual-task is rated statistically lower when tactile feedback was provided (**($p < 0.01$)**). The magnitude of this significance was found to be high ($\eta^2 = 0.23$). Furthermore, participants were highly satisfied with the driving simulation experience, with an average satisfaction rating of 82% when tactile feedback is provided.

V. Discussion

Results of this study demonstrated that augmenting virtual touchscreen with mid-air tactile feedback significantly improved driving performance in both the primary and secondary tasks. Furthermore, participants perceived the secondary task as significantly less difficult and more satisfying when tactile feedback was provided.

As for the differences in performance between button and slider, the slider involves motor commands in order to complete the swiping task. The differences in interaction time between clicking a button and swiping a slider can be explained by previous studies showing that touch seems to be critical in the transformation of a reaching movement into a motor command [33]. This is the case with the slider interaction and not the button click. This explains why the performance with tactile feedback was statistically better for the slider interaction compared to the button click, as it involves motor commands sent to the arm muscles to move the finger along the swiping direction. Furthermore, other studies showed that performance decreased with the increase of the secondary task's difficulty (a slider interaction is more challenging than clicking a button) [34].

Results demonstrated important differences between the two conditions (tactile or no tactile feedback) for the primary task (average speed error, car deviation, number of collisions, and off-road glances) and the perceived difficulty. However, these differences were not important for the secondary task (reach time). It seems that the type of the secondary task (complexity, duration, motor skills, etc.) greatly influences the secondary task performance. Future research could examine the effects of secondary task specifications on dual-task performance.

Even though our results showed that tactile feedback plays a crucial role in improving performance in dual-task situations, some limitations should be noted. First of all, previous studies showed that driving experience influences driving performance [35], [36]. The current study did not consider that. Indeed, around half of the participants in the study had previous driving experience where the rest did not. Another factor that could influence the results is the previous experience in gaming. The current study did not look into any potential relationships between previous gaming experience and the dual-task performance.

VI. Conclusion

This study explored the effects of adding mid-air tactile feedback to create co-located mid-air tactile-visual touchscreen to improve dual-task performance. Comparisons between the two conditions of "Tactile On" and "Tactile Off" during a driving task had shown that participants performed statistically better in both the primary and the secondary tasks, as well as the quality of experience, when tactile feedback was available. Future work includes exploring the effects of age groups, via a comparison between young and older adults, on the effectiveness of tactile feedback to improve performance in dual-task situations. Another exciting avenue of research could be to examine and compare the effects of tactile feedback to improve dual-task performance in other applications such as texting on a mobile phone while driving or walking.

References

[1] S. Maekawa, "Floating touch display," in *Proc. 2nd Int. Symp. Universal Commun.*, 2008, pp. 1–6.

[2] K. Harrington, D. R. Large, G. Burnett, and O. Georgiou, "Exploring the use of mid-air ultrasonic feedback to enhance automotive user interfaces," in *Proc. 10th Int. Conf. Automot. User Interfaces Interactive Veh. Appl.*, 2018, pp. 11–20.

[3] A. Sano and N. Koizumi, "Mid-air imaging technique for architecture in public space," *Electron. Imag.*, vol. 2018, no. 4, pp. 111–1, 2018.

[4] K. Yasuda, K. Saichi, and H. Iwata, "Haptic-based perception-empathy biofeedback enhances postural motor learning during high-cognitive load task in healthy older adults," *Frontiers Medicine*, vol. 5, 2018, Art. no. 149.

[5] M. Eid, M. Orozco, and A. El Saddik, "A guided tour in haptic audio visual environments and applications," *Int. J. Adv. Media Commun.*, vol. 1, no. 3, pp. 265–297, 2007.

[6] J. Mullenbach, M. Blommer, J. E. Colgate, and M. A. Peshkin, "Reducing driver distraction with touchpad physics," Master's thesis, Northwestern Univ., Evanston, IL, USA, 2013.

[7] M. S. Prewett, L. R. Elliott, A. G. Walvoord, and M. D. Coovert, "A meta-analysis of vibrotactile and visual information displays for improving task performance," *IEEE Trans. Syst., Man, Cybern., C, Appl. Rev.*, vol. 42, no. 1, pp. 123–132, 2011.

[8] E. M. Altmann and J. G. Trafton, "Memory for goals: An activation-based model," *Cogn. Sci.*, vol. 26, no. 1, pp. 39–83, 2002.

[9] S. A. Lu, C. D. Wickens, J. C. Prinet, S. D. Hutchins, N. Sarter, and A. Sebok, "Supporting interruption management and multimodal interface design: three meta-analyses of task performance as a function of interrupting task modality," *Human Factors*, vol. 55, no. 4, pp. 697–724, 2013.

[10] R. Sodhi, I. Poupyrev, M. Glisson, and A. Israr, "Aireal: Interactive tactile experiences in free air," *ACM Trans. Graph.*, vol. 32, no. 4, 2013, Art. no. 134.

[11] Y. Suzuki and M. Kobayashi, "Air jet driven force feedback in virtual reality," *IEEE Comput. Graph. Appl.*, vol. 25, no. 1, pp. 44–47, Jan.-Feb. 2005.

[12] T. Hasegawa, T. Kido, T. Iizuka, and C. Matsuoka, "A general theory of rayleigh and langevin radiation pressures," *J. Acoust. Soc. Jpn*, vol. 21, no. 3, pp. 145–152, 2000.

[13] T. Carter, S. Seah, B. Long, S. Subramanian, and B. Drinkwater, "Ultrahaptics: Multi-point mid-air haptic feedback for touch surfaces." in *Proc. 26th Annu. ACM Symp. User Interface Softw. Technol.*, 2013, pp. 505–514.

