International Journal of Industrial Ergonomics 57 (2017) 1–9

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Non-visual traffic signal information: An investigation of the recognition performance of blind users using the wearable tactile traffic lights assist device

Hsinfu Huang*, Tai-Chun Lin, Dengchuan Cai

Department of Industrial Design, National Yunlin University of Science and Technology, Taiwan, ROC

A R T I C L E I N F O

Article history:
Received 11 December 2015
Received in revised form
5 October 2016
Accepted 2 November 2016
Available online 11 November 2016

Keywords:
Wearable tactile traffic lights assistive device (WTTLAD)
Tactile recognition
Performance

A B S T R A C T

Visually impaired people face numerous obstacles and troubles in their daily life. In particular, safely crossing the road is an obvious problem. In this study, a wearable tactile traffic lights assistive device (WTTLAD) was designed for visually impaired people, and its effectiveness was verified through a performance experimental design. We recruited visually impaired and blindfolded sighted subjects to test the WTTLAD. The subjects' performance was investigated in two experimental fields: in a laboratory (indoor field) and at a road intersection (outdoor field). The results show that the tactile recognition performance of the visually impaired subjects was higher than that of their blindfolded counterparts for the WTTLAD. The correct recognition rate did not differ significantly between the visually impaired and blindfolded sighted subjects in the indoor field. By contrast, a significant difference was observed in the outdoor field. Overall, the visually impaired subjects attained more stable performance than the blindfolded sighted subjects did in the outdoor experimental field, and their average correct recognition rate reached 96.67%. The results indicate that the blindfolded subjects were more likely to be disturbed by preexisting visual experiences and environmental noise. The tactile working memory of the visually impaired subjects was a crux on the preponderance of their tactile recognition performance. We anticipate enhancing the safety and reliability of visually impaired people by promoting the proposed device to assist them with crossing road intersections.

1. Introduction

In humans, the visual receptors are generally the main receptors for receiving most messages and information (Fox, 2010; Widmaier et al., 2013). However, people must rely on other sensory organs in low light conditions or when their vision is impaired. The tactile receptors are the most widely distributed in the human body and enable people to feel the shape of surface materials (Marieb and Hoehn, 2009; Widmaier et al., 2013). Even in darkness, the tactile senses play a critical role in exploring and perceiving the shape of objects. Thompson et al. (2003) indicated that visual and tactile perceptions differ considerably. Although vision is extremely effective for processing most information, the tactile system imposes numerous restrictions on a person's ability to process information holistically. Therefore, tactile perception has a crucial and essential function that cannot be neglected. The tactile system also provides an additional channel for information input, particularly when the visual and auditory systems are overloaded (Brewster and Brown (2004a,b); Raj et al., 2000; Rodriguez-Sanchez et al., 2014; Schrope, 2001; Sears et al., 2003; Van Erp, 2005). In addition, the tactile system can reduce the load on other perceptual channels and improve the accuracy of information recognition. For example, Ghiani et al. (2009) studied vibrotactile feedback and found that the feedback from mobile devices provided frequent unobtrusive indications of useful dynamic information. Therefore, an optimal tactile interface not only increases the success rate of receiving information, but also provides another assistive channel of information.

Tactile perception in particular can enable blind people to explore information; thus, relevant research in this field is ongoing. However, the number of studies on tactile perception is lower than that on visual perception, especially in the practical application of tactile design. In the present study, several related previous works

* Corresponding author. 123 University Road, Section 3, Douliou, Yunlin 64002, Taiwan, ROC.
E-mail address: hfhuang@yuntech.edu.tw (H. Huang).

http://dx.doi.org/10.1016/j.ergon.2016.11.002
0169-8141/

were investigated. The main research aspects of tactile perception can be divided into the recognition of tactile textures (explored tactile perception) and tactile messages (interactive tactile perception). The targets of the active and interactive tactile aspects are mostly entities and tactile interactive interface objects, respectively. These related works are summarized and described as follows.

1.1. Explored tactile perception

The use of hand to touch an object to feel its shape and recognize its surface texture has been discussed in early tactile research. Jenkins (1947) recognized two lever grips by using a tactile coding method. The results indicated that the tactile system effectively assisted recognition and rarely caused confusion. Norman (1988) indicated that to reduce the burden on a machine operator's vision in a manufacturing process and to enhance the accuracy of the operation, knobs and lever handles should be designed to have different shapes, and different tactile sensations should be utilized to identify their differences. Furthermore, tactile exploration was also investigated to assess the performance of accessible products. For example, Courtney and Chow (2000) redesigned a tile for tactile guide pathways and evaluate its effectiveness. The study indicated that changing the layout of raised tactile strips on pathways that could improve the mobility of visually impaired people.

The concept of tactile operation or touch has also been extended to the field of computer interface design, namely in the development of tangible user interfaces (TUIs). The main concept involves linking a computer to the physical environment through a physical interface to achieve interactive message communication (Ishii, 2004; Sato and Lim, 2000; Weiser, 1991). In addition, Ishii and Ullmer (1997) stressed that graphical user interfaces (GUIs) should be converted into tangible tactile interfaces. Fig. 1 illustrates the physical instantiation of GUI elements in a TUI. Fishkin (2004) proposed a taxonomy for tangible interfaces and asserted that

Fig. 1. Prototype of the WTTLAD.

