IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 6 September 2023, accepted 25 September 2023, date of publication 4 October 2023, date of current version 16 October 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3321802

RESEARCH ARTICLE

Novel Wrist-Worn Vibrotactile Device for Providing Multi-Categorical Information for Orientation and Mobility of the Blind and Visually Impaired

MYUNGJOONG LEE[1,2], (Member, IEEE), AND HYUNKI IN[1], (Member, IEEE)
[1]Korea Institute of Science and Technology, Seoul 02792, Republic of Korea
[2]Division of Nano-Information Technology (HCI and Robotics), University of Science and Technology, Daejeon 34113, Republic of Korea

Corresponding author: Hyunki In (inhk@kist.re.kr)

This work was supported in part by Korea Institute of Science and Technology (KIST) Institutional Program under Project2E32272, and in part by University of Science and Technology (UST) Young Scientist Program under Project 2021-YS-23.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board of Korea Institute of Science and Technology (KIST) under Application No. KIST-202209-HR-019, and Application No. KIST-202209-HR-006.

ABSTRACT Considering the ambulatory principles for the blind and visually impaired individuals (BVI), who encounter difficulties in independent walking and wayfinding, the acquisition of diverse types of information is required. For independent walking, the spatial and status information are required in addition to directional information. However, delivering information of several types poses a problem because it decreases the perception rate of the information. To address this problem, we applied a strategy that configures the group of vibrotactile information by combining both stationary and moving tactons, as opposed to using stationary or moving alone. In this study, we introduce a novel wrist-worn tactile display with eight vibrators, which can deliver easily distinguishable directional, spatial, and status information. For improving the recognition rate of information provided, the vibration patterns were categorized according to spatial characteristics and were provided to express the different types of information. Through the preliminary study, it was confirmed that the capacity of information transmission improved significantly when employing a combination of stationary and moving tactons, as opposed to relying solely on stationary or moving tactons. The effectiveness of the proposed device was evaluated through user tests with the blind and visually impaired participants. Overall, the categorized vibrotactile information was quickly identified, and it enabled the blind to walk independently without any pre-learned knowledge about the route.

INDEX TERMS Haptic feedback, navigation for the visually impaired people, vibrotactile display, wearable device.

I. INTRODUCTION

An estimated 253 million individuals worldwide are visually impaired–this includes 36 million with complete blindness [1], who commonly face challenges with independent walking and wayfinding. Blind and visually impaired individuals (BVI) rely on walking as their primary mode of mobility owing to the inconvenience of utilizing transportation [2]. However, they encounter challenges in reaching their destinations independently because of the lack of necessary information while walking. The BVI have longer walking times than sighted people, and they rely heavily on information acquired through repeated orientation and mobility training while walking [3]. However, the information provided is mostly insufficient, thereby resulting in a significant percentage (81.4 %) of the BVI respondents reporting

The associate editor coordinating the review of this manuscript and approving it for publication was Lei Wei.

walking challenges [4]. Therefore, information that is more accessible and accurate is required to aid the BVI in walking and wayfinding.

Walking aids for the BVI have been extensively studied regarding their ability to provide vibrotactile feedback; such feedback is used as an alternative sensory modality for the BVI [5], [6]. These aids are available in numerous forms ranging from portable devices such as modified white canes [7], [8]; hand-held devices [9]; and wearable devices such as waist belt-type [10], [11], [12], [13], vests [14], [15], [16], [17], [18], head mounts [19], [20], ear-shaped earphones [21], footwear [22], and necklace-type [23]. These tactile displays solely provide either information about obstacle presence or directional cues for obstacle avoidance, but not both simultaneously. As a consequence, these devices possess limitations as they do not provide sufficient information necessary for the independent walking of visually impaired individuals.

Because based on the ambulatory principles for the BVI emphasizing the importance of continuous awareness of a pedestrian's location, destination, and route [34], various types of information are required for the independent walking of the BVI. To enable effective navigation, tactile displays should not only offer obstacle-related information as discussed above but also include essential spatial information for localization within the surrounding environment, such as major landmarks. Additionally, it is crucial to provide location information indicating where a change of direction is required along the route to the destination, accompanied by the corresponding directional cues. To avoid accidental falls and unwanted contact with obstacles [35], walking status information is also necessary. Furthermore, all of this information should be delivered appropriately, tailored to the specific walking situation.

In recent years, there has been considerable research on wrist-worn tactile displays as walking aids for the BVI. The wrist-worn tactile displays have been investigated owing to the high sensitivity of the wrist to vibrotactile stimulation. The widespread availability of commercial products such as smartwatches has made wrist-worn devices popular and widely accepted [24], [25]. Moreover, a wrist-wearable device offers hands-free convenience, which is particularly beneficial for visually impaired pedestrians who use canes while walking. However, they still encounter the same issues in providing only a restricted range of information. Schätzle et al. [26], [27] used six cylindrical eccentric rotating mass motors (ERM) and Luces et al. [28], [29]; Salazar et al. [30] proposed a device comprising six pancake-type ERMs only for directional guidance. Wei et al. [52] demonstrated a fundamental directional guide using a single ERM (Eccentric Rotating Mass) on each wrist. Hong et al. [31], [32] compared two types of tactile displays composed of four or eight ERMs to evaluate the accuracy of only directional guidance. Tang et al. [33] proposed a display with eight ERMs only for directional feedback in three-dimension. Additionally, N. Bayat et al. [53] provided vibrotactile directional information to indicate environmental detection and collision prediction using six ERMs (details are listed in table 1). All the devices solely provide directional information, which is insufficient and fragmented to support independent walking for individuals with visual impairments. This limitation arises from the difficulty in delivering a wide range of information through vibrotactile stimuli.

In summary, prior studies have limitations that primarily focused on delivering insufficient fragmented information, such as simple obstacle alarms or directional information, to proceed in a particular direction or avoid obstacles. To address this challenge, our study explores ways to enhance the scope of information available to support independent walking for BVI. Furthermore, we propose a novel method of designing vibrotactile information to improve the recognition rate of the provided information, which may decrease as more information is presented. Finally, we introduce a novel wrist-worn tactile display that provides essential tactile information with a high recognition rate for use during walking.

II. RELATED WORK

To provide all the aforementioned information, the types of tactons, which are feedback used to convey information or messages [36], [37], must be diversified. Vibrotactile displays modulate tactons by varying the frequency, intensity, duration of stimulus (DOS), stimulus onset asynchrony (SOA), interstimulus interval (ISI), or a combination thereof. However, as the number of provided tactons increases, distinguishing between them becomes increasingly challenging. To overcome this, previous studies have explored methods to improve recognition rates.

To improve the amount of information that can be conveyed, researchers have explored strategies for creating tactons by adjusting the spatial parameters in vibrotactile displays with multiple vibrators which have different locations. Some researchers have constructed different groups of tactons using specific parameters: a stationary tacton group that feels stationary regardless of the number of activated vibrators and a moving tacton group (apparent motion [40], [41] applied) that feels as if it is in motion with multiple activated vibrators. Y. Kim et al. [38] introduced a handheld device featuring a sequential arrangement of four vibrators and designed three tacton groups comprising four tactons respectively. They achieved high recognition rates with a stationary tacton group, modifying the intensity and location of activated tactors simultaneously. Novich and Eagleman [39] presented a back-worn device with nine actuators and composed three different tacton groups with eight tactons respectively. They found that a moving tacton group with different sequential movement directions yielded a high recognition rate. However, in these studies, there is a limitation originating from the threshold of human perception for tactile sensations on the body's skin [51], whether tactons belong to a stationary group or a moving group. Due to the constrained area of the body part,

TABLE 1. Review of prior studies on wrist-worn vibrotactile displays. (S: sighted people, VI: visually impaired people, m: male, f: female.)

Reference	Actuator	Information	Participants	Task	Metric / Result
B. Weber et al. [6]	ERM , 6 (Cylindrical)	Spatial guidance	18 (1f, 17m) S. Age: 22 ~ 43	Targeting to specific positions	Translational Accuracy (ratio of path length) : VT6=1.9, VT4=2.1, VB=2.0 Rotational Accuracy (Higher is lower accuracy) : VT=6.2, VB=7.5
S. Schätzle et al. [26]	ERM , 6 (Cylindrical)	Collision feedback in VR (scenario)	-	-	-
Schätzle, S. et al. [27]	ERM , 6 (Cylindrical)	Motion guidance (direction, distance)	16 (13f, 3m) S. Age: 23 ~ 48.	- Spatial Acuity - Tageting positions at random distance	- Percent correct: 95.2 % - Relative path length: 1.40 (best in coding 7)
J. V. S. Luces et al. [28]	ERM , 6 (Pancake-type)	Position guidance (direction, distance)	6 (5m, 1f) S, age: 21 ~ 24	Targeting to arbitrary positions in 3m x 2.5m (xy plane)	Motion path Efficiency (ME) - pattern A: 46.9% - pattern B: 49.1%
J. V. S. Luces et al.[29]	ERM , 6 (Pancake-type)	Motion guidance (directional cue)	10 (10m) S, age: 21 ~ 30	Targeting to 4 positions in the X-Y plane in 10s. (comparing 'push', 'pull')	Motion path Efficiency (ME) - 'push': 44.26%, - 'pull': 52.41%
J. Salazar, et al. [30]	ERM , 6 (Pancake-type)	Motion guidance (directional cue)	20 (20m) S, age: 20 ~ 36	Path (M shape) following in the coronal plane.	Root Mean Squared Error (RMSE) : 26.2%
J. Hong et al. [31]	ERM , 4 | 8 (Circular)	Direction guidance	20 (10f, 10m) S, age: 19 ~ 58	Targeting 32 directions (resolution: 11.25 degree)	Number of correct trials - 4 motor: 54.3%, 8 motor: 56.4% Movement Error: - 4 motor (23.2°), 8 motor (25.4°)
J. Hong et al. [32]	ERM , 4 | 8 (Circular)	Direction guidance	14 (8f, 6m) VI, age: 22 ~ 64	Path-tracing	Accuracy: Error - 4 motor: 7.4 mm (SD = 2.9) - 8 motor: 10.6 mm (SD = 4.1)
J.-H. Tang et al. [33]	ERM , 8 (Circular)	Direction guidance	36 (18f, 18m) S, age: 20 ~ 30	Identification test	Recognition rate : 85.7% (best in 8cm, Motion)
Z. Wei et al. [52]	ERM , 1 (each wrist)	Object localization (direction guidance)	4 S (age: 25.5 ± 4.2) 3 VI (age: 22.6 ± 1.5)	Targeting test	Success rate : 95.5 ± 0.18 % (virtual) : 81.2 ± 0.4 % (real)
N. Bayat et al. [53]	ERM , 6 (Pancake-type)	Obstacle detection, Collision prediction	-	-	-

there exists a finite threshold for enhancing information by increasing the number of vibrators. Additionally, activating multiple vibrators located closely to each other may lead to tactile illusions, such as phantom sensations. These constraints pose difficulties in accurately simultaneously increasing the amount of conveyed information and ensuring distinguishability by adjusting the spatial parameters, which involve changing the location of activated vibrators, within a single group of tactons.

Therefore, some researchers have attempted to construct tactons by integrating both the aforementioned stationary and moving tacton groups to enhance the amount of information conveyed while maintaining accuracy of information transfer (IT). Piateski and Jones [42]; Jones et al. [43] composed 7 to 8 tactons with both stationary tactons that depicted a simple X-shape and the location of the center by modifying spatial parameters, and moving tactons that delivered directional information through spatiotemporal parameter variations. Reed et al. [44], [55], [56] and Tan et al. [54] proposed a tactile display delivering an extensive set of 39 tactons, each corresponding to distinct phonemes, that integrate both a stationary tacton group that describes consonants and a moving tacton group meaning vowels. Due to variations in the number of tactors used and the placement of these on different body parts compared to the single-tacton group studies mentioned earlier, direct comparison of information transfer accuracy becomes challenging. Nevertheless, attempts have been made to enhance the information recognition rate by integrating two groups of tactons with distinct tactile stimuli. However, there remains a lack of experimental verification regarding the impact of combining stationary and moving tacton groups to convey information accurately, along with a comparison with previous methods like a single-tacton group. Therefore, further research is necessary to assess the influence of a combination of multiple groups of tactons on information recognition accuracy.

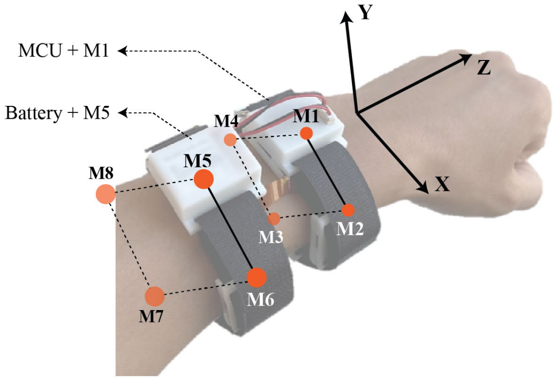

FIGURE 1. Three-dimensional spatial arrangement of eight vibration modules.

In this study, we research a strategy for constructing tactons that enable the distinction of a large amount of information, and propose a novel wrist-worn tactile display designed to assist the BVI in navigating outdoor environments. Our primary objective is to assess the effectiveness of a tacton configuration method that integrates two distinct groups: stationary and moving tactons. Through our evaluation, we have validated that the combination of these two groups significantly enhances the accuracy of information recognition. As a secondary objective, we applied this method to design various tactons that are crucial for facilitating independent navigation among the BVI. The effectiveness and usability of these tactons was assessed by recruiting blind participants. The assessment revealed that, participants successfully and independently reached their destinations.

III. THE PROPOSED SYSTEM DESIGN

This paper presents the development of a novel wrist-worn tactile display that utilizes a small vibration actuator to convey information to the user through tactile stimulation.

The design of the display includes eight multiple vibration modules (vibrator) as shown in the figure 1. Considering that this device will be worn on the wrist by BVI during walking, an excessive number of vibrators could potentially impede the overall comfort and usability. Furthermore, to convey 3D direction information with a minimal number of vibrators, we employed a 4 × 2 vibrator array, which is on a similar level to prior studies [6], [26], [27], [28], [29], [30], [31], [32], [33]. These vibration modules are strategically arranged in a spatially optimal configuration to enable users to identify unique vibration patterns associated with different types of information.

A. ARRANGEMENT OF VIBRATORS AND PROTOTYPE DESIGN

The proposed prototype positioned a vibration module within the defined local coordinate system of the wrist to convey information in a three-dimensional space (figure 1). To provide basic directional information in two dimensions and enhance the intuitive perception of those, we designed a rhombus-shaped vibrator array consisting of dorsal (up), right, left, and volar (down) positions on the wrist. An additional array was added to represent the forward and backward directions, resulting in a 4 × 2 array configuration. This arrangement enables the device to provide information in three-dimensional space, with the vibrator plane perpendicular to the X-, Y-, and Z-axes.

To ensure accurate delivery of tactile information, each vibrator must be positioned precisely according to the user's wrist. Therefore, the design must include an adjustable mechanism that accommodates different wrist circumferences. The prototype employed a velcro strap, which is easy to adjust and detach, and the cap of the module was designed to be easily positioned and fixed (figure 2, right most image). Regardless of the thickness of the user's wrist, the vibration module can be easily positioned and worn for optimal performance.

B. VIBRATING MODULE: ACTUATOR + VIBRATION AMPLIFYING STRUCTURE

We utilized a piezo actuator (PowerHap 2.5 g, TDK Electronics, Japan) as the primary vibrator for our proposed device, because fast response time and the ease of controlling vibration intensity and frequency of this actuator can offer advantages for creating more diverse tacton designs in the future.

To enhance the vibration intensity of the actuator, an amplification structure made of steel was implemented above and below it (figure 2, left two images). For optimal performance, the metal was required to exert an appropriate pressure of approximately 3 N on the actuator while maintaining continuous contact. To fulfill these requirements, a strategy involving the arrangement of small magnets at the four corners between the materials at the top and bottom was employed.

C. ELECTRONIC PARTS

The electronic part of the device mainly comprises two components: the controller and vibration-driving unit. The controller is equipped with an STM0 series microcontroller unit (STMicroelectronics, Switzerland), and it functions by receiving and processing commands from external devices such as smartphones and PCs. Through wireless Bluetooth communication, the controller receives commands and generates corresponding tactons. To output the vibration, 80 sampled digital data instances are transmitted to the vibration driver via serial peripheral interface (SPI) communication at a rate of 8 KHz, resulting in the generation of a 100-Hz sine wave. Among eight available modules, a specific vibrator is selected using the chip select signal of SPI to drive the vibration.

The vibration-driving unit includes a haptic driver (BOS1901 piezo driver, Boréas Technologies, Canada) and an actuator that can generate a sine wave of up to 60 V using the data received from the controller. The control and driving units are connected using a flexible printed circuit wire, which allows seamless data transmission and reception.

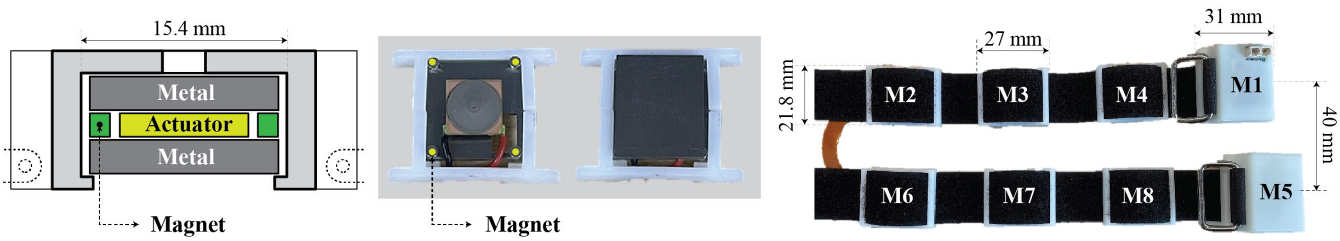

FIGURE 2. Diagram of vibrating module (left two images) and image of the entire device comprising of eight modules (right).

IV. PRELIMINARY STUDY

This section presents the fundamental research and experimental results regarding the construction of tactons as a strategy to enhance the rate of recognition of information. This approach addresses the potential decrease in the rate of information recognition by individuals with visual impairments when used for navigation, which requires a considerable amount of information. Our hypothesis suggests that participants' discernment of information in the tacton group will be significantly improved when the tacton group contains both stationary and moving tactons, as opposed to when tactons are presented as stationary alone or moving alone. In contrast to prior research [42], [43] that created tacton groups through the random combination of stationary and moving tactons, devoid of explicit criteria, our proposed approach employs stationary and moving tactons in a manner that reflects both the spatial configuration of the device and the distinctive attributes of the intended information. Furthermore, unlike previous studies [38], [39] where vibrators were arranged linearly or within a two-dimensional plane, our approach leverages a three-dimensional vibrator array encircling the wrist, which has spatial distinctiveness through variations in spatial parameters. Hence, our hypothesis posits that tactons aligning with both the semantic attributes of conveyed information and the sensory characteristics inherent in distinct vibrotactile feedback for stationary and moving tactons may offer enhanced benefits for differentiation and identification. To investigate this, we compared the recognition rates of the aforementioned two tacton groups and another tacton group that combines both.

A. METHOD

1) PARTICIPANTS

This study recruited ten sighted participants (7 males and 3 females) aged between 20 and 39 years (mean = 26.8, SD = 3.43). All participants were right-handed and none had prior experience with the vibratory tactile display used in this study. None of them had any problem with their sense of touch. Informed consent was obtained from them through a protocol approved by our Institutional Review Board, and they received compensation for their participation.

2) EXPERIMENT CONDITIONS

The objective of this experiment was to compare and evaluate the information recognition rates of three different tacton groups (figure 3): two control groups using a single set of tactons, one stationary (ST) and one moving (MV), and an experimental group with a combination of the aforementioned two sets (ST + MV). The tactons were designed to include modules representing the most basic spatial positions, such as top, bottom, right, left, front, back, horizontal, and vertical. To enable movement in the MV, its pattern must comprise of at least two vibrators. Thus, the tactons within ST group were designed to be driven by two vibrators of identical location to control the variability caused by differences in the number and position of driven vibrators. The stationary (ST) group was established by simultaneously activating two vibrators at specific locations. This created an illusion of vibration located at the center point between the two corresponding vibrators, which elicited phantom sensations. The moving (MV) group was created by sequentially driving two vibrators in a specific direction, thereby leading to a perception of the vibratory movement through an illusionary tactile sensation. The experimental group used in this study was a hybrid tacton group that combined stationary and moving tactons (ST + MV). Additionally, to evaluate the recognition rate of tactons without any specific meaning or messages associated with them, the numbers were mapped to the tactons while excluding any intentional mapping of specific meanings to them.

3) PROCEDURE

Prior to commencement of the experiment, the participants were provided written instructions and verbal explanations by the researcher. Next, the participants wore the devices on their dominant arms, i.e., their right wrists, and assumed a comfortable posture while placing their arms on a prepared table (figure 4). The experiment involved three sessions designed to assess the recognition rate of information conveyed through different tacton groups. Each session included a training part to familiarize participants with the tactons of the respective tacton group, and a main part that involved an absolute identification test to measure the information recognition rate. Throughout all sessions, participants were guided to verbalize the corresponding tacton number they perceived upon presentation of the vibratory stimulus. The absolute identification test comprised 80 randomized trials in which each of the eight pieces of information (tactons) in a pattern group was repeated 10 times. The experiment

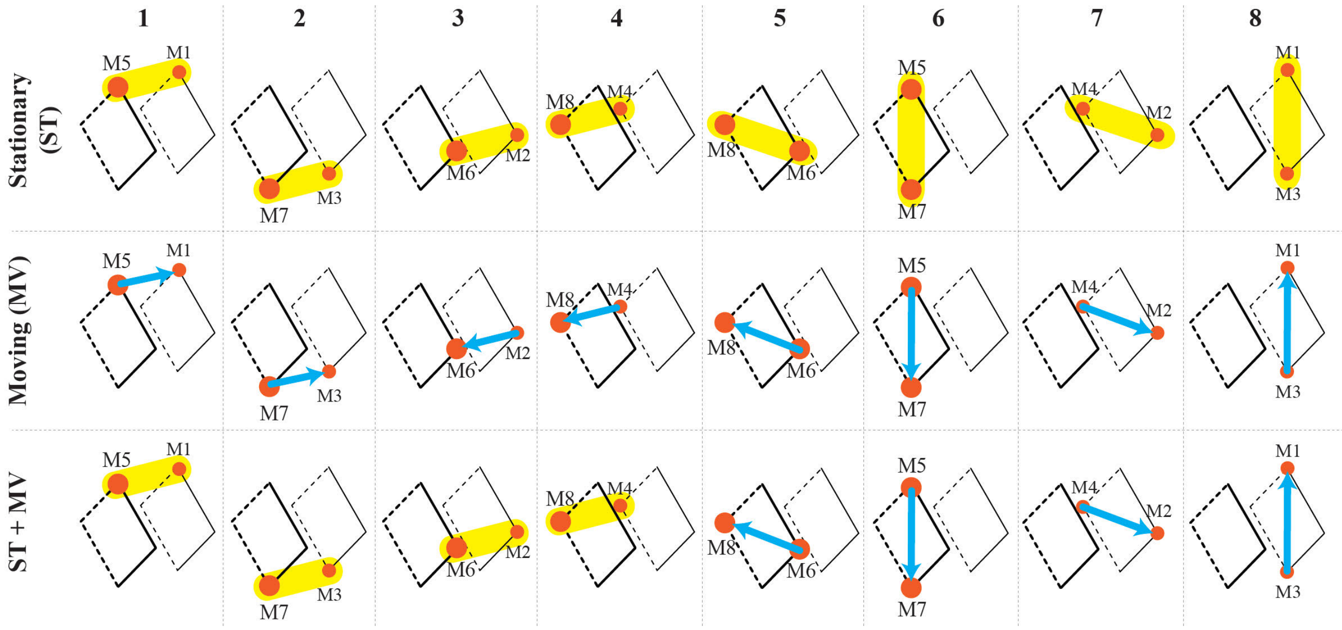

FIGURE 3. Configured tactons for each groups: ST, MV, and ST + MV (categorization strategy applied).

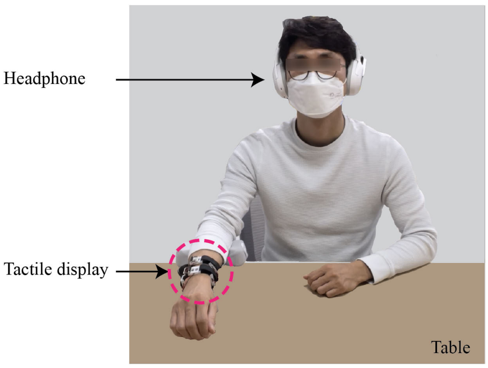

FIGURE 4. Experimental set-up for evaluation of preliminary study.

employed a within-subjects design, and each participant performed all the pattern groups in a randomized order to exclude the learning effect. Each session included a 10 min break, thus resulting in a total experiment time of approximately 1 h 30 min.

4) METRICS

This study aims to evaluate the recognition accuracy of tactons as a measure of information clarity within a configured tacton group. We adopted the absolute identification paradigm to evaluate the participants' ability to identify different tactons. The estimate of information transfer (IT_{est}) can be calculated from a participant's stimulus-response confusion matrix, with the following relation:

$$IT_{est} = \sum_{j=1}^{k} \sum_{i=1}^{k} \frac{n_{ij}}{n} \log_2 \left(\frac{n_{ij} \cdot n}{n_i \cdot n_j} \right) \tag{1}$$

where n is the total number of trials, n_{ij} is the number of trials that the participant identified the stimulus i (S_i) as j (R_j). n_i is the total number of times that the stimulus i is presented ($n_i = \sum_{j=1}^{k} n_{ij}$), and n_j is the total count of the response j ($n_j = \sum_{i=1}^{k} n_{ij}$). More detailed explanations on absolute identification experiment design and related issues can be found in [50]. Furthermore, during each training session, participants were allowed to freely experience the desired tactons, and the time taken by participants to become adequately acquainted with the tactons until they judged that all tactons were distinguishable was recorded as the 'learning time,' enabling an examination of the speed and efficiency of information acquisition.

Through these metrics, a comparative analysis and evaluation of information recognition accuracy and recognition speed among the tacton groups was performed. As previously mentioned, the order in which participants experienced the tacton groups was randomized to mitigate any potential learning effect. We compared and evaluated the IT rate and learning time based on the experimental sequence to ascertain the presence of any learning effect.

B. RESULTS

1) VERIFICATION OF LEARNING EFFECT

Prior to checking for any differences in the information recognition rate between the tacton groups, we first checked for a potential learning effect based on the order of the sessions. We analyzed the information recognition rate (percentage of correct answers) according to the order of the sessions using ANOVA and found no significant difference ($F(2, 27) = 0.20, p = 0.8199$). The IT rate did not exhibit any specific trend such as increasing or decreasing. By contrast, the

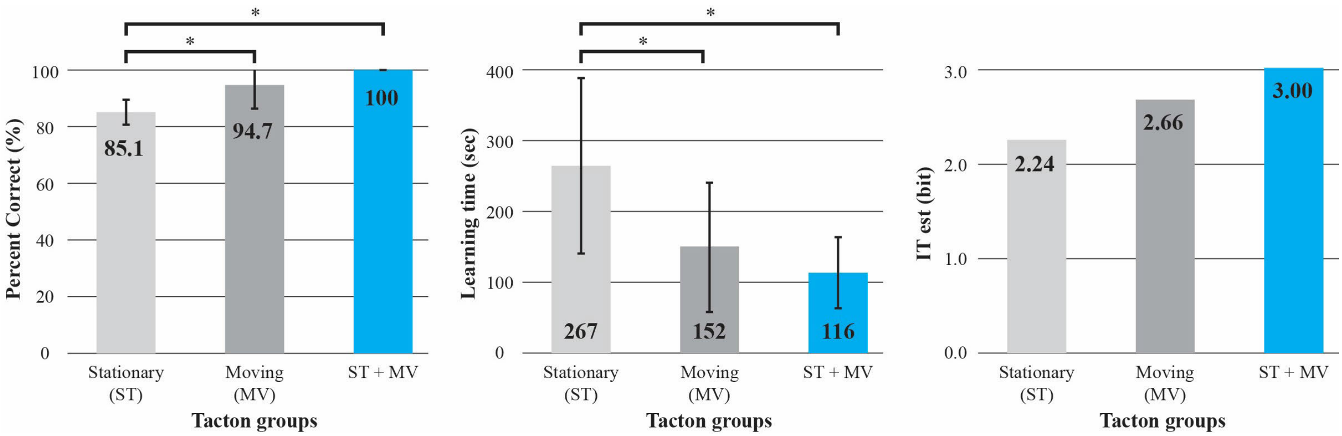

FIGURE 5. Result of identification test in preliminary study. The mark * indicates a significant difference between the tacton groups at 0.05 significance level.

learning time showed a statistically significant difference ($F(2, 27) = 4.44, p = 0.0215$). The results confirmed that as the session progressed regardless of the tacton group, familiarity with tactons increased and the learning speed also tended to increase. However, no learning effect was observed on the information recognition rate.

2) RECOGNITION RATE

Regarding the information recognition accuracy, the ST group, MV group, and their combination, ST + MV group exhibited average recognition rates of 85.1%, 94.7%, and 100%, respectively (figure 5). These results indicate that the tacton group containing MV tactons, either wholly or partially, demonstrated a higher recognition rate than the ST tacton group. Notably, all subjects were able to distinguish tactons without confusion in the case of ST + MV. Next, we conducted an ANOVA to assess the information recognition rate between the tacton groups. Our analysis revealed a significant difference between the three groups ($F(2, 27) = 18.20, p = 9.89 \times E^{-6}$). According to post-hoc analyses (Tukey's HSD), the mean differences in recognition rates between the ST and MV groups and between the ST and ST + MV groups were statistically significant at a significance level of 0.05. Although no significant difference was found between the MV and ST + MV groups, there was a noteworthy improvement in the recognition rate.

3) LEARNING TIME

The experimental results on learning time for the tacton group are shown in figure 5. ANOVA conducted on the learning time between the tacton groups, regardless of the order of sessions, revealed a significant difference among the three groups ($F(2, 27) = 7.05, p = 0.0034$). Consistent with the previous findings, the post-hoc analyses (Tukey's HSD) revealed that the mean differences in recognition rates between the ST and MV groups and between the ST and ST + MV groups were statistically significant, whereas no significant difference was found between the MV and ST + MV groups at a significance level of 0.05. The difference in learning time may be attributed to individual variability; however, ST + MV required less time to learn, on average, than the other pattern groups, thereby suggesting that it was the easiest pattern to learn.

4) IT RATE

To evaluate the IT rates, confusion matrices from all participants were analyzed (figures 5 and 6). The results revealed a trend consistent with the information recognition rates, with the ST + MV tacton group exhibiting the highest IT rate, followed by the MV and ST groups. The ST + MV tacton group achieved a maximum IT rate of 3 bits when all 8 pieces of information were accurately transmitted without errors. This finding highlights the effectiveness of the ST + MV tacton group in transmitting information with high accuracy.

Further analysis of the confusion matrices revealed that the ST tacton group had a higher number of incorrect answers than the MV and ST + MV tacton groups. Specifically, tacton numbers 5-8, which comprised driving modules located across each other rather than adjacent modules, were more prone to errors. These tactons resulted in confusion in cognition due to difficulties in discriminating between the front/back or horizontal/vertical directions, thereby leading to several incorrect answers (e.g., erroneously identifying tacton 7 as 5 and tacton 8 as 6 during front/back discrimination and misidentifying tacton 6 as 5 and tacton 8 as 7 during horizontal/vertical discrimination).

C. DISCUSSION

In our experimental trials, the ST group exhibited the worst performance, followed by the MV and ST + MV groups. By analyzing instances in the confusion matrix in which more than four subjects provided incorrect responses, we identified several underlying factors. First, most participants provided the feedback that the front/back judgment of whether the vibration was driven in the front or back array of the vibrators

No. of persons wrong answer: 7, 6, 5, 4

1. Stationary (ST)

Response (j) \ Stimulus (i)	1	2	3	4	5	6	7	8
1	95	0	0	0	0	4	0	2
2	0	94	0	0	1	3	2	4
3	0	1	95	0	1	0	7	0
4	0	0	0	95	5	1	7	0
5	0	0	3	4	91	8	22	1
6	2	2	0	0	0	79	1	5
7	1	0	0	0	1	1	57	5
8	1	3	0	1	0	4	4	83

2. Moving (MV)

Response (j) \ Stimulus (i)	1	2	3	4	5	6	7	8
1	95	0	0	0	0	0	2	1
2	1	97	0	0	0	0	3	2
3	0	0	98	0	0	0	1	0
4	1	0	0	90	0	0	4	0
5	0	0	1	0	100	0	1	1
6	2	2	0	1	0	99	2	0
7	0	0	1	7	0	0	87	2
8	1	1	0	1	0	1	0	94

3. ST + MV

Response (j) \ Stimulus (i)	1	2	3	4	5	6	7	8
1	100	0	0	0	0	0	0	0
2	0	100	0	0	0	0	0	0
3	0	0	100	0	0	0	0	0
4	0	0	0	100	0	0	0	0
5	0	0	0	0	100	0	0	0
6	0	0	0	0	0	100	0	0
7	0	0	0	0	0	0	100	0
8	0	0	0	0	0	0	0	100

FIGURE 6. Result of confusion matrix according to each tacton group.

was unclear. Second, in the ST group, when the vibrators that were located opposite each other, e.g., tacton numbers 5-8 vibrated simultaneously, a challenging distinction occurred owing to phantom sensation. Finally, distinguishing tactons in which vibrators, e.g., module numbers 2 or 4, which are in contact with relatively rigid parts of the wrist are activated, poses a challenge. An analysis of these issues is as follows.

The ST group employed simultaneous vibrations from two vibrators to generate a phantom-sensation illusion. For instance, in the cases of tactons 5 and 6, the perceived location of the phantom sensation for both tactons was close to the central position between the two vibrators. This concurrent vibration of the two vibrators at the crossing position may lead to confusion in the perception of the ST tacton. In addition, vibrations generated by modules 2 or 4, such as tacton 7, may propagate to the surrounding area, thereby leading to a reduction in tacton perception. These challenges were addressed by designing tactons 5-8 within the MV group. By sequentially activating the two vibrators, the first vibrator served as a reference for discerning the direction of movement, thereby enabling judgments for forward and backward as well as horizontal and vertical movements. Distinct mapping of movement direction also contributed to the enhancement of recognition rates. The MV group mitigated confusion in information recognition compared with the tactile information provided solely by the ST group. Furthermore, the combination of these two groups resulted in an improved information recognition rate.

V. USER TEST

This user test aims to apply the following finding, which combining tacton groups with distinct vibration characteristics proved more effective for information recognition, to a navigation system for individuals with visual impairments (BVI). Furthermore, this test also assesses the effectiveness and usability of this system. To apply this configuring tacton method to a navigation system, we used a categorization strategy that categorizes the information to be provided based on its characteristics and maps the respective tacton groups to the corresponding categorized information groups. The evaluation was conducted with blind participants to validate the proposed approach.

TABLE 2. Categorized information with respect to characteristics of it.

Category	A	B
Characteristics of Information	Providing continuously	Providing when an event occurred
Categorized Information	**1. Status information** Veering **2. Direction information** Turning Point Forward, Backward Right, Left	**3. Spatial information** Obstacles Stairs Doors Arrival (destination)
Vibration pattern	**Stationary**	**Moving**

A. CATEGORIZATION OF INFORMATION

The categorization strategy classifies information based on its characteristics and maps it to different groups of tactons. This approach aims to enhance the speed and accuracy of information recognition by matching tacton groups with characteristics that closely represent the distinctive features of the categorized information. The information required by visually impaired individuals for wayfinding includes spatial information for assessing the surrounding environment, status information for monitoring walking progress, and directional information for orientation. Based on the characteristics of the information, it is divided into two categories (table 2). The first category comprises the status and directional information that must be frequently provided while walking. The second category comprises the spatial information that is occasionally provided upon the occurrence of specific events, such as reaching a particular location. This categorized information was mapped to different tacton groups; these tactons are described in figures 8.

B. TACTON WITH RESPECT TO CATEGORIZED INFORMATION

Based on the results of the preliminary study, the device utilizes both ST tactons for status and directional information and MV tactons for spatial information to convey categorized information (figures 8). The use of this simple and intuitive ST tacton is expected to minimize fatigue accumulation and cognitive errors resulting from continuous information delivery while walking. Spatial information, which includes information on potentially dangerous elements such as obstacles and stairs, requires enhanced recognition, and it was conveyed using the MV tacton group. The details of each tacton group for the categorized information are as follows:

1) STATUS INFORMATION

Status information is composed within ST tacton group and conveyed through one type of tacton: "Veering." The "Veering" tacton informs pedestrians about their path-following accuracy by comparing their current direction to the planned direction and distinguishing between "Weak Veering" (15°) and "Strong Veering" (45°). For example, when a deviation occurs in the left direction, the device transmits a vibration signal to the left module, indicating the need for orientation correction to the right. Conversely, if the user veers to the right, vibrations emanate from the right-sided M2 module. These vibrotactile stimulations are delivered to effectively communicate the direction of the veering. This tacton was developed based on the findings from our prior pilot experiment, where it was interpreted as conveying the meaning *"avoid moving in that direction"* when the "Veering" signal was presented to the participants. The "Weak Veering" and "Strong Veering" are distinguished by using a different number of vibrators driven and temporal parameters (as shown in figure 8). The situation in which no tactons are output, signifies the "Going Well" status.

2) DIRECTIONAL INFORMATION

Directional information includes the "Turning Point" tacton to indicate the point at which pedestrians must change direction and the "Direction" tactons to head to, also created with the ST tacton group. The directional information is presented in the front vibrator array (M2-M4) closest to the hand. The array provides directions through activation of the vibration modules associated with the intended direction (e.g., M2 on the right and M4 on the left), each being activated for a duration of 1.2 seconds, as illustrated in Figure 8. To indicate forward movement, the M1 module is activated for a duration of 1.2 seconds. Only a single-point vibrator is activated at each corresponding location. To ensure a clear differentiation from the status information, the temporal parameter is applied differently. Additionally, prior to providing directional information, a "Turning Point" tacton is provided to alert the user of an upcoming change in direction. The sets of four modules (M1-M4) in the front array vibrate simultaneously three times for different durations.

3) SPATIAL INFORMATION

The spatial information that aids in orientation while walking is composed within MV tacton group and comprises

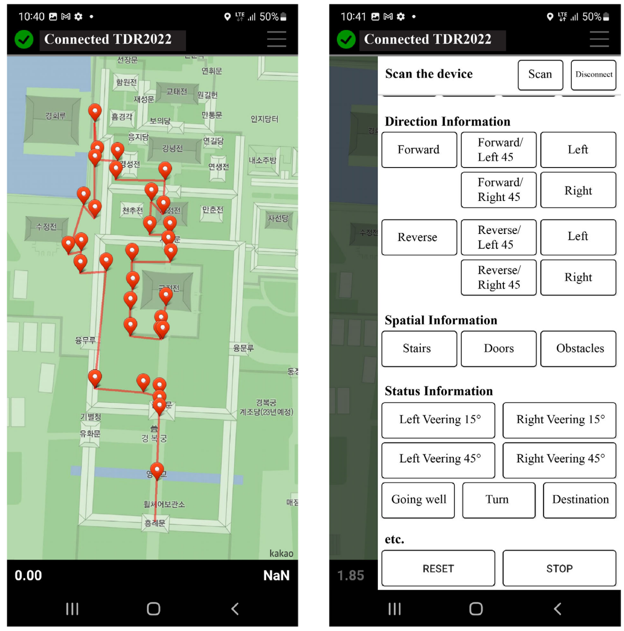

FIGURE 7. UI design of developed mobile application.

important landmarks such as "Stairs," "Door," and "Obstacle" as shown in figure 8. The number and placement of the vibrators activated for each tacton differ, and the tactons are designed with distinct temporal parameters, such as vibration time and interstimulus interval, to ensure clear differentiation between them.

To effectively provide tactile information to visually impaired individuals as an alternative channel, it is important to simplify the information provided [47], [48]. The "Stair" tacton was designed using the three modules of the sagittal plane (M7→M3→M1) to simulate the sensation of ascending from the flat ground. Ascending and descending stairs were symbolized as a single tacton, rather than providing them separately. The "Door" tacton was created using modules M2, M4, M6, and M8 in the transverse plane to mimic the horizontal opening and closing motions. The "Obstacle" tacton was represented as a rotating pattern that starts at module M1 in the coronal plane; passes through M2, M3, and M4; and finally returns to M1. Given the various types of obstacles encountered while walking, generating tactile information from them may decrease the recognition rates. Therefore, we chose to represent all obstacles using this particular tacton.

The spatial information encompasses an "Arrival (destination)" tacton, which indicates reaching the final destination. This was configured as a tacton that moves along both the vertical and horizontal planes to distinguish it from the other tactons.

C. MOBILE APPLICATION

The device was specifically designed to work in conjunction with a smartphone while walking independently, and an

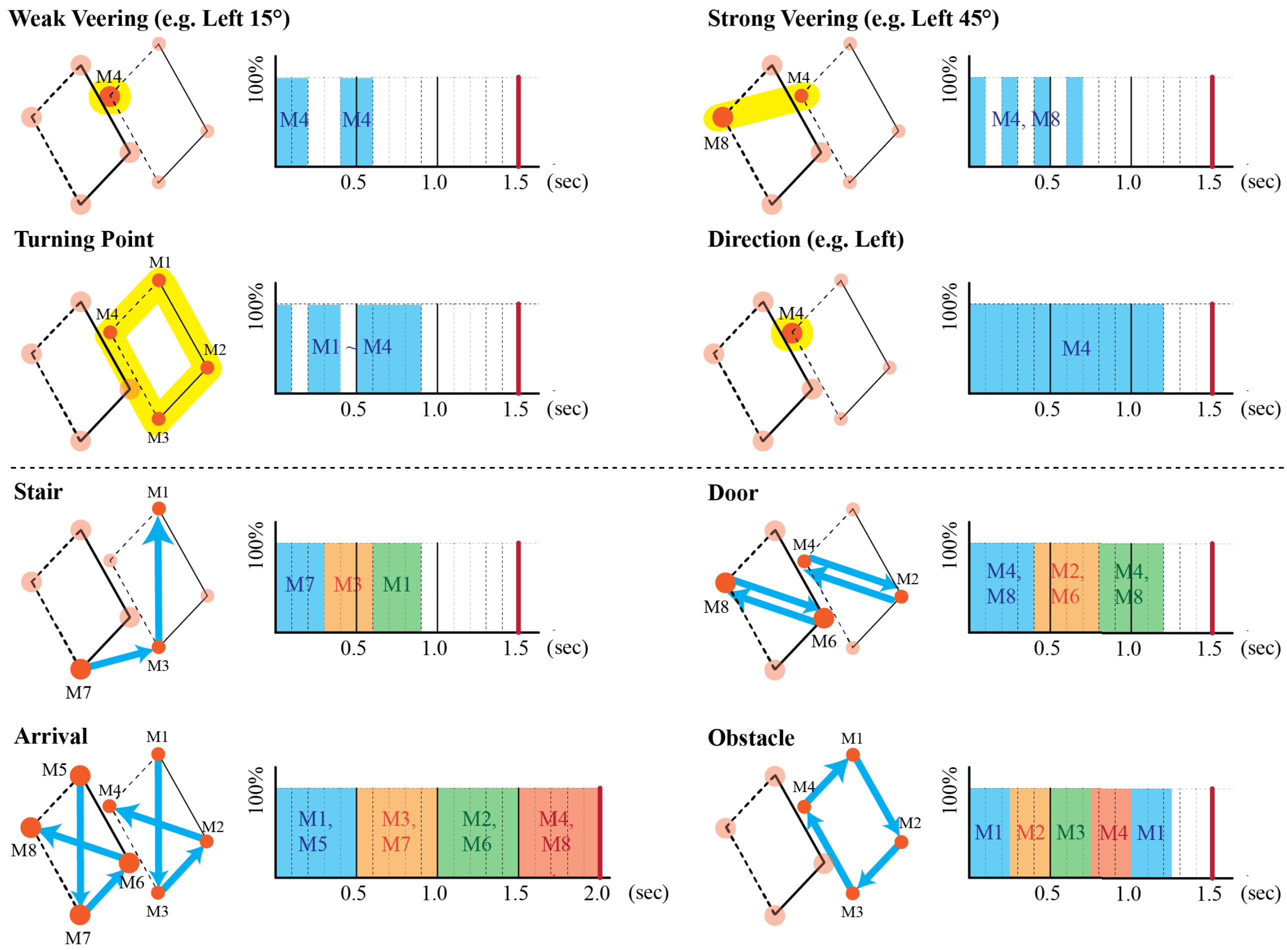

FIGURE 8. Tactons applied by the categorization strategy based on information provided during navigation for the BVI.

Android OS-based application was developed to enable this integration (figure 7). The mobile application was designed with a user interface (UI) to transmit commands directly to the tactile display, as shown in figure 7 (right). The experimenter, through the UI, transmitted the commands regarding the tactons to be delivered to the participants within the experimental space. Although the application can be used to automatically convey tactile information by utilizing GPS data, it was not employed in this experiment because of the inherent margin of error of approximately 3-7 m in GPS data accuracy [45], [46]. Furthermore, the interface can be effectively utilized for learning tacton in practical scenarios.

D. EXPERIMENTAL DESIGN

In this section, we discuss an experiment conducted to evaluate the usability of our device as a navigation system for the BVI during outdoor walks. The effectiveness of the configuration tacton method, which utilizes a categorization strategy, was validated through blind participants.

1) PARTICIPANTS

This study recruited seven blind participants (five males and two females) aged between 20 and 53 years (mean = 33, SD = 13.4). All the participants were right-handed and had no prior experience with the vibratory tactile display used in this study. None of them had any problem with their sense of touch. Informed consent was obtained from them through a protocol approved by our Institutional Review Board, and they received compensation for their participation.

2) EXPERIMENT CONDITION

Gyeongbokgung Palace in Seoul, South Korea, a pedestrian-only area with rich cultural and historical significance, was selected as the location for the walking task (figure 9) to minimize exposure to traffic hazards and ensure participant safety. The predetermined walking path included all the necessary information and covered a total distance of 727 m, starting from Geunjeongmun Gate and ending in front of Geunjeongjeon Gate. The walking route can be divided into two primary segments. The first segment is a prolonged 383-meter straight path with few turns, while the second segment is 344 meters long and includes more turning points and prominent landmarks. Because the experimental space was a palace, the pathway was paved with large stones or soil instead of typical pedestrian sidewalks, in which the cane got occasionally lodged, but

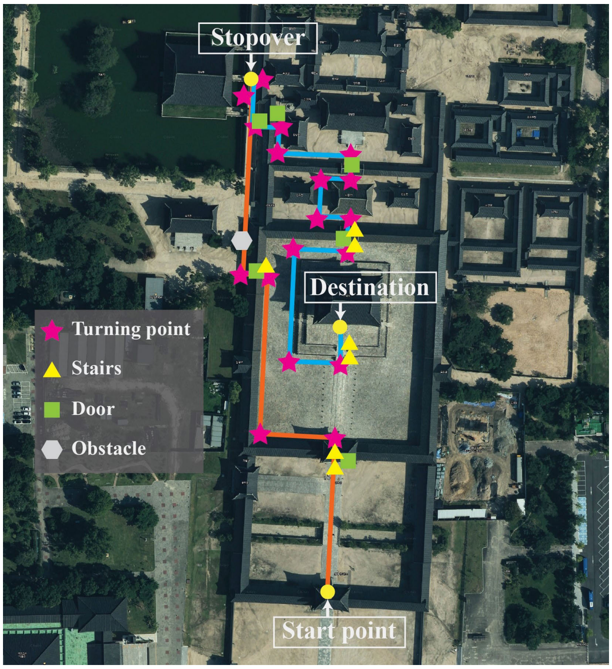

FIGURE 9. Pre-planned route for walking task. The orange line corresponds to segment 1 of the designated route, while the blue line represents segment 2 of the same route.

walking was not impeded. The path encompassed a total of 16 spatial information points and 19 turning points. Within the first segment, there were 7 spatial information points and 5 turning points, while the second segment had 9 spatial information points and 14 turning points. Additionally, there were 19 directional information points. The subjects received spatial and directional information according to their location, and status information based on their condition during walking.

3) PROCEDURE

The experiment involved a training session to familiarize the participants with the provided tactile information and a main session for the actual walking tasks. The training session was conducted indoors with the participants comfortably seated. They were provided with a tactile device to be worn on the left wrist. To avoid interference with the participants' white cane, the device was worn on the non-dominant arm.

The participants were given an explanation of the different types of tactile information, including status, directional, and spatial information. They were allotted approximately 15 min to learn the corresponding tactons. After a short break of approximately 5 min, the main session began and the participants were guided to the starting point of the walking task by the experimenter. The participants had no prior knowledge of the route and had to rely solely on the tactile information provided by the device to reach the destination. Upon completion of the task, subjective feedback was received from the participants. The entire process lasted for approximately 1 h 30 min.

TABLE 3. Result of mobility aspect in the walking task. (Seg is the segment of the walking route.)

Subject	Walking time (sec)			No. of walking error		
	Total	Seg 1	Seg 2	Total	Seg 1	Seg 2
A	1,571	840	731	22	14	8
B	1,494	806	688	30	21	9
C	1,503	793	710	39	24	15
D	1,138	565	573	25	18	7
E	1,220	648	572	17	11	6
F	1,128	566	562	16	8	8
G	1,492	808	684	12	11	1
Average	1,363.7	717.8	645.8	23	15.3	7.7
SD	192.8	120.9	73.2	9.3	5.4	3.8

In this experiment, the experimenter directly transmitted the necessary commands to provide tactile information to the device in proximity to the subject without using GPS data, to avoid any risks resulting from GPS data errors. In addition to command transmission, no other interventions were performed by the experimenter.

4) METRICS

To evaluate the usability of the device, two aspects were considered: 1) ability to recognize information and 2) mobility. To assess the users' ability to recognize information as the first aspect, both the information recognition rate and the corresponding response time were quantified. To measure the information recognition rate, the subjects were asked to verbally identify the information provided by the device when they recognized the tacton. The recognition rate was calculated as the percentage of correct answers from the total number of information outputs, which varied based on each participant's walking situation. The response time was determined by calculating the time elapsed between two consecutive events: the moment information was presented and the point at which subjects initiated their verbal responses.

As the second aspect of evaluation focuses on users' mobility, measurements encompassed both walking error and walking time. The occurrence of veering while walking was considered a walking error, and the number of errors was recorded. The duration of walking from the initial starting point to the destination was measured. All experimental procedures were recorded with a camera upon the informed consent of the subjects. The walking errors and duration were analyzed using the recorded video.

E. RESULTS AND DISCUSSION

1) RECOGNITION ASPECT

The results indicated that participants had a high level of accuracy in perceiving tactile information, with an average correct perception rate of 94.78% (SD = 3.65), as presented in table 4. Our results demonstrated a higher level of accuracy than approximately 70% of the results reported in [39] and 85.7% of those in [33]. Moreover, our results are comparable with 95.2% reported in [28] based on spatial acuity. In our detailed analysis of average information recognition rates categorized by the type of information provided, the following order was observed: directional information achieved a recognition rate of 97.9% (SD = 2.1), status information attained 96.1% (SD = 8.6), and spatial information exhibited 84.1% (SD = 9.8). The recognition of directional and status information, both composed of stationary tactons, showed higher accuracy compared to spatial information, which consists of moving tactons. This observation can be attributed to the lower cognitive load imposed by stationary tactons in scenarios necessitating continuous assessment of surrounding conditions and movement, such as during walking.

Notably, subject E achieved the highest accuracy rate, correctly recognizing 76 out of 77 tactile information deliveries, whereas subject G struggled to identify turning points, obstacles, and doors, resulting in 8 false responses out of 68 tactile information deliveries. Subject G exhibited the most substantial wrist dimensions among the participants, which posed a constraint on the proper positioning of each module of the device on the wrist. This limitation could potentially have contributed to difficulties in accurately recognizing the intended vibrotactile feedback for each tacton. Based on these findings, it can be concluded that implementation of the categorization strategy is highly effective for information recognition in navigation systems designed for the BVI.

The response times for recognizing tactile information varied across the different categories. Participants required an average of 5.42 s (SD = 2.24) to recognize spatial information, 3.03 s (SD = 1.08) for status information, and 2.41 s (SD = 1.05) for directional information. Directional information was recognized quickly compared to other information, because it was provided after the turning point tacton. However, spatial information, which consists of the MV group and can only be distinguished once the vibration pattern ends, required longer to recognize. Nonetheless, the recognition rate of it still remains high at 84.1%, and any potential inefficiencies may be mitigated through the minimization of response time, achieved by reducing the vibration duration of each tacton. Because obstacles and stairs in spatial information can indicate potential dangers, there is a need to develop tactons that can be recognized more quickly. Subjects E and G had the fastest (1.94 s) and slowest (5.52 s) response times in average, respectively, across all the types of information.

2) MOBILITY ASPECT

All participants successfully completed the walking task, with an average walking time of 22 min and 43 s (1,363 s, SD = 192 s); the results of the walking task are presented in figure 10 and table 3. When analyzed by segment, the first segment exhibited an average duration of 11 min and 57 s (717 s, SD = 120 s), while the second segment had an average duration of 10 min and 46 s (646 s, SD = 73 s), both segments maintaining an average speed of approximately 0.53 m/s, with no significant difference observed. Compared with the average walking speed of visually impaired individuals on a straight unobstructed walking path [49], approximately double time was required to complete the course. Given the challenging terrain of the course, which was paved with stones and soil, it was expected that more time would be required to complete the walking task than that on regular pedestrian roads. Furthermore, the given route, with its numerous obstacles, turning points, and staircases, and the large number of tourists in the experimental location might have been the factors which impeded the participants' walking. In addition, variations in walking speed and skill level may have contributed to the differences in completion times between the participants.

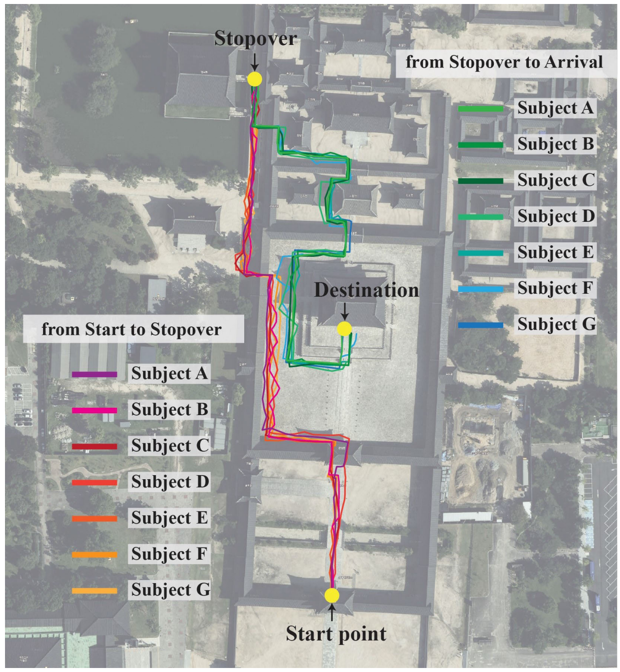

FIGURE 10. Walking routes of each participant in the walking task.

On average, the participants committed 23 errors (veering) (SD = 9.27). Specifically, during the first segment, an average of 15.3 walking errors occurred (SD = 5.4), which was nearly double the rate compared to the second segment, where an average of 7.7 walking errors were observed (SD = 3.8). While the results revealed the challenge faced by visually impaired participants in maintaining a straight line during long-distance walks, the number of observed errors was not considered a significant number, given the lack of guiding structures such as walls or curbs. Although the observed frequency of errors may appear substantial and walking accuracy remains an important consideration, it is even more crucial to recognize errors and make real-time adjustments to remain on a planned path for the BVI who frequently encounter formidable challenges in maintaining a consistent linear path [20]. Therefore, rather than interpreting a decrease in the efficiency of orientation and mobility as a direct result

TABLE 4. Result of recognition aspect in the walking task. (Sp: spatial information, St: status information, Di: directional information.)

Subject	Rate of correct perception				Number of information provided	Number of correct perception	Response time (sec)		
	Total	Sp	St	Di			Sp	St	Di
A	94.94	76.5	100	100	79	75	7.51	3.65	1.85
B	97.73	88.2	100	100	88	86	3.51	2.12	1.83
C	93.48	82.4	97.4	94.4	92	86	7.42	3.79	2.01
D	92.86	70.6	100	97.6	84	78	6.58	2.85	2.60
E	98.7	94.4	100	100	77	76	2.57	1.91	1.36
F	97.53	100	100	95.8	81	79	3.12	2.11	2.67
G	88.24	76.5	75.0	97.4	68	60	7.24	4.77	4.54
Average	94.78	84.1	96.1	97.9	81.3	77.1	5.42	3.03	2.41
SD	3.65	9.8	8.6	2.1	7.83	8.76	2.24	1.08	1.03

of errors, it can be observed that overall efficiency in the walking task can be enhanced from the participants' capacity that re-establishing the original trajectory through the Veering tacton even in the presence of errors. In some cases, making fine turns as feedback for "weak veering" was challenging, thereby resulting in zigzag walking patterns. However, all the participants were able to reach their destinations without losing their way.

In summary, participants were able to quickly learn the categorized tactile information provided by the device, typically within 15 min. Moreover, they successfully navigated to their intended destinations by relying solely on tactile information obtained through the device, without prior knowledge of the route.

VI. CONCLUSION

This study proposed a novel wrist-worn vibrotactile display with eight vibrators that can deliver easily distinguishable directional, spatial, and status information necessary for the navigation of the BVI. To improve the recognition rates for large amounts of information, a categorization strategy was used to design the tactons. The respective information was categorized according to the characteristics and expressed by different groups of tactons. In a preliminary study, combining two tacton groups, namely ST and MV, each characterized by distinct vibration patterns, proved to be more effective for information recognition, thereby achieving a 100% recognition rate. The validated results were then applied to our navigation system for the BVI. Through a user test, seven blind novices were able to learn the vibrotactile information provided over a short period. Although there were slight differences depending on the subject, the results provided an accurate recognition rate of 94.78% on average. Finally, all participants could reach the destination using only the tactile information obtained through the device, without any prior information about the route. Overall, the proposed vibrotactile display and categorization strategy represent an important step in developing walking aids for the BVI. Further studies can improve the usability and effectiveness of our research.

In this study, only four types of spatial information was used to provide for the BVI: "Stairs," "Doors," "Obstacles," and "Arrival." The selection was based on the need to keep the information simple and relevant to the experimental space. While this device provides the relevant information, it operates based on GPS data rather than using detection technology. Therefore, combined utilization with a white cane is recommended in the current state, particularly in light of existing GPS limitations and inaccuracies. In future studies, additional landmarks relevant to a general road environment should be included with appropriate tactons. In addition, a database that incorporates obstacle location data into the mobile map of the system is necessary because of the diverse types and large number of obstacles.

Regarding directional information, modules arranged around the wrist provide the corresponding directional information. However, this approach is limited because the changes in wrist orientation are not reflected. To address this issue, a sensor that can measure position and orientation in real time can be integrated into our system. This would enable the target direction to be consistently mapped and displayed according to the user's wrist position. Moreover, haptic rendering can be designed to provide precise directional information in 3D by using the device arrangement.

REFERENCES

[1] P. Ackland, S. Resnikoff, and R. Bourne, "World blindness and visual impairment: Despite many successes, the problem is growing," *Community Eye Health*, vol. 30, no. 100, p. 71, 2017.

[2] *Survey on the Convenience of the Transportation Vulnerable*, Ministry Land, Infrastruct. Transp., Sejong, South Korea, 2015.

[3] W. Kim, Y. Lee, and S. Kim, "Examination of public transit use patterns and development of high-tech walking-aid system at public transit facilities for the blind and visually impaired," *Seoul Stud.*, vol. 10, no. 3, pp. 97–114, 2009.

[4] W. Kim, S. Lee, and S. Kim, "A study on travel behavior of the mobility handicapped and custom-made transit information system," *Seoul Stud.*, vol. 9, no. 2, pp. 105–119, 2008.

[5] L. A. Jones and N. B. Sarter, "Tactile displays: Guidance for their design and application," *Hum. Factors, J. Hum. Factors Ergonom. Soc.*, vol. 50, no. 1, pp. 90–111, Feb. 2008.

[6] B. Weber, S. Schätzle, T. Hulin, C. Preusche, and B. Deml, "Evaluation of a vibrotactile feedback device for spatial guidance," in *Proc. IEEE World Haptics Conf.*, Jun. 2011, pp. 349–354.

[7] Y. Wang and K. J. Kuchenbecker, "HALO: Haptic alerts for low-hanging obstacles in white cane navigation," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2012, pp. 527–532.

[8] J. Hertel, A. Schaare, P. Feuerbach, O. Ariza, and F. Steinicke, "STIC—Sensory and tactile improved cane," in *Proc. Mensch Comput.*, Sep. 2019, pp. 765–769.

[9] C. Shah, M. Bouzit, M. Youssef, and L. Vasquez, "Evaluation of RU-netra—Tactile feedback navigation system for the visually impaired," in *Proc. Int. Workshop Virtual Rehabil.*, 2006, pp. 72–77.

[10] G. Flores, S. Kurniawan, R. Manduchi, E. Martinson, L. M. Morales, and E. A. Sisbot, "Vibrotactile guidance for wayfinding of blind walkers," *IEEE Trans. Haptics*, vol. 8, no. 3, pp. 306–317, Jul. 2015.

[11] A. Cosgun, E. A. Sisbot, and H. I. Christensen, "Evaluation of rotational and directional vibration patterns on a tactile belt for guiding visually impaired people," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Feb. 2014, pp. 367–370.

[12] R. K. Katzschmann, B. Araki, and D. Rus, "Safe local navigation for visually impaired users with a time-of-flight and haptic feedback device," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 3, pp. 583–593, Mar. 2018.

[13] D. Ni, L. Wang, Y. Ding, J. Zhang, A. Song, and J. Wu, "The design and implementation of a walking assistant system with vibrotactile indication and voice prompt for the visually impaired," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2013, pp. 2721–2726.

[14] V. Pradeep, G. Medioni, and J. Weiland, "Robot vision for the visually impaired," in *Proc. IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognit. Workshops*, Jun. 2010, pp. 15–22.

[15] V. Pradeep, G. Medioni, and J. Weiland, "A wearable system for the visually impaired," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol.*, Aug. 2010, pp. 6233–6236.

[16] S.-B. Han, D.-H. Kim, and J.-H. Kim, "Fuzzy gaze control-based navigational assistance system for visually impaired people in a dynamic indoor environment," in *Proc. IEEE Int. Conf. Fuzzy Syst. (FUZZ-IEEE)*, Aug. 2015, pp. 1–7.

[17] N. Bourbakis, R. Keefer, D. Dakopoulos, and A. Esposito, "A multimodal interaction scheme between a blind user and the Tyflos assistive prototype," in *Proc. 20th IEEE Int. Conf. Tools Artif. Intell.*, Nov. 2008, pp. 487–494.

[18] D. Dakopoulos and N. Bourbakis, "Towards a 2D tactile vocabulary for navigation of blind and visually impaired," in *Proc. IEEE Int. Conf. Syst., Man Cybern.*, Oct. 2009, pp. 45–51.

[19] V. A. de Jesus Oliveira, L. Nedel, A. Maciel, and L. Brayda, "Localized magnification in vibrotactile HMDs for accurate spatial awareness," in *Haptics: Perception, Devices, Control, and Applications*. London, U.K.: Springer, Jul. 2016, pp. 55–64.

[20] V. A. de Jesus Oliveira, L. Nedel, A. Maciel, and L. Brayda, "Anti-veering vibrotactile HMD for assistance of blind pedestrians," in *Haptics: Perception, Devices, Control, and Applications*. Pisa, Italy: Springer, Jun. 2018, pp. 500–512.

[21] S. Vorapatratorn and K. Teachavorasinskun, "iSonar-2: Obstacle warning device, the assistive technology integrated with universal design for the blind," in *Proc. 11th Int. Conv. Rehabil. Eng. Assistive Technol.*, 2017, p. 22.

[22] R. Velázquez and O. Bazán, "Preliminary evaluation of podotactile feedback in sighted and blind users," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol.*, Aug. 2010, pp. 2103–2106.

[23] S. Schaack, G. Chernyshov, K. Ragozin, B. Tag, R. Peiris, and K. Kunze, "Haptic collar: Vibrotactile feedback around the neck for guidance applications," in *Proc. 10th Augmented Hum. Int. Conf.*, Mar. 2019, pp. 1–4.

[24] E. Pezent, P. Agarwal, J. Hartcher-O'Brien, N. Colonnese, and M. K. O'Malley, "Design, control, and psychophysics of Tasbi: A force-controlled multimodal haptic bracelet," *IEEE Trans. Robot.*, vol. 38, no. 5, pp. 2962–2978, Oct. 2022.

[25] K. J. Kim and D.-H. Shin, "An acceptance model for smart watches: Implications for the adoption of future wearable technology," *Internet Res.*, vol. 25, no. 4, pp. 527–541, Aug. 2015.

[26] S. Schätzle, T. Ende, T. Wüsthoff, and C. Preusche, "VibroTac: An ergonomic and versatile usable vibrotactile feedback device," in *Proc. 19th Int. Symp. Robot Hum. Interact. Commun.*, Sep. 2010, pp. 670–675.

[27] S. Schätzle and B. Weber, "Towards vibrotactile direction and distance information for virtual reality and workstations for blind people," in *Universal Access in Human-Computer Interaction. Access to Interaction*. Los Angeles, CA, USA: Springer, Aug. 2015 pp. 148–160.

[28] J. V. S. Luces, K. Ishida, and Y. Hirata, "Human position guidance using vibrotactile feedback stimulation based on phantom-sensation," in *Proc. IEEE Int. Conf. Cyborg Bionic Syst. (CBS)*, Sep. 2019, pp. 235–240.

[29] J. V. S. Luces, K. Okabe, Y. Murao, and Y. Hirata, "A phantom-sensation based paradigm for continuous vibrotactile wrist guidance in two-dimensional space," *IEEE Robot. Autom. Lett.*, vol. 3, no. 1, pp. 163–170, Jan. 2018.

[30] J. Salazar, K. Okabe, and Y. Hirata, "Path-following guidance using phantom sensation based vibrotactile cues around the wrist," *IEEE Robot. Autom. Lett.*, vol. 3, no. 3, pp. 2485–2492, Jul. 2018.

[31] J. Hong, L. Stearns, J. Froehlich, D. Ross, and L. Findlater, "Evaluating angular accuracy of wrist-based haptic directional guidance for hand movement," in *Proc. Graph. Interface*, 2016, pp. 195–200.

[32] J. Hong, A. Pradhan, J. E. Froehlich, and L. Findlater, "Evaluating wrist-based haptic feedback for non-visual target finding and path tracing on a 2D surface," in *Proc. 19th Int. ACM SIGACCESS Conf. Comput. Accessibility*, Oct. 2017, pp. 210–219.

[33] J.-H. Tang, G. Raffa, and L. Chan, "Design of vibrotactile direction feedbacks on wrist for three-dimensional spatial guidance," in *Cross-Cultural Design. User Experience of Products, Services, and Intelligent Environments*. Copenhagen, Denmark: Springer, Jul. 2020, pp. 169–182.

[34] D. J. Gense, M. Gense, and R. Marsh, "The importance of orientation and mobility skills for students who are deaf-blind," Nat. Inf. Clearinghouse Children Who Are Deaf-Blind, Helen Keller Nat. Center Perkins School Blind Teach. Res., Watertown, MA, USA, 1999.

[35] G. Virgili and G. Rubin, "Orientation and mobility training for adults with low vision," *Cochrane Database Systematic Rev.*, no. 5, 2010, Art. no. CD003925.

[36] K. MacLean and M. Enriquez, "Perceptual design of haptic icons," in *Proc. EuroHaptics*, 2003, pp. 351–363.

[37] S. A. Brewster and L. M. Brown, "Tactons: Structured tactile messages for non-visual information display," in *Proc. Australas. User Interface Conf.*, Dunedin, New Zealand, 2004, pp. 15–23.

[38] Y. Kim, M. Harders, and R. Gassert, "Identification of vibrotactile patterns encoding obstacle distance information," *IEEE Trans. Haptics*, vol. 8, no. 3, pp. 298–305, Jul. 2015.

[39] S. D. Novich and D. M. Eagleman, "Using space and time to encode vibrotactile information: Toward an estimate of the skin's achievable throughput," *Exp. Brain Res.*, vol. 233, no. 10, pp. 2777–2788, Oct. 2015.

[40] H. E. Burtt, "Tactual illusions of movement," *J. Exp. Psychol.*, vol. 2, no. 5, p. 371, 1917.

[41] A. Israr and I. Poupyrev, "Tactile brush: Drawing on skin with a tactile grid display," in *Proc. SIGCHI Conf. Human Factors Comput. Syst.*, May 2011, pp. 2019–2028.

[42] E. Piateski and L. Jones, "Vibrotactile pattern recognition on the arm and torso," in *Proc. 1st Joint Eurohaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2005, pp. 90–95.

[43] L. A. Jones, J. Kunkel, and E. Piateski, "Vibrotactile pattern recognition on the arm and back," *Perception*, vol. 38, no. 1, pp. 52–68, Jan. 2009.

[44] C. M. Reed, H. Z. Tan, Z. D. Perez, E. C. Wilson, F. M. Severgnini, J. Jung, J. S. Martinez, Y. Jiao, A. Israr, F. Lau, K. Klumb, R. Turcott, and F. Abnousi, "A phonemic-based tactile display for speech communication," *IEEE Trans. Haptics*, vol. 12, no. 1, pp. 2–17, Jan. 2019.

[45] A. Spiers, E. Young, and K. J. Kuchenbecker, "The S-BAN: Insights into the perception of shape-changing haptic interfaces via virtual pedestrian navigation," *ACM Trans. Comput.-Hum. Interact.*, vol. 30, no. 1, pp. 1–31, Feb. 2023.

[46] A. J. Spiers and A. M. Dollar, "Design and evaluation of shape-changing haptic interfaces for pedestrian navigation assistance," *IEEE Trans. Haptics*, vol. 10, no. 1, pp. 17–28, Jan. 2017.

[47] G. Jansson, "Basic issues concerning visually impaired people's use of haptic displays," in *Proc. Int. Conf. Disabilities*, 2000, pp. 33–38.

[48] T. Pun, P. Roth, G. Bologna, K. Moustakas, and D. Tzovaras, "Image and video processing for visually handicapped people," *EURASIP J. Image Video Process.*, vol. 2007, pp. 1–12, Dec. 2008.

[49] D. D. Clark-Carter, A. D. Heyes, and C. I. Howarth, "The gait of visually impaired pedestrians," *Hum. Movement Sci.*, vol. 6, no. 3, pp. 277–282, Sep. 1987.
[50] H. Z. Tan, "Identification of sphere size using the PHANToM^{TM}: Towards a set of building blocks for rendering haptic environment," in *Proc. ASME Int. Mech. Eng. Congr. Expo.*, vol. 18244. New York, NY, USA: American Society of Mechanical Engineers, 1997, pp. 197–203.
[51] K. Myles and M. S. Binseel, "The tactile modality: A review of tactile sensitivity and human tactile interfaces," U.S. Army Res. Lab., Aberdeen Proving Ground, MD, USA, Tech. Rep. ARL-TR-4115, 2007.
[52] Z. Wei, A. Song, and X. Hu, "Object localization assistive system based on CV and vibrotactile encoding," in *Proc. 44th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2022, pp. 2882–2885.
[53] N. Bayat, J.-H. Kim, R. Choudhury, I. F. Kadhim, Z. Al-Mashhadani, M. A. D. Virgen, R. Latorre, R. D. L. Paz, and J.-H. Park, "Vision transformer customized for environment detection and collision prediction to assist the visually impaired," *J. Imag.*, vol. 9, no. 8, p. 161, Aug. 2023.
[54] H. Z. Tan, C. M. Reed, Y. Jiao, Z. D. Perez, E. C. Wilson, J. Jung, J. S. Martinez, and F. M. Severgnini, "Acquisition of 500 English words through a tactile phonemic sleeve (TAPS)," *IEEE Trans. Haptics*, vol. 13, no. 4, pp. 745–760, Oct. 2020.
[55] C. M. Reed, H. Z. Tan, Y. Jiao, Z. D. Perez, and E. C. Wilson, "Identification of words and phrases through a phonemic-based haptic display: Effects of inter-phoneme and inter-word interval durations," *ACM Trans. Appl. Perception*, vol. 18, no. 3, pp. 1–22, Jul. 2021.
[56] C. M. Reed, D. Kanevsky, J. G. Desloge, J. S. Martinez, and H. Z. Tan, "Phonemic-based tactile supplement to lipreading: Initial findings on consonant identification," in *International Workshop on Haptic and Audio Interaction Design, HAID 2022, London, UK, August 25–26, 2022, Proceedings*. Springer, 2022, pp. 25–34.

MYUNGJOONG LEE (Member, IEEE) is currently pursuing the Ph.D. degree with the Center for Healthcare Robotics, Korea Institute of Science and Technology, and the Division of Nano-Information Technology (HCI and Robotics), University of Science and Technology. His research interests include human–computer interaction, interaction design, and assistive device for the blind and visually impaired, with a focus on tactile display and tangible media.

HYUNKI IN (Member, IEEE) received the Ph.D. degree. He is currently a Mechanical Engineer with an interest in wearable robots, care robots, and devices. He is also a Senior Researcher with the Center for Healthcare Robotics, Korea Institute of Science and Technology.