[14] H. Lee *et al.*, "Mid-air tactile stimulation using laser-induced thermoelastic effects: The first study for indirect radiation," in *Proc. IEEE World Haptics Conf.*, 2015, pp. 374–380.

[15] Y. Makino, Y. Furuyama, S. Inoue, and H. Shinoda, "Haptoclone (haptic-optical clone) for mutual tele-environment by real-time 3d image transfer with midair force feedback," in *Proc. Conf. Human Factors Comput. Syst*, 2016, pp. 1980–1990.

[16] E. Ebbini and C. Cain, "Multiple-focus ultrasound phased-array pattern synthesis: Optimal driving-signal distributions for hyperthermia." *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, vol. 36, no. 5, pp. 540–548, 1989.

[17] K. Yoshino and H. Shinoda, "Visio-acoustic screen for contactless touch interface with tactile sensation," *Proc. World Haptics Conf.*, 2013, pp. 419–423.

[18] G. Korres and M. Eid, "Haptogram: Ultrasonic point-cloud tactile stimulation," *IEEE Access*, vol. 4, pp. 7758–7769, 2016.

[19] Y. Monnai, K. Hasegawa, M. Fujiwara, K. Yoshino, S. Inoue, and H. Shinoda, "Haptomime: Mid-air haptic interaction with a floating virtual screen," in *Proc. 27th Annu. ACM Symp. User Interface Softw. Technol.*, 2014, pp. 663–667.

[20] Y. Gaffary and A. Lécuyer, "The use of haptic and tactile information in the car to improve driving safety: A review of current technologies," *Frontiers ICT*, vol. 5, pp. 1–11, 2018.

[21] A. Murata and T. Kuroda, "Effects of auditory and tactile warning on drivers' response to hazard under noisy environment," in *Proc. Int. Conf. Eng. Psychol. Cogn. Ergonom.*, 2015, pp. 45–53.

[22] L. Diwischek and J. Lisseman, "Tactile feedback for virtual automotive steering wheel switches," in *Proc. 7th Int. Conf. Automot. User Interfaces Interactive Veh. Appl.*, 2015, pp. 31–38.

[23] M. Hirokawa, N. Uesugi, S. Furugori, T. Kitagawa, and K. Suzuki, "Effect of haptic assistance on learning vehicle reverse parking skills," *IEEE Trans. Haptics*, vol. 7, no. 3, pp. 334–344, 2014.

[24] D. I. Katzourakis, J. C. de Winter, M. Alirezaei, M. Corno, and R. Happee, "Road-departure prevention in an emergency obstacle avoidance situation," *IEEE Trans. Syst., Man, Cybern.: Syst.*, vol. 44, no. 5, pp. 621–629, 2013.

[25] T. Grah, F. Epp, A. Meschtscherjakov, and M. Tscheligi, "Dorsal haptic sensory augmentation: Fostering drivers awareness of their surroundings with a haptic car seat," in *Proc. Int. Conf. Persuasive Technol.*, 2016, pp. 59–62.

[26] R. Gray, C. Ho, and C. Spence, "A comparison of different informative vibrotactile forward collision warnings: Does the warning need to be linked to the collision event?" *PloS One*, vol. 9, no. 1, 2014, Art. no. e87070.

[27] Y. Kurihara, T. Hachisu, M. Sato, S. Fukushima, and H. Kajimoto, "Periodic tactile feedback for accelerator pedal control," in *Proc. World Haptics Conf.*, 2013, pp. 187–192.

[28] S. A. Birrell, M. S. Young, and A. M. Weldon, "Vibrotactile pedals: provision of haptic feedback to support economical driving," *Ergonomics*, vol. 56, no. 2, pp. 282–292, 2013.

[29] M. J. Pitts, G. Burnett, L. Skrypchuk, T. Wellings, A. Attridge, and M. A. Williams, "Visual–haptic feedback interaction in automotive touchscreens," *Displays*, vol. 33, no. 1, pp. 7–16, 2012.

[30] G. Shakeri, J. H. Williamson, and S. Brewster, "May the force be with you: Ultrasound haptic feedback for mid-air gesture interaction in cars," in *Proc. 10th Int. Conf. Autom. User Interfaces Interactive Veh. Appl.*, 2018, pp. 1–10.

[31] A. Dosovitskiy, G. Ros, F. Codevilla, A. Lopez, and V. Koltun, "CARLA: An open urban driving simulator," in *Proc. 1st Annu. Conf. Robot Learn.*, 2017, pp. 1–16.

[32] S. Birrell and M. Fowkes, "Glance behaviours when using an in-vehicle smart driving aid: A real-world, on-road driving study," *Transp. Res., F, Traffic Psychol. Behaviour*, vol. 22, no. 1, pp. 113–125, 2014.

[33] F. R. Sarlegna and R. L. Sainburg, "The roles of vision and proprioception in the planning of reaching movements," *Advances Exp. Madicine Biol.*, vol. 629, no. 1, pp. 317–335, 2013.

[34] R. F. Adler and R. Benbunan-Fich, "The effects of task difficulty and multitasking on performance," *Interacting Comput.*, vol. 27, no. 4, pp. 430–439, 2014.

[35] Y. Ge, X. Xu, J. Li, X. Lu, and K. Zhang, "The effect of secondary task on driving performance, physiological indices and mental workload: A study based on simulated driving," in *Proc. 1st Int. Conf. Transp. Eng.*, 2007, pp. 491–496.

[36] L. Nabatilan, F. Aghazadeh, A. Nimbarte, C. Harvey, and S. Chowdhury, "Effect of driving experience on visual behavior and driving performance under different driving conditions," *Cognition, Technol. Work*, vol. 14, no. 4, pp. 355–363, 2012.