TUI characteristics include input events (e.g., tilting, shaking, squeezing, pushing, and, most often, moving), senses (i.e., an alteration in state), and output events (e.g., alteration of the display surface, such as zooming in and out, making sounds, and providing tactile feedback). Matsunaga et al. (2013) indicated that a tactile information interface could also be considered a type of tactile display and developed an application for tactile displays on the basis of shape memory. A tactile display interface was designed as a 10×10 protruding matrix that presents tactile patterns, symbols, and simple text, and can be touched for recognition. This concept accords with our previous study (Huang and Tsai, 2014). However, we displayed tactile information by using a sequential vibrotactile matrix rather than a synchronous protruding matrix. Therefore, the protruding synchronous display emphasized touch recognition of exploration, whereas the sequential tactile messages were focused on tactile esthesia. More specifically, in converting a visual interface into a tactile interface, the interface patterns differ significantly in how they present information. These studies have indicated that numerous tactile-related works were being seriously considered, and several design applications have since been designed.

1.2. Interactive tactile perception

In this perspective, tactile icons are the most frequently mentioned. Tactile icons are mainly used to provide users positive tactile information. They are designed to transmit information through tactile actuators (tactors). Tactile icons can be considered a type of non-visual display (Schrope, 2001; Van Erp, 2005) and interactive tactile interaction. In recent years, tactile icons have been given the proper name "tactons" (Brown and Kaaresoja, 2006; Castle and Dobbins, 2004; Hoggan and Brewster, 2007; Qian et al., 2011; Van Erp, 2005). Brewster and Brown (2004a,b) indicated that tactons could be used to construct a communication interface of tactile messages for visually impaired users. The properties of such tactile messages include frequency, amplitude, waveform, pulse duration, and body location. Furthermore, Brown and Kaaresoja (2006) proposed tactons that utilized haptic feedback. Their results showed that tactile recognition rates of 72% were achieved. It is possible to communicate multidimensional information in mobile device by tactile encoding to provide haptic feedback. Therefore, tactile information (i.e., interactive tactile perception) is not recognized through visual presentations, but through vibrotactile mark detected by the tactile senses. The system emphasizes interactive information communication and provides a guiding mechanism for tactile interface devices such as "vibromessages" on mobile devices, non-visual vibroinformation alerts for pilots, and wayfinding systems. Accordingly, most relevant studies have explored the application of tactile navigation displays. For example, Van Erp (2005) designed a tacton belt device that could successfully deliver vibrotactile messages to direct the user. Similarly, Pielot and Boll (2010) developed a torso-type tacton device to reduce the risk of colliding with obstacles while walking. Rochlis and Newman (2000) developed a tacton locator system (TLS), which is a display that conveys position and velocity information by using a vibrotactile stimulus fixed to the subject's neck and torso. They emphasized that the TLS was designed to provide clues on body sensory activity and compensate for a lack of visual information. Similar applications of vibrotactile guidance have been explored often (Hoggan and Brewster, 2007). Tactile vibrators are often worn on the waist or torso; however, this can cause inconvenience and generate psychological pressure for visually impaired people, particularly when such information already seems to visually impaired users.

Rodriguez-Sanchez et al. (2014) developed a smartphone-based wayfinding system for visually impaired people. By using the system, users could navigate to a destination on the basis of tactile vibration and presentation frequency, indicating that the information embedded in tactile vibrations can be received and distinguished when used in wayfinding systems. Notably, numerous studies have explored various wayfinding systems for assisting visually impaired people (Ghiani et al., 2009; Hoggan and Brewster, 2007; Lewis et al., 2015; Rochlis and Newman, 2000; Rodriguez-Sanchez et al., 2014; Van Erp, 2005; Coughlan& Manduchi, 2009). For example, Rousek and Hallbeck (2011) indicated the deficits of wayfinding elements under the condition of visual impairment. The participants in their study wore vision simulator goggles to simulate visual impairment and to evaluate wayfinding elements in a hospital environment (e.g., signage, paths or target sites, lighting, and flooring). The study concluded that many of the deficiencies and difficulties still exist in public facility layouts and that these must be improved for visually impaired people. However, other real-life situations may have been overlooked. Traffic signals are also crucial wayfinding elements and even an obstacle for visually impaired people crossing roads. Therefore, improving accessibility in space or product design provides a friendlier environment for visually impaired people.

For both interactive and explored tactile systems, many issues in the field of tactile perceptions remain unexplored and must be developed for assistive device applications for people with sensory impairments. Numerous recent studies have actively explored tactile-based product applications and accessibility designs (Raisamo et al., 2007; Lahav and Mioduser, 2008; Ghiani et al., 2009; Matsunaga et al., 2013; Rodriguez-Sanchez et al., 2014), all of which have indicated that tactile-based applications can offer an additional perceptual channel for exploring information. For example, Ghiani et al. (2009) incorporated vibrotactile feedback into a system for assisting blind users and indicated that each device, service, and environmental accessibility design should be designed to enhance accessibility. Raisamo et al. (2007) designed a tactile memory game on a vibrotactile device for visually impaired children. The device exhibited high usability and playability. These designs, which were based on tactile perception and feedback, could greatly assist disabled people.

In Taiwan, a type of traffic light buzzer is installed at crossroads to assist visually impaired people. A cuckoo buzzer sound is used at the north–south crossing and mechanical bird sounds are used at the east–west crossing. Similar traffic lights with sound signals are also used in other countries such as Japan and Hong Kong. However, using two types of birds sound could be difficult to distinguish and could easily cause confusion when combined with traffic noise. The difficulty visually impaired people experience in recognizing auditory information increases in noisy environments. In addition, the noise-shielding effect frequently affects the performance of people (Poulton, 1978; Szalma and Hancock, 2011). Traffic accidents and other safety concerns caused by the hearing misjudgment are concerning. Therefore, a critical issue for visually impaired people is how to safely cross the road.

The problems and limitations of intersection buzzers have long been known but are yet to be resolved. To enhance the accuracy and reliability of road intersection assistive devices for visually impaired people, this study designed a wearable tactile traffic lights assist device (WTTLAD) as a non-visual information interface. In addition, this study also considered user particularities. A performance experiment was conducted to investigate the actual efficiency and effectiveness of the tactile traffic lights assist device for visually impaired people. In this study, a WTTLAD was developed for visually impaired people. The main concept of this device was presenting a hand vibrotactile signal design that could transmit alerts to users with visual or auditory channel impairment such as in the case of blindness and multisensory disorders. The disadvantage of traffic lights with sound signal alerts is obvious; if the traffic environment is too noisy, then the hearing of blind people might be affected or suppressed, rendering them unable to recognize the type or frequency of a sound. However, a tactile-based information interface design could be a reliable source of alert messages. The core goal of this study was to assist visually impaired people in safely crossing road intersections. Traffic lights were presented in the form of vibrotactile signals that visually impaired people can easily learn and recognize. Furthermore, information on accessibility and useful redundant dimensions was also emphasized in this design concept. To verify the applicability of the proposed design, a user performance experiment was conducted. The results provide practical implications for relevant research on tactile guidance.

2. Method

2.1. Subjects

The experiment was based on a between-subjects design. In total, 18 visually impaired and 18 blindfolded sighted people participated in the experiment. The visually impaired subjects were recruited from the Visually Impaired Care Association in Yunlin County, Taiwan, and the blindfolded sighted subjects were university students. The level of impairment of the visually impaired subjects was severe (visual acuity < 0.01; standard automated perimetry, SAP > 20 dB; no light perception). The characteristics of the two groups are listed in Table 1.

2.2. Materials

The prototype of the WTTLAD (Fig. 1) is a major piece of laboratory equipment. Three vibrotactile codes were designed for the device, corresponding to different traffic light colors (i.e., red, green, or yellow light). The details of the vibrotactile patterns are provided in Table 2. In this experiment, the main independent variables were the experimental field, eyesight, and test section. The experimental field had two levels (indoors: laboratory vs. outdoors: intersection). The eyesight had two levels (visually impaired vs. blindfolded sighted). A complete experimental test comprised five sections: Section 01 (red light), for recognizing when stop; Section 02 (green light), for recognizing when to cross; Section 03 (red light), for recognizing when to stop; Section 04 (green light), for recognizing when to cross, and Section 05 (yellow light), for recognizing when to cross rapidly. All vibrosignals were transmitted to the WTTLAD through Wi-Fi. The dependent variables were the correct rate of tactile recognition (percentage) and time taken to complete the experimental test (seconds).

To explore the effect of the environment on user performance, the experiment was performed in two fields for all the subjects. The fields were a laboratory (indoor environment) and an actual intersection (outdoor environment). The outdoor experimental field was arranged at a road intersection that was 12 m wide. A diagram of the road intersection is shown in Fig. 2. A complete horizontal and vertical testing path of the intersection was designed for the outdoor experiment. An experimental security person and video equipment were provided at each section. The outdoor experimental field is shown in Fig. 3b. The indoor experimental field was arranged in a laboratory at the university, and the experiment was conducted in an isolated booth (Fig. 3a).

2.3. Procedure

The experimental procedure was as follows: (1) Before the experiment, the researcher explained the purpose of the

Table 1
Characteristics of the subjects who participated in the experiment.

Subject group	Average age	Gender	Eyesight
Visually impaired	28.62(SD = 4.12)	9 Female 9 male	VA < 0.01, SAP > 20DB, no light perception (Congenital blindness; Early-blind)
Blindfolded sighted	25.88(SD = 2.86)	9 Female 9 male	VA = 0.8–1.0 (Two-eyes were covered with an opaque eye mask)

Table 2
Type of vibrotactile coding.

Lights	Coding	Frequency	Vibrotactile pattern
Red	1 s (Vibration)- 2 s (Pause)- (Loop)	0.33 Hz	Slow intervals
Green	Sustained and stable vibration	1 Hz	Uninterrupted
Yellow	2 s (Vibration)- 1 s (Pause) (Loop)	0.66 Hz	Hurried intervals

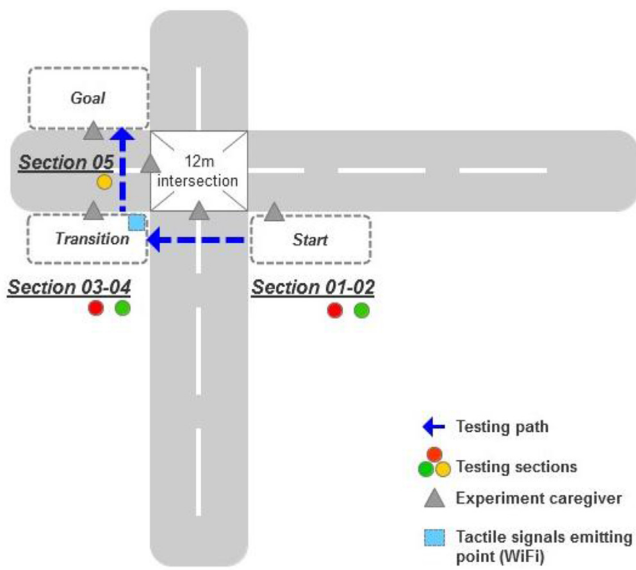

Fig. 2. Arrangement of the experimental intersection.

experiment and rules to the subjects. (2) The researcher assisted the subjects with fitting the WTTLAD. The subject was required to wear an opaque eye mask. (3) To ensure consistency among the subjects' vibrotactile experiences, the researcher conducted a vibrotactile signal pretest (random signal exercises) to ensure that the subjects fully understood and experienced the sensation of the vibrotactile signals. (4) The subject performed the vibrotactile recognition test with traffic lights in an indoor environment. (5) After the indoor test, the researcher led the subjects to the outdoor road intersection. (6) The researcher verified that the vibrotactile Wi-Fi signals consistently matched the frequency of the traffic lights and confirmed that the signals were received by the WTTLAD in the subject's hand. (7) In the outdoor field, the subjects were required to walk from the start area to the transition area by relying on the vibrotactile traffic light signals and then turn right to arrive at the goal area. (8) The vibrotactile signals for crossing (green light) and stopping (red light) were presented in Sections 01–04 (before the subjects crossed the road), and the hurried signal was presented in Section 05 (when the subject was approaching the middle of the road). (9) Each subject's testing process was recorded and observed, including the time spent, correct rate of recognition, walking path, and behavioral reaction. To obtain a subjective evaluation, a questionnaire was distributed to the subjects when they reached the goal area. (10) Experimental fields of noise were measured using a noise meter. The researcher recorded one sample (measured in decibels) every 10 s over a 2-min period and then averaged the results. The average noise levels indoors and outdoors were 68.2 and 96.4 dB, respectively. (11) Each experiment was completed within 30 min.

3. Results

The correct tactile recognition rates of the blindfolded sighted and visually impaired subjects in the different experimental fields are shown in Table 3. The visually impaired subjects attained a higher correct recognition rate than the blindfolded sighted subjects did (mean = 96.11 > 88.33).

Vision ($F = 8.167$, $p < 0.01$), field ($F = 4.167$, $p < 0.05$), and section ($F = 4.854$, $p < 0.01$) significantly affected the tactile recognition rates. Furthermore, the interaction effect between the variables was analyzed through a three-way analysis of variance (ANOVA). The results showed that vision and field differed significantly in their effects ($F = 6.00$, $p < 0.01$); however, the other factors exhibited no significant effect. Furthermore, the results of a post hoc test for these two factors indicated that the correct recognition rate of the blindfolded sighted subjects was significantly lower in the outdoor field than in the indoor field ($p < 0.01$). The visually impaired and blindfolded sighted subjects did not differ significantly in their correct recognition rates in the indoor field ($p > 0.05$). However, in the outdoor field, the visually impaired subjects attained higher rates than the blindfolded sighted subjects did ($p < 0.01$). Regardless of the field, the correct recognition rate of the visually impaired subjects did not differ. This result showed that the performance of the visually impaired subjects was stable when using the WTTLAD.

The performance of the visually impaired and blindfolded sighted subjects in the different experimental fields is depicted in Fig. 4. The correct recognition rate of the blindfolded sighted subjects varied considerably; however, that of the visually impaired subjects was relatively stable. In addition, the performance of the blindfolded sighted subjects was lower than that of the visually impaired subjects, particularly in the outdoor environment.

The correct recognition rate of each passing section is shown in Table 4. The ANOVA results indicated that the section significantly influenced the correct recognition rate ($F = 4.854$, $p < 0.01$). Moreover, the Duncan grouping results indicated that the correct recognition rate in Section 05 (Mean = 80.56%) was significantly lower than that in the other sections. The performance of the subjects in each section was further observed by comparing the rates of different subjects in indoor and outdoor experimental fields. In the indoor field, the performance of the two subject groups was similar. However, the performance of the blindfolded sighted subjects was lower than that of the visually impaired subjects in the outdoor, particularly in Section 05 (green light changing to yellow). The performance might have been slightly lower when the subjects were subjected to repetitive signal testing. This phenomenon is evident in the results in Section 3. Overall, the visually impaired subjects attained more stable performance than the blindfolded sighted subjects did in the outdoor experimental field, and their average correct recognition rate reached 96.67%.

(a) Laboratory (indoor) (b) Intersection (outdoor)

Fig. 3. The indoor and outdoor experimental situations.

Table 3
Comparison of the correct tactile recognition rate in different experimental fields.

Visual status	Field	*n*	Mean	SD
Blindfolded sighted	Lab (indoor)	90	94.44	23.034
	Street (outdoor)	90	82.22	38.447
	Total	180	88.33	32.192
Visually impaired	Lab (indoor)	90	95.56	20.723
	Street (outdoor)	90	96.67	18.051
	Total	180	96.11	19.387
Total	Lab (indoor)	180	95.00	21.855
	Street (outdoor)	180	89.44	30.813
	Total	360	92.22	26.819

Note. Unit: correct recognition rate (percentage).

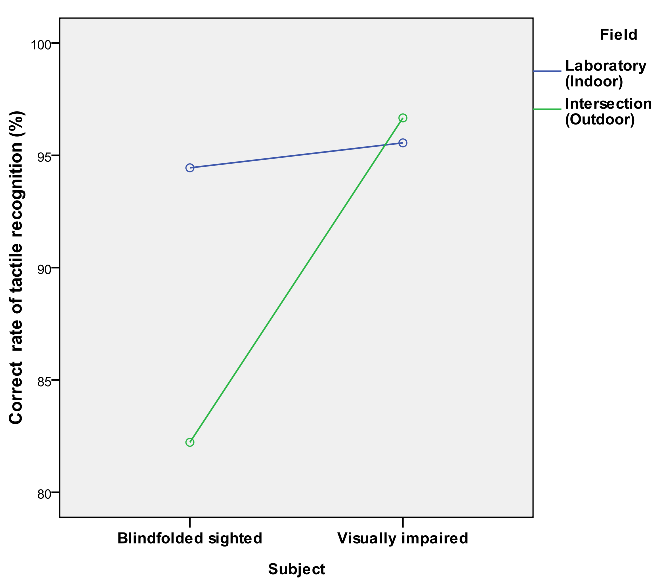

Fig. 4. Correct recognition rate between the subject groups.

Fig. 5 shows a comparison of recognition performance of the subjects in the five sections and two experimental fields. The correct recognition rates of the subjects clearly declined in the outdoor field, particularly those of the blindfolded sighted subjects. By contrast, the visually impaired subjects maintained a high recognition rate (89%–100%). During the third testing section, the correct recognition rates of the visually impaired subjects were higher in the outdoor field than in the indoor field ($p < 0.01$).

Regarding the operating times of the different subjects in the two experimental fields, the blindfolded sighted subjects spent more time (mean = 40.33 s, SD = 19.91) than the visually impaired subjects (mean = 38.83 s, SD = 9.07) in the indoor field. By contrast, the visually impaired subjects spent more time (mean = 77.22 s, SD = 11.17) than the blindfolded sighted subjects (mean = 75.22 s, SD = 13.88) in the outdoor field. And, the *t*-test results indicated no significant difference in the operating times between the two subject groups in the indoor field ($p = 0.773 > 0.05$) or outdoor field ($p = 0.637 > 0.05$). Thus, the subject groups had similar operating times in each of the experimental fields.

However, a significant difference was observed between the experimental fields ($F = 121.38$, $p < 0.01$). The subjects spent more time in the outdoor field (mean = 76.22, SD = 12.45) than in the indoor field (mean = 39.58, SD = 15.27). These results showed that the outdoor field was more difficult to navigate than the indoor field was, which affected the operating time of the subjects. Finally, the results of an independent-samples *t*-test indicated that gender did not influence the recognition rate or operating time ($p > 0.05$).

4. Discussion

4.1. Differences between the experimental fields

Related studies have typically compared perceptual performance (such as tactile and auditory performance) for normal-vision, blindfolded, and visually impaired subjects (Bliss et al., 2004; Castronovo and Seron, 2007; Collignona et al., 2005; Lerens and Renier, 2014; Pigeon and Marin-Lamellet, 2015; Thompson

Table 4
Descriptive statistics of the correct recognition rates stratified by section.

Vision	Field	Section	*n*	Mean	Std. deviation
Blindfolded sighted	Laboratory (indoor)	01	18	94.44	23.570
		02	18	100.00	0.000
		03	18	94.44	23.570
		04	18	100.00	0.000
		05	18	83.33	38.348
		Total	90	94.44	23.034
	Intersection (outdoor)	01	18	83.33	38.348
		02	18	88.89	32.338
		03	18	94.44	23.570
		04	18	83.33	38.348
		05	18	61.11	50.163
		Total	90	82.22	38.447
Visually impaired	Laboratory (indoor)	01	18	100.00	0.000
		02	18	100.00	0.000
		03	18	88.89	32.338
		04	18	100.00	0.000
		05	18	88.89	32.338
		Total	90	95.56	20.723
	Intersection (outdoor)	01	18	94.44	23.570
		02	18	100.00	0.000
		03	18	100.00	0.000
		04	18	100.00	0.000
		05	18	88.89	32.338
		Total	90	96.67	18.051

Note. Unit: correct recognition rate (percentage).

et al., 2003). However, these studies have performed experiments that typically involve stimulus–response perceptual testing in a laboratory field such as the N-back test, plus–minus task, attention test, and tactile picture recognition experiment. Few studies examining perceptual performance in different environmental fields (i.e., field surveys) have provided a practical device for their subjects, and few have for compared the differences in their perceptual performance. In the present study, the visually impaired and blindfolded sighted subjects used the proposed WTTLAD. The findings reveal the difference in their tactile perceptual performance and actual response between the visually impaired and blindfolded sighted subjects.

The results show that the tactile recognition performance of the visually impaired participants was higher than that of the blindfolded sighted participants, irrespective of the experimental field. In addition, the visually impaired participants attained stable performance in the tactile recognition of traffic lights, and they demonstrated consistently adequate attention. Conversely, the performance of the blindfolded sighted participant was slightly lower, particularly in the outdoor field. In a recent study involving laboratory experiments for perceptual testing, the attention and working memory of visually impaired people were superior to those of normal-sighted people (Pigeon and Marin-Lamellet, 2015). The results of their laboratory experiments are consistent with the findings of the present study although the test in this study was conducted in a real environment. The high perceptual sustainability of the visually impaired subjects was also verified in an outdoor field experiment. In addition, the present study verified these results by testing the actual operation of a tactile device. The correct recognition rates for the five sections indicate that the sustainability of tactile recognition of the visually impaired subjects was higher than that of the blindfolded sighted subjects, particularly in the outdoor field (i.e., Section 05). Moreover, the correct rate of rerecognition of the visually impaired subjects was higher than that of the blindfolded sighted subjects in Sections 02, 03, and 04. The performance indicated the stability and sustainability of tactile recognition for traffic light signals in the visually impaired subjects.

4.2. Working memory advantage for visually impaired people

The results of a tactile picture perception study by Thompson et al. (2003) showed that visually impaired and blindfolded sighted subjects differed in their tactile performance. They indicated that preexisting visual experiences affected their tactile recognition performance. Visually impaired people usually get confused when external information acquired through the touch of hand is incomplete. Preexisting visual experience is crucial for tactile exploration and spatial cognition for blindfolded sighted people (Postma et al., 2007). In the present study, the tactile information was derived from tactile vibration rather than tactile exploration with the hand. The experimental observation reveals that the signal presentation of tactile vibration was a working memory search rather than a long-term memory or preexisting experienced review for the visually impaired subjects. Obviously, the tactile recognition performance of the visually impaired subjects was higher than that of the blindfolded sighted subjects because they were unaffected by long-term memory or preexisting visual experience.

Cohen et al. (2011) also deduced that the tactile working memory of visually impaired people was better than that of normal-sighted people. In their model of experience-based multisensory working memory, they stressed that perceptual working memory might not be limited to only five to nine items; however, the amount of information that could be stored was limited. Moreover, Cohen et al. indicated that to maintain the balance of perception, one perceptual channel might be enhanced in the case of the loss of another perceptual channel. Therefore, the results of the current experiments show that the three vibrotactile coding designs of traffic lights were easy to recognize and conformed to the capacity of the visually impaired subjects' working memory. By contrast, preexisting visual experiences and memory significantly interfered with the tactile recognition rate and performance of stability in the normal-sighted subjects (blindfolded), particularly in the outdoor environment. This finding shows that the performance of the blindfolded subjects was impeded by preexisting visual experiences and predicted possible obstacles on the road (in

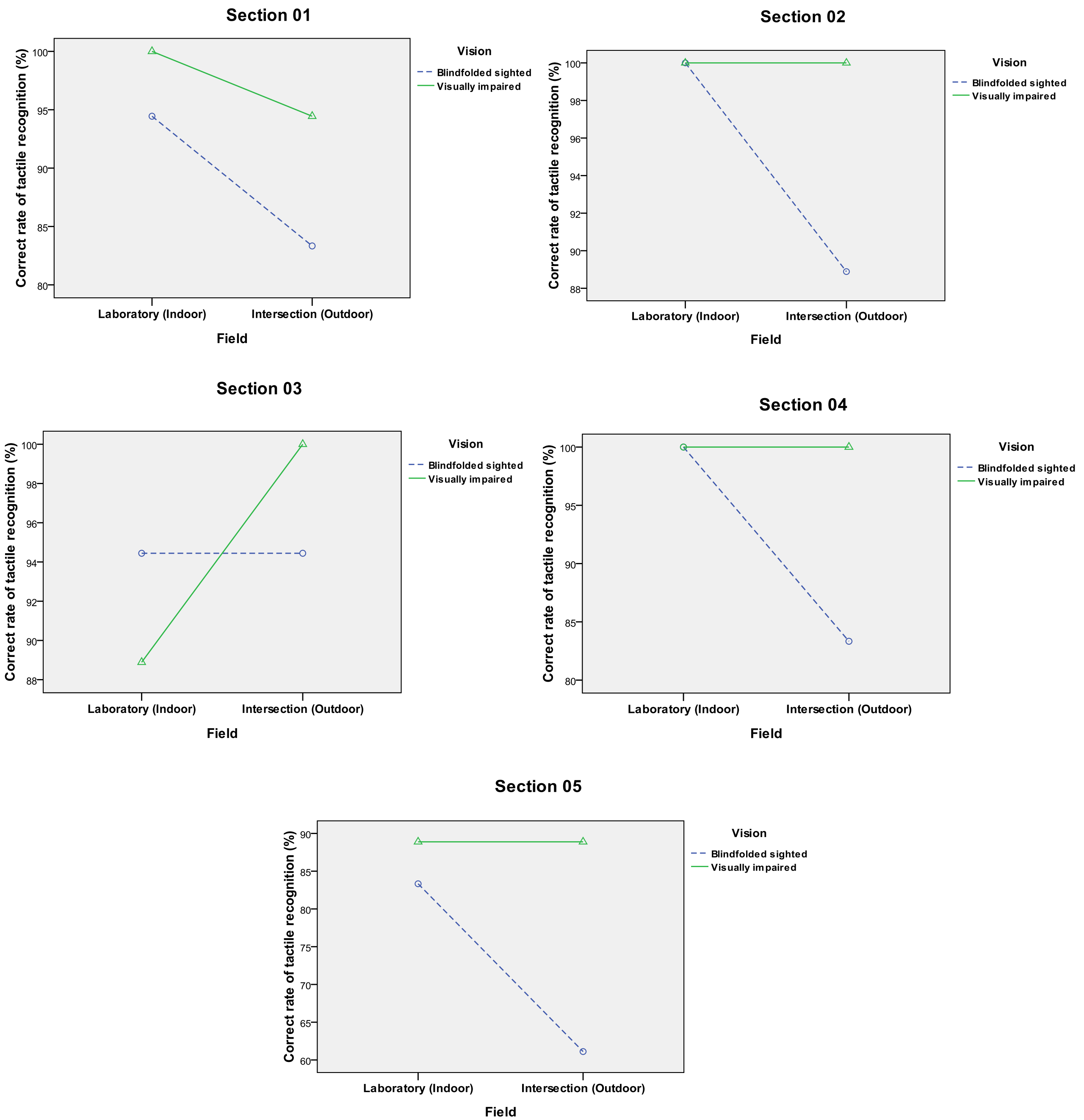

Fig. 5. Comparison of the recognition performance of the vision of different subjects in the different sections and experimental fields.

fact, there were none). The probability of them experiencing a perceptual false alarm increased during the process of walking. Nevertheless, the results indicate that the visually impaired subjects experienced no such distress, even in different environments (indoor and outdoor).

4.3. *Influence of visual experience and attention*

Walking blindfolded remained a challenge for the sighted subjects. They were more easily accustomed to searching for visual experience and were more fearful of unknown dangers. Therefore, distractions might have reduced their tactile recognition performance and resulted in longer operating times. Furthermore, walking blindfolded can be regarded as a divided-attention task for the blindfolded sighted subjects according to their attention characteristics (Moray, 1981; Sanders and McCormick, 1993; Wickens, 1984). They must simultaneously recognize tactile information obtained by the hand while focusing on walking. The blindfolded sighted subjects could not coordinately complete the task because a single perceptual resource was divided across these two types of attention. Visually impaired people seem more able to coordinate these two types of attention and stably balance their perceptual resources. Similarly, Pigeon and Marin-Lamellet, 2015 indicated that the divided attention of normal-sighted people was inferior to that of visually impaired people in an attention test.

The performance trends of the blindfolded sighted and visually impaired subjects in the present study were similar those in the indoor field. This result shows that the main performance difference was because of actual outdoor environmental interference. The performance of the subjects in the different experimental fields indicated that both the blindfolded sighted and visually impaired subjects experienced environmental interference, and the blindfolded sighted people were more likely to be disturbed. The blindfolded sighted subjects exhibited lower tactile recognition performance when crossing the road intersection. This might be due to interference from environmental noise such as heavy traffic, car horns, and background noise. Their auditory channel was partially occupied; hence, they were distracted or unable to concentrate on the tactile information channel. Therefore, their tactile recognition performance was reduced and the probability of a false alarm occurring increased. However, the visually impaired subjects were experienced in walking blind; hence, they could focus their attention on information processing, and their mental workload was lower than that of the blindfolded sighted subjects. Overall, preexisting visual experience, inattention, and noise were the main interference factors that reduced the tactile recognition performance of the blindfolded sighted subjects.

Furthermore, this study compared the operating time of the subjects in the same experimental field; the results show that the two subject groups did not differ. However, significant differences were observed in different experimental fields. For the two of subject groups, the operating process in the outdoor field was more difficult than that in the indoor field. Therefore, both the subject groups walked very carefully and slowly. Lahav and Mioduser (2008) also indicated that regardless of whether people were blind or normal-sighted, they typically walk slowly and hesitantly when in an unknown environment for the first time. The two subject groups did not differ in their behavior in the indoor field; however, the performance of the visually impaired subjects indicated that they had greater confidence and more effective adaptation in the walking and operating the device in the outdoor field. Their performance was also more stable than that of the blindfolded sighted subjects.

This study also indicated that the basic tactile response did not differ between the two subject groups. In addition, the visually impaired subjects were not particularly sensitive to physiological tactile stimuli. This result echoes results reported in the literature. Collignon et al. (2006) indicated that visually impaired and normal sighted subjects did not differ significantly in their physiological receptors in a basic reaction time test. However, the reaction time of the visually impaired subjects was shorter than that of the normal-sighted subjects in a selective spatial attention test of the tactile and auditory senses. Collignon et al. explained that the key was that the visually impaired subjects could enhance their attention intuitively. Furthermore, gender did not affect tactile performance, which is consistent with the results of the present study.

4.4. Summary

All of the subjects reported that the WTTLAD was usable and its tactile signals were easy to recognize. The tactile recognition performance of the traffic lights was compared between the visually impaired (early-blind) and normal-sighted subjects. Obviously, the tactile recognition performance of the visually impaired subjects was higher than that of the normal-sighted subjects. More specifically, the perceptual channel concentration and low mental load of the visually impaired subjects were the main reasons for the results of the experiment. The type of visual impairment can be divided into congenital blindness (early blind) and acquired blindness (late blind). The tactile perception of the subjects might have differed slightly in the perceptual experiment (Collignon et al., 2006; Heller et al., 2003; Pigeon and Marin-Lamellet, 2015; Postma et al., 2007). This is an issue worth investigating. Therefore, late-blind people should be invited to participate in the future studies on tactile recognition performance. In this study, the design concept of the WTTLAD was proposed and its usability was verified. Previous studies have widely discussed various issues associated with wayfinding systems and navigation devices. However, traffic lights are on most roads that people walk on and can be regarded as a barrier to road crossing. Moreover, walking and crossing an intersection are the most challenging tasks visually impaired people encounter. Thus, a relevant wayfinding system should combine the design concept of the WTTLAD to contribute to a higher level of safety in blind walking and way finding.

In summary, people can obtain more accurate signals and alarms by using the information design of the tactile channel in non-visual tasks (e.g., walking in a dark environment) and divided-attention tasks (e.g., driving). Although this WTTLAD was mainly designed for visually impaired people, future studies can incorporate the concept of a universal design. Thus, assistive devices could be developed to give people intuitive and perceptible information for working in conditions with poor vision, such as in sewers, mines, and underwater environments.

5. Conclusion

Currently, road intersections with accessible traffic lights rely on utilizing the auditory channel. This type of system can easily lead to the loss of perceptual information channels or result in false alarms, particularly with the shielding effect of vehicle noise and ambient noise. This study attempted to resolve this problem by using the tactile channel design, which is an efficient and critical approach.

The non-visual design of the WTTLAD, which was based on vibrotactile information, was proven to be effective. Furthermore, we found that favorable conditions for high tactile recognition performance should be considered to maintain simple tactile perception tasks and eliminate interference from preexisting visual experiences. The quality of tactile information received through the perceptual channels still requires improvement. Thus significantly enhancing the signal was necessary to make it more intense and distinctive. The tactile senses cannot replace any other perceptual channel, but it is a channel for redundant information that can be actively exploited.

The tactile recognition performance of the visually impaired subjects was generally higher than that of the blindfolded sighted subjects. This might be a compensation effect that could be attributed to their enhanced perceptual channel. However, future research should focus on identifying the internal compensation schema and how much it was affects recognition performance.

Acknowledgments

This study was partially supported by the Ministry of Science and Technology, ROC under Grant No. 103-2410-H-224-037 MOST.

References

Bliss, I., Kujala, T., Hämäläinen, H., 2004. Comparison of blind and sighted participants' performance in a letter recognition working memory task. Cogn. Brain Res. 18, 273–277.

Brewster, S.A., Brown, L.M., 2004a. Non-visual information display using Tactons. In: Extended Abstracts of ACM CHI. ACM Press, pp. 787–788.

Brewster, S.A., Brown, L.M., 2004b. Tactons: Structured Tactile Messages for Non-visual Information Display. AUIC, pp. 15–23.

Brown, L.M., Kaaresoja, T., 2006. Feel Who's Talking: Using Tactons for Mobile Phone Alerts. Extended Abstracts on Human Factors in Computing Systems. ACM Press, NY.

Castle, H., Dobbins, T., 2004. Tactile display technology: a brief overview of its benefits over visual and audio displays. Technol. Innov. 31–34.
Castronovo, J., Seron, X., 2007. Numerical estimation in blind subjects: evidence of the impact of blindness and its following experience. J. Exp. Psychol. Hum. Percept. Perform. 33, 1089–1106.
Cohen, H., Scherzer, P., Viau, R., Voss, P., Lepore, F., 2011. Working memory for Braille is shaped by experience. Commun. Integr. Biol. 4, 227–229.
Collignon, O., Renier, L., Bruyer, R., Tranduy, D., Veraart, C., 2006. Improved selective and divided spatial attention in early blind subjects. Brain Res. 1075, 175–182.
Coughlan, J., Manduchi, R., 2009. Functional assessment of a camera phone-based wayfinding system operated by blind and visually impaired users. Int. J. Artif. Intell. Tools 18 (3), 379–397.
Courtney, A., Chow, H.M., 2000. A study of tile design for tactile guide pathways. Int. J. Ind. Ergon. 25, 693–698.
Fishkin, K.P., 2004. A taxonomy for and analysis of tangible interfaces. Personal Ubiquitous Comput. 8, 347–358.
Fox, S., 2010. Human Physiology. McGraw-Hill Science, NY.
Ghiani, G., Leporini, B., Paterno, F., 2009. Vibrotactile feedback to aid blind users of mobile guides. J. Vis. Lang. Comput. 20, 305–317.
Heller, M.A., Wilson, K., Steffen, H., Yoneyama, K., Brackett, D.D., 2003. Superior haptic perceptual selectivity in late-blind and very-low-vision subjects. Perception 32, 499–511.
Hoggan, E., Brewster, S.A., 2007. Designing audio and tactile crossmodal icons for mobile devices. In: Proceedings of ACM International Conference on Multimodal Interfaces, pp. 162–169.
Huang, H.F., Tsai, W.C., 2014. An investigation of tactile recognition performance on Tactons' message exchange device. Proc. 1st Asian Conf. Ergon. Des. 69.
Ishii, H., Biderman, A., Ratti, C., 2004. Continuous tangible interfaces: bringing clay and sand into digital design. BT J. 22, 287–299.
Ishii, H., Ullmer, B., 1997. Tangible bits: towards seamless interfaces between people. In: Bits and Atoms. Proc, CHI 1997. ACM Press, pp. 234–241.
Jenkins, W.O., 1947. The Tactual Discrimination of Shapes for Coding Aircraft Type Controls. In: Psychological Research on Equipment Design. U.S Government Printing Office, pp. 199–205.
Lahav, O., Mioduser, D., 2008. Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. Int. J. Hum. Comput. Stud. 66, 23–35.
Lerens, E., Renier, L., 2014. Does visual experience influence the spatial distribution of auditory attention? Acta Psychol. 146, 58–62.
Lewis, L., Sharples, S., Chandler, Ed., Worsfold, J., 2015. Hearing the way: requirements and preferences for technology supported navigation aids. Appl. Ergon. 48, 56–69.
Marieb, E.N., Hoehn, K., 2009. Human Anatomy & Physiology. Benjamin Cummings, San Francisco, CA.
Matsunaga, T., Totsu, K., Esash, M. i., Haga, Y., 2013. Tactile display using shape memory alloy micro-coil actuator and magnetic latch mechanism. Displays 34, 89–94.
Moray, N., 1981. The role of attention in the detection of errors and the diagnosis of failures in man-machine systems. Hum. Detect. Diagn. Syst. Fail. 15, 185–198.
Norman, D.A., 1988. The Psychology of Everyday Things. Doubleday Business, NY.
Pielot, M., Boll, S., 2010. Tactile wayfinder: comparison of tactile waypoint navigation with commercial pedestrian navigation systems. In: Proceedings of the 8th International Conference on Pervasive Computing, pp. 152–158.
Pigeon, C., Marin-Lamellet, C., 2015. Evaluation of the attentional capacities and working memory of early and late blind persons. Acta Psychol. 155, 1–7.
Postma, A., Zuidhoek, S., Noordzij, M.L., Kappers, A.M.L., 2007. Differences between early blind, late blind and blindfolded sighted people in haptic spatial configuration learning and resulting memory traces. Perception 36, 1253–1265.
Poulton, E.C., 1978. A new look at the effects of noise: a rejoinder. Psychol. Bull. 85, 1068–1079.
Qian, H., Kuber, R., Sears, A., 2011. Towards developing perceivable tactile feedback for mobile devices. Int. J. Hum. Comput. Stud. 69, 705–719.
Raisamo, R., Patomäki, S., Hasu, M., Pasto, V., 2007. Design and evaluation of a tactile memory game for visually impaired children. Interact. Comput. 19, 196–205.
Raj, A.K., Kass, S.J., Perry, J.F., 2000. Vibrotactile displays for improving spatial awareness. In: Proceedings of the IEA 2000/HFES 2000 Congress, pp. 181–184.
Rochlis, J.L., Newman, D.J., 2000. A tactile display for international space station extravehicular activity (EVA), aviation, space and environmental medicine. Aerosp. Med. Assoc. 71, 571–578.
Rodriguez-Sanchez, M.C., Moreno-Alvarez, M.A., Martin, E., Borromeo, S., Hernandez-Tamames, J.A., 2014. Accessible smartphones for blind users: a case study for a wayfinding system. Expert Syst. Appl. 41, 7210–7222.
Rousek, J.B., Hallