Identification of Vibrotactile Patterns Encoding Obstacle Distance Information

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Abstract—Delivering distance information of nearby obstacles from sensors embedded in a white cane—in addition to the intrinsic mechanical feedback from the cane—can aid the visually impaired in ambulating independently. Haptics is a common modality for conveying such information to cane users, typically in the form of vibrotactile signals. In this context, we investigated the effect of tactile rendering methods, tactile feedback configurations and directions of tactile flow on the identification of obstacle distance. Three tactile rendering methods with temporal variation only, spatio-temporal variation and spatial/temporal/intensity variation were investigated for two vibration feedback configurations. Results showed a significant interaction between tactile rendering method and feedback configuration. Spatio-temporal variation generally resulted in high correct identification rates for both feedback configurations. In the case of the four-finger vibration, tactile rendering with spatial/temporal/intensity variation also resulted in high distance identification rate. Further, participants expressed their preference for the four-finger vibration over the single-finger vibration in a survey. Both preferred rendering methods with spatio-temporal variation and spatial/temporal/intensity variation for the four-finger vibration could convey obstacle distance information with low workload. Overall, the presented findings provide valuable insights and guidance for the design of haptic displays for electronic travel aids for the visually impaired.

Index Terms—H.1.2 [Models and principles]: user/machine systems – human information processing, H.5.2 [information interfaces and presentation]: user interfaces – Haptic I/O, electronic travel aids, psychophysics, vibrotactile display

1 Introduction

Independent and safe navigation is one of the most challenging yet desirable activities for blind and visually impaired persons, and has a strong impact on the quality of life [1], [2]. To date, the white cane is the most widely used mobility aid, while a small number of blind and visually impaired persons rely on the assistance of a guide dog [3]. Both are proven mobility aids that also serve an important signaling function, but the former is limited in its detection range and bound to obstacles at the leg level, while the latter requires an important amount of training, care and investment. With the aim of extending the sensing range of the conventional white cane and complementing its functionality, electronic travel aids (ETAs) have been introduced to facilitate independent navigation in the blind and visually impaired.

ETAs commonly extend the detection range of obstacles with respect to the conventional white cane. They support building a mental representation of the environment or indicate the direction to a destination or target. In general, an ETA consists of both sensing and display elements. Typical sensing elements can comprise ultrasonic or infrared sensors, laser range finders, depth cameras, global positioning systems (GPS), or radio-frequency identification (RFID) [4], [5], [6], [7], [8], [9], [10], [11], [12]. As visually impaired persons rely mainly on auditory and haptic feedback, the displays of ETAs typically transmit visual information via the auditory or haptic channel. Auditory feedback generally provides simple binary cues to notify the user of the presence of an obstacle [6]. An alternative is the modulation of frequency or amplitude according to the distance to obstacles [7], [9], [13]. As an example, the Teletact system generates 28 tones (ranging from 131 to 1,974 Hz) representing different distance intervals (ranging from 12-16 to 2,000-3,000 cm) [9]. Further work relying on auditory feedback signals has been reported in [7], [14]. However, owing to the importance of the auditory channel in accessing information from the vicinity for safe ambulation (e.g., approaching cars, acoustic signals from pedestrian crossings or announcements in public transport/buildings), several groups, including ours, have focused on haptic signals to convey information from the sensing elements to the user.

Various haptic displays have been developed to deliver obstacle information in mobility systems for the visually impaired. Meers and Ward employed electrical pulses to the ten fingers to provide obstacle information of ten divided areas captured by two video cameras [15]. In the augmented white cane [6], the virtual impact of the white cane with distant obstacles was rendered through the abrupt braking of a small inertial wheel, thereby generating a mechanical impulse. Among the haptic displays presented to date, vibrotactile actuators have been the most widely used in applications providing tactile cues for sensory substitution or augmentation, such as in prosthetic

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Manuscript received 31 Aug. 2014; revised 8 Feb. 2015; accepted 11 Mar. 2015. Date of publication 19 Mar. 2015; date of current version 14 Sept. 2015. Recommended for acceptance by L. Jones.
For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below.
Digital Object Identifier no. 10.1109/TOH.2015.2415213

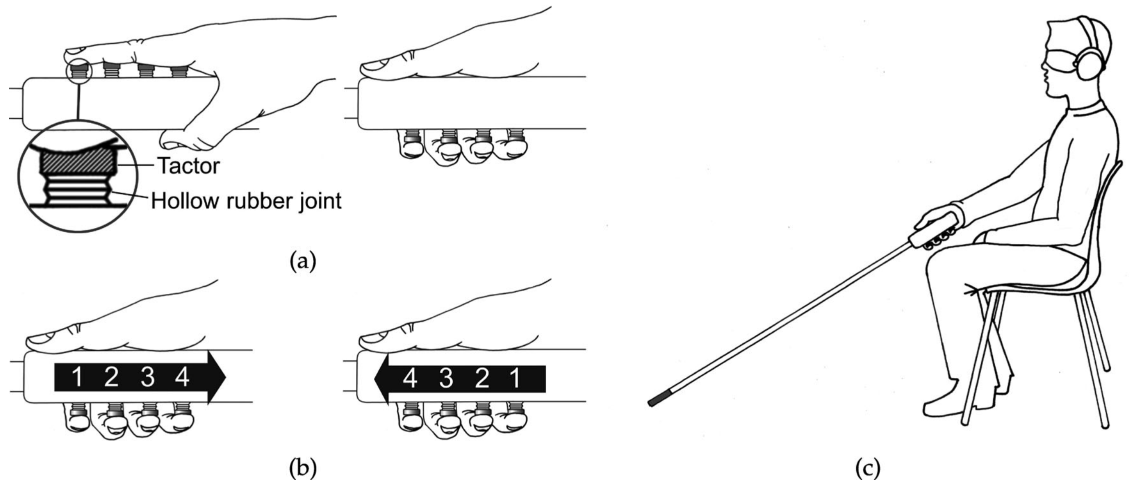


Fig. 1. Experimental setup. (a) Tactor arrangement for two investigated vibration feedback configurations: single-finger vibration (left), four-finger vibration (right). (b) Tactile direction flow: inward (left), outward (right). (c) A subject during the experiment.

and assistive devices, entertainment, navigation systems for the visually impaired or for rescue/military applications, letter displays or contact notification of a virtual object [16], [17], [18], [19], [20] as they are compact, lightweight, affordable and easily integrated into portable systems. As such, also the majority of haptic displays in ETAs employ vibrotactile actuators [5], [6], [10], [11], [21]. Single or multiple vibration motors are attached to body parts or the handle of an ETA to provide information about the surroundings. However, the rendering strategies for these haptic displays have so far been rather basic, and there is a lack of investigations into optimal rendering strategies for conveying distance information via a multi-vibrator haptic display. Primitive and non-intuitive feedback strategies, respectively strategies that require intensive training, are likely also major reasons for the lack of adoption of ETAs by the blind and visually impaired. In fact, only about 2 percent of visually impaired people employ ETAs according to the survey in [22]. The psychophysical limits of haptic perception were often not considered or not investigated in detail. While previous work has suggested that having a vibration motor at each finger is preferred by subjects, there have been no systematic investigations into this matter [23].

The goal of this work is to investigate optimal rendering methods for encoding obstacle distance through vibrotactile feedback in the context of ETAs, using well-perceivable and easily comprehensible signals. An intuitive and well-perceivable rendering method can reduce training time and increase user acceptance of ETAs. We focus on optimal tactile rendering of obstacles in the context of walking while sweeping a white cane, assuming that the sensors and vibrotactile display are integrated into the cane. A psychophysical study on vibration pattern identification was carried out with 24 participants. We report on recognition performance for three different tactile rendering methods, two feedback configurations and two directions of tactile flow. Further, task workload is analyzed based on the NASA TLX [24], and the preference on vibration feedback configurations and rendering methods is investigated based on an ad hoc questionnaire.

2 METHODS

2.1 Subjects

Twenty-four subjects (four females, 20 males) aged 22 to 56 (mean: 29.38, standard deviation (SD): 6.62), including four congenitally visually impaired male persons, participated in the experiment. The subject population was mixed, as we could not recruit a sufficient number of visually impaired participants. According to previous research, visually impaired and normally sighted persons exhibit similar performance with regard to detection threshold, grating discrimination, light vibration, and two-point discrimination [25], [26], [27], [28]. Therefore, mixing participants of both populations was considered acceptable. None of the participants reported any tactile sensory deficits. One sighted subject was left handed, while the other subjects were all right handed. The mean length of the index finger, measured on the palmar side of the dominant hand was 73.04 mm (SD: 3.93 mm). Participants were equally divided into two groups; the four female sighted subjects and the four visually impaired participants were evenly distributed between the two groups. The study was approved by the ETH Zurich ethics committee, and all participants signed a written consent form before being enrolled in the study. All subjects participated voluntarily in the experiment without compensation and were informed of the option of withdrawing from the experiment at any time.

2.2 Vibroatctile Interface

The vibrotactile display comprised of four eccentric rotating mass (ERM) motors (DMJBRK30CU: 10 mm diameter, 3.0 mm thickness, Samsung Electro-Mechanics, Korea) fixed to a custom-made handle that was attached to a conventional white cane. The vibration motors, also called tactors, were attached to the cane handle via hollow rubber joints (Tyco electronics, USA) as illustrated in Fig. 1a. Gallo et al. investigated the optimal damping material among direct contact, foam, elastic bands and hollow rubber joints by measuring acceleration transmitted from the tactors to the cane [6]. Since the hollow rubber joints absorb vibration the most along all three axes, they were utilized to isolate the vibrations from each motor.

Half of the cane handle was covered with viscoelastic polyurethane foam to improve comfort and decrease fatigue while holding the cane with a firm grip during the experiment. The distance between the centers of the motors was fixed at 20 mm which is greater than the two-point discrimination distance for vibration stimuli on the index finger, reported to lie between 2.1 and 5.1 mm depending on the pulse repetition period [29]. A microcontroller unit (ATmega 128, Atmel, USA) attached to the cane was used to control vibration stimuli through pulse width modulation (PWM). A bipolar transistor (BC547B) generated proportional level of PWM signal to control the motor. The vibration patterns were transmitted wirelessly from a PC using a Bluetooth communication module (FB155BC, FirmTech, Korea).

2.3 Vibration Feedback Configuration and Direction of Tactile Flow

In our study, two different vibration feedback configurations were examined. In the first, the index finger was placed over all four tactors, while in the second the tip of each finger contacted a separate tactor, as depicted in Fig. 1a. As a further independent variable, we investigated the effect of the direction of tactile flow—inwards towards the body and outwards away from the body (see Fig. 1b. for the pattern direction, shown for the four-finger vibration condition).

2.4 Tactile Rendering Methods

Tactile stimulus patterns can be described by three attributes, i.e., by their spatial, temporal, and intensity characteristics. Spatial attributes include the spacing between tactors, the location on the skin (body area), the stimulus area (size), the number of tactors and their spatial arrangement. Temporal aspects include the duration of a stimulus, the interstimulus interval (ISI), the repetition period and temporal pattern of the presented stimuli. Intensity attributes include amplitude and frequency of the stimuli as well as contact pressure between the tactors and the skin.

In most tactile rendering methods of ETAs, amplitude or frequency of vibration has been inversely changed to a distance from an obstacle with several resolution steps. However, we assumed that providing more distinguishable stimuli by combining attributes would result in a better distance recognition. Moreover, we also expected a reduced cognitive workload due to this.

Thus, three rendering methods with different combinations of the attributes were investigated in our experiment. Specifically, we used temporal variation (Tactile rendering method 1), temporal and spatial variation (Tactile rendering method 2), as well as temporal, spatial, and intensity variation (Tactile rendering method 3).

When designing the tactile rendering for obstacle distance information in ETAs, the total duration of the tactile feedback becomes an important parameter. To determine the available time window, both the maximum distance at which an ETA can detect an obstacle and the walking speed of visually impaired people should be considered. In a previous study [30], the mean walking speed of congenitally blind and late blind persons was found to be 0.86 and 1.11 m/s, respectively. The maximum tactile duration for each distance level t_{max} can be obtained from the number of distance levels

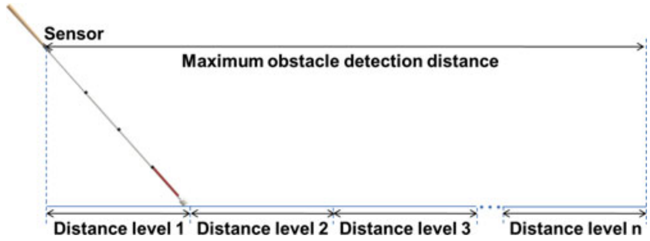


Fig. 2. Schematic of distance levels of an approaching obstacle in the walking direction.

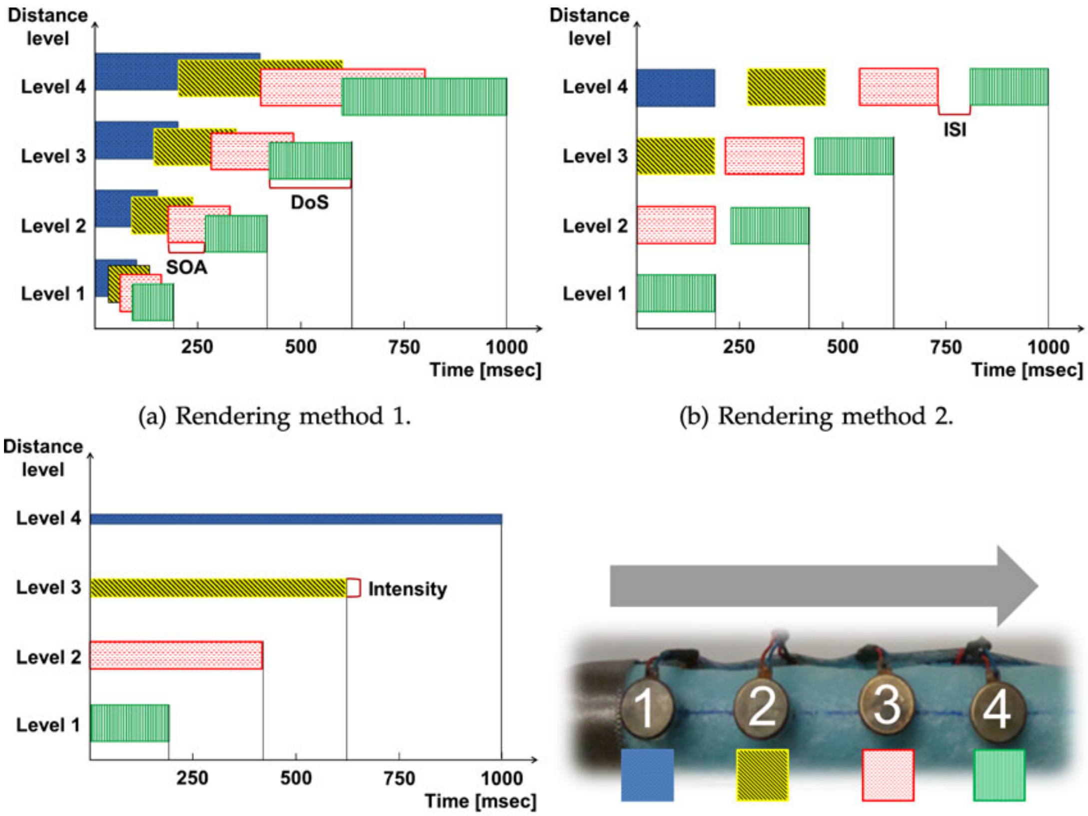
n_{levels} to be encoded, the walking speed $s_{walking}$, and the maximum obstacle sensing distance $d_{predepth}$ as follows:

$$t_{max} = \frac{d_{predepth}}{s_{walking} \times n_{levels}}. \quad (1)$$

In our experiment, we assumed an average walking speed of white cane users of about 1 m/s. Based on a preliminary survey on desirable maximum obstacle detecting range and number of distance levels of white cane users (Fig. 2), four different distance levels and a sensing range of 4 m were selected. Distance level 1 refers the closest distance range, while Distance level 4 corresponds to the farthest. With an assumed maximum sensing range of 4 m, we determined a value of 1,000 ms of the maximum tactile duration.

Rendering method 1. For the first rendering method, we designed a pattern eliciting tactile apparent movement [31]. This phenomenon describes a percept of continuous motion between tactors while the actual consecutive activation is discrete. The four different distance levels were encoded by varying two temporal properties—the duration of the stimulus (DoS) and the stimulus onset asynchrony (SOA). The former describes the total activation time of a given tactor per display period, while the latter denotes the temporal gap between the sequential activation of two tactors, as illustrated in Fig. 3a. In previous work, optimal values for SOA were determined for each DoS in order to elicit the apparent movement illusion [31], [32]. In a related study, Kohli et al. showed that the just noticeable difference (JND) of SOA is about 16 to 26 percent, depending on the DoS [33]. In general, to induce the percept of tactile apparent movement, the SOA should be shorter than the DoS, i.e., the activation period of consecutive actors should overlap. For distance levels 1, 2, 3, and 4 (see Fig. 2), the DoS was set to 100, 150, 200, and 400 ms and the SOA to 30, 90, 140, and 200 ms, respectively. This results in a total rendering time of 190, 420, 620, and 1,000 ms for each distance level, respectively, using the maximal rendering duration defined above. Pattern duration and tactile apparent movement speed were thus inversely proportional to the distance level. For instance, the longest stimulus duration and slowest apparent velocity are employed for an obstacle located within the farthest (level 4) distance range. A duty ratio of 100 percent was employed for the tactor intensity in all distance levels.

Rendering method 2. The main idea of the second rendering method is to activate a different number of tactors in sequence, depending on the distance level of an obstacle, as depicted in Fig. 3b. For instance, when the obstacle is located within distance level 4, all tactors are activated sequentially, whereas for level 1 only one tactor is activated.



(a) Rendering method 1. (b) Rendering method 2. (c) Rendering method 3. (d) Activation order of tactors for the case of inward signal flow.

Fig. 3. Schematic representation of the tactile rendering methods employed in this study, including modulation of tactor signal intensity, duration, and activation sequence. Each plot depicts tactor activation patterns over time for four distance levels (note that the overall pattern duration of a specific level is equal across rendering methods). Each tactor is represented by a different color and pattern (as shown in d). In method 3, the height of the bars represents the activation intensity. (a) Tactile apparent movement. Tactors are activated sequentially with temporal overlap (bars are shifted vertically for better visibility), distance is encoded by varying duration. (b) Consecutive activation of a varying number of tactors, distance is encoded by the number of activated tactors. (c) The tactors are mapped to the individual distance levels, and each tactor renders a distinct duration and intensity.

The DoS was set to 190 ms for each tactor at all distance levels. The inter-stimulus interval defines the temporal gap between two consecutive stimuli in a pattern. In the experiment, the ISI for each distance level was adjusted such as to homogenize the total pattern duration for all three tactile rendering methods. For instance, the ISI for distance level 4 was set to 80 ms. As with rendering method 1, the same intensity was applied to all distance levels.

Rendering method 3. In the third rendering method, each tactor represents one specific distance level. Additionally, both activation time and vibration intensity are adjusted for each level, as illustrated in Fig. 3c. The intensity was varied from 25 to 100 percent through PWM control via a bipolar transistor (BC547B). The vibration amplitude was measured through a small accelerometer (ADXL325, Analog Device) attached to the center of motor 1 where the index finger tip is placed. Analog sensor data were captured by a data acquisition device (NI-USB 6008, National Instruments). The mean L2-norm of the peak acceleration amplitude along the x and y axes corresponded to 0.14, 0.92, 1.72, and 2.07 G, respectively, when the motor was loaded by the index finger for both grip types (single-finger vibration and four-finger vibration). The frequencies calculated using a fast Fourier transform in MATLAB (The MathWorks) were approximately 63, 92, 113, and 124 Hz for 25, 50, 75, and 100 percent duty ratio, respectively. The total pattern duration for each level was again identical to the other rendering methods.

2.5 Procedure

At the beginning of the experiment, subjects were prompted to sit comfortably on a chair. They were asked to wear a blindfold and headphones playing white noise (Fig. 1c). The latter was important to block out sounds from the vibrotactile display as well as the office environment. The tactile display was integrated into a white cane, which the participants held using their dominant hand, with the finger(s) touching the tactors. Both groups of subjects were presented with all three tactile rendering methods, and were tested on both the single-finger and the four-finger vibration. The only difference between the two groups was the direction in which the patterns were presented (tactile flow). Group I received patterns rendered inwards (towards the body), while Group II received them outwards. In total, each subject experienced six different conditions (three tactile rendering methods and two vibration feedback configurations). At the beginning of each condition, the four patterns of corresponding distance levels were presented in sequential order to familiarize the subjects with the specific stimuli. After the familiarization session, 20 practice trials were performed for each condition. At the start of each practice trial, a tactile

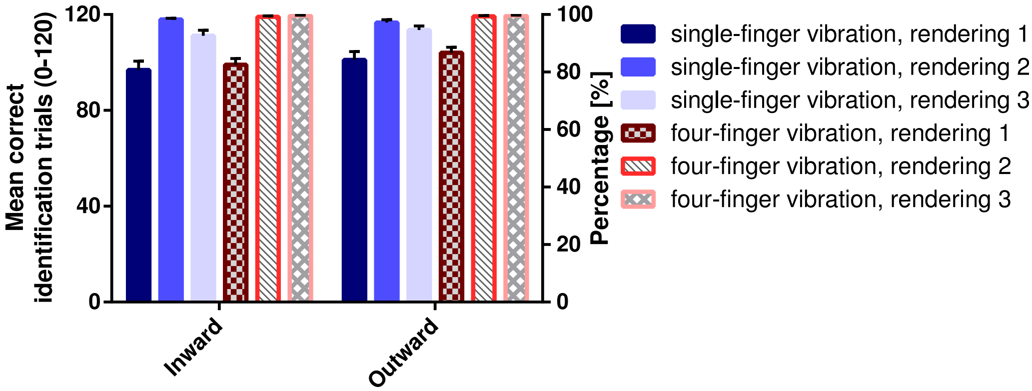


Fig. 4. Results of correct pattern identification. The error bars indicate standard error. Inward direction data of the tactile patterns were obtained from Group I, and the outward data from the Group II.

stimulus was presented. Subjects were then asked to verbally identify the perceived distance level. As all subjects were blindfolded during the task, the experimenter recorded the oral responses. During the practice sessions, the correct answer was given verbally by the experimenter at the end of each trial. In the actual experiment, 120 trials were presented for each condition via a graphic experiment interface. Thus, for each subject a total number of 720 trials were recorded throughout the whole experiment. To avoid fatigue, participants could take a break between trials and sessions on request. In order to avoid biased responses, distance levels were presented in a pseudo-randomized order. The order of the tactile rendering methods and vibration feedback configurations were balanced. Half of the participants of each group started with the single-finger vibration and then switched to the four-finger vibration, and vice versa. Subjects were then again asked to identify the distance level for a presented tactile pattern. No feedback about correctness of the answers was given during the experimental session. After completion of each of the six conditions, subjects were asked to complete a paper and pencil version of the NASA task load index (TLX) assessment [34] to measure subjective workload. It consisted of six sub-scales (i.e., mental/physical/temporal demand, performance, effort, and frustration) with 21 gradations. All subscales had the positive feedback at the left end of the scale. Additionally, subjects were asked to provide a ranking of their preferred vibration feedback configuration type and tactile rendering method.

2.6 Data Analysis

To assess the impact of each condition on the performance, we analyzed the data by employing a three-way mixed design ANOVA, combining one between-subjects and two within-subjects factors using standard software (IBM SPSS Statistics 20, IBM Corp., USA). The between-subjects factor is the direction of the tactile flow, and the within-subjects factors are tactile rendering method and vibration feedback configuration. Homogeneity of variance was assessed through Levenes test. Yet, Mauchlys test of sphericity showed a significant result ($p < .05$) indicating violation of the sphericity assumption for the tactile rendering method. Thus, following Greenhouse-Geisser correction (for $\varepsilon < .75$) or Huynh-Feldt (for $\varepsilon > .75$) could be used to correct the degrees of freedom [35]. Since the sphericity of the vibration feedback configuration could not be calculated due to two levels, a conservative Greenhouse-Geisser correction was selected to adjust the degrees of freedom. Simple main effects comparisons and post hoc analysis with Bonferroni correction were further performed to test for significant interaction effects. Wilcoxon signed rank tests and Friedman tests were conducted to compare the preferences among the two vibration feedback configurations and three tactile rendering methods.

3 Results

The overall correct pattern identification rate from a total of 17,280 trials was about 93 percent (SD: 8 percent). Fig. 4 depicts the mean correct identification rate of the 120 trials in each condition. It can be seen that in all conditions, the four-finger vibration performed slightly better than the single-finger vibration.

The main effect of direction of tactile flow did not show a significant difference, $F(1, 22) = 1.376$, $p = .253$, partial eta-squared effect size (η_p^2) = .059. There was a significant main effect of the tactile rendering method, $F(1.132, 24.9) = 64.291$, $p < .001$, $\eta_p^2 = .745$ and vibration feedback configuration $F(1, 22) = 30.54$, $p < .001$, $\eta_p^2 = .581$.

A significant interaction between the vibration feedback configuration and tactile rendering method was found, $F(1.336, 29.397) = 3.873$, $p < .05$, $\eta_p^2 = .15$, while there was no statistically significant interaction for other combinations of factors (i.e. direction of tactile flow $\times$ tactile rendering method, direction of tactile flow $\times$ vibration feedback configuration, and direction of tactile flow $\times$ vibration feedback configuration $\times$ tactile rendering method).

We further examined the simple main effects of the tactile rendering methods for each vibration feedback configuration with Bonferroni adjustment. Table 1 summarizes the result of the simple main effects to decompose interaction effects. In the case of the single-finger vibration, there were significant differences in all comparisons. However, no significant differences were found between tactile rendering method 2 and 3 when employing the four-finger vibration.

The results of the NASA TLX questionnaires are shown in Fig. 5. The reported workload for the single-finger vibration was always higher than that of the four-finger vibration, across all tactile rendering methods. Furthermore, the performance of the former was also rated lower than the latter. In addition, tactile rendering method 1 resulted in higher workload and lower performance compared to the other methods.

TABLE 1
Simple Main Effects

Vibration feedback configuration	Tactile rendering method A	Tactile rendering method B	p - value
Single-finger vibration	Rendering 1	Rendering 2	$p < .001^{**}$
Single-finger vibration	Rendering 1	Rendering 3	$p < .005^{**}$
Single-finger vibration	Rendering 2	Rendering 3	$p < .01^{*}$
Four-finger vibration	Rendering 1	Rendering 2	$p < .001^{**}$
Four-finger vibration	Rendering 1	Rendering 3	$p < .001^{**}$
Four-finger vibration	Rendering 2	Rendering 3	$p = .362^{*}$

$^{*}p < .05$, $^{**}p < .005$

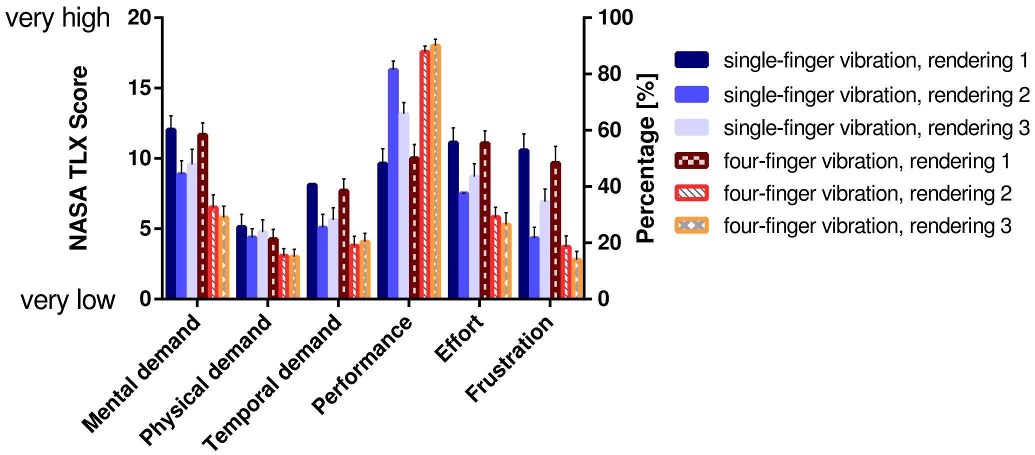


Fig. 5. Results of NASA TLX questionnaires. The error bars indicate standard error. The plots represent the NASA TLX score for different combinations of rendering methods and vibration feedback configurations.

TABLE 2
Post hoc Test for Tactile Rendering Method Preference

Vibration feedback configuration	Tactile rendering method A	Tactile rendering method B	Z	p - value
Single-finger vibration	Rendering 1	Rendering 2	-3.070	$p < .017^{*}$
Single-finger vibration	Rendering 1	Rendering 3	-2.443	$p < .017^{*}$
Single-finger vibration	Rendering 2	Rendering 3	-1.661	$p = .097$
Four-finger vibration	Rendering 1	Rendering 2	-4.237	$p < .001^{**}$
Four-finger vibration	Rendering 1	Rendering 3	-4.329	$p < .001^{**}$
Four-finger vibration	Rendering 2	Rendering 3	-1.815	$p = .070$

$^{*}p < .017$, $^{**}p < .001$

Twenty-one of the 24 participants – including the four white cane users – preferred the four-finger vibration over the single-finger vibration. Regarding the preference of tactile rendering, rendering method 2 obtained the highest mean rank for the single-finger vibration condition (rendering method 2 > rendering method 3 > rendering method 1), while rendering method 3 was the most preferred for the four-finger vibration condition (rendering method 3 > rendering method 2 > rendering method 1).

To statistically analyze the preference of vibration feedback configuration and tactile rendering methods, further tests were performed. A Wilcoxon singed ranks test revealed that there was a significant difference in preference between the two vibration feedback configurations ($Z = 3.674$, $p < .001$). A Friedman test showed a significant difference in preference between tactile rendering methods for both vibration feedback configurations ($\chi^2(2) = 14.333$, $p < .001$ for single-finger vibration, $\chi^2(2) = 32.333$, $p < .001$ for four-finger vibration). A Wilcoxon post hoc test with an adjusted significance level ($p = .017$), calculated by utilizing Šidák Correction [36] for three comparisons of tactile rendering methods, revealed significant differences, which are summarized in Table 2.

4 Discussion & Conclusion

In this paper, we investigated the efficiency of tactile patterns in conveying obstacle distance information without intensive training in terms of the direction of tactile flow, feedback configuration and tactile rendering method. In accordance with the findings of Bellik and Farcys [23], participants preferred the four-finger vibration over the single-finger vibration. We further investigated the effect of vibration feedback configuration and tactile rendering method on the identification rate and workload. The correct distance level identification rate of the four-finger vibration was higher than that of the single-finger vibration, while the reported task workload was lower. This could be explained by the higher spatial acuity of the fingertip compared to the base of the finger [37]. The ability to distinguish between the distance levels rendered via vibration patterns is potentially less apparent when the tactors are arranged along one finger compared to the four fingertips. The reduced acuity may thus lead to a higher workload, which is in accordance with the results of our experiments, and may have resulted in the lower preference for the single-finger vibration. According to the experimental results, the tactile rendering methods that involved spatial variation encoding showed a high correct recognition rate of 99.27 and 99.62 percent for rendering methods 2 and 3, respectively, in the four-finger vibration configuration. Thus, in this case spatial variation might be more informative for distance identification than temporal variation. One point that has to be taken into account in the context of a practical application is the travelled distance during the rendering of the signal. One potential remedy of this problem could be the reduction of the duration of the distance levels (e.g., 250 msec per level). This would allow the detection of abruptly appearing dynamic obstacles when the tactile feedback is spatially modulated. This will be studied in future work.

Overall results between the tactile rendering method 2 and 3 showed no difference especially in four-finger vibration condition. Namely, tactile rendering based on only temporal and spatial variation resulted in high performance and preference ratings, and an additional variation of intensity did not have a significant effect. Generally, the magnitude of vibration stimuli associates with both its frequency and amplitude. In this study, ERM motors were utilized. Their frequency and amplitude are directly related to the applied input voltage. Thus, frequency and amplitude are coupled, and thus increased or decreased concurrently rather than independently [38]. In contrast to this, a linear resonant actuator allows varying the amplitude (at a resonance frequency), while a voice coil-actuator permits the control of both amplitude and frequency. When both amplitude and frequency are varied for the discrimination of vibration signals, a greater number of levels can be distinguished [39]. Thus, controlling both amplitude and frequency separately may improve the correct identification rate in the one-finger vibration condition. Further work is required to validate this aspect in the context of our targeted application.

Tactile rendering method 1 relied only on the variation of the temporal characteristic. In the experiment, the distance level identification rates were significantly lower than for the other methods. The key problem could be the absolute identification of four distance levels with different speeds without any reference, as absolute music tone identification becomes difficult without a reference tone. This presumably led to the reduced performance of this method. Nevertheless, as majority people who are not able to accurately identify the correct tone, are becoming possible to notify correct tone without external reference after long repeated exposure [40], extended training might lead to better performance with rendering method 1. Moreover, it should be mentioned that all presented tactile rendering methods yielded detection rates of more than 80 percent without long training periods. Still, to ensure safe navigation of visually impaired persons, a 100 percent detection rate is desirable.

It is interesting to note that better distance range identification rates are paired with less mental demand in the NASA TLX score. This indicates that intuitive augmented sensory feedback may help reducing task workload, while providing accurate information, thus promoting safe and confident usage of ETAs.

According to the results of our experiment, distance levels were equally well identified for both inward and outward signal flow directions. Many ETAs utilizing tactile spatial rendering instead of frequency modulation, such as the Teletact II and the augmented white cane [6], [41], employ only inward rendering with several tactors. Using the opposite spatial direction mapping should result in similar performance in those ETAs. The direction of signal flow could be selected based on the personal preference of the user, as it does not affect recognition rates.

Both visually impaired and sighted persons participated in this experiment. Although, for some aspects of tactile perception, visually impaired persons have exhibited performance superior to sighted people [42], it is generally believed that tactile sensitivities are similar in both visually impaired and sighted people [25], [26], [27], [28]. In general, we assumed no difference between the two populations. It should be noted that differences between the populations might have been stronger if participants were walking instead of being seated, due to the experience of visually impaired persons with white cane usage and navigation. We intend to examine these points in future work.

In summary, the results of the experiments can provide guidance to the design of intuitive tactile patterns to encode obstacle distance information in ETAs, which require only short training times. In future work, we will investigate whether the preferred methods will maintain higher correct identification rates during ambulation with a white cane.

Acknowledgments

The authors would like to express their gratitude to all the participants of this study, and to the Swiss Foundation Access for All for assisting in the recruitment of participants, as well as for providing valuable input from the point of view of white cane users. This research was supported by the Swiss Commission for Technology and Innovation (Project 11393.1 PFNM-NM) and the National Center of Competence in Neural Plasticity and Repair of the Swiss National Science Foundation (NCCR Neuro). This work was also supported in parts by the EU project Beaming 248620 and the SNSF project DDMOAR. Roger Gassert is the corresponding author.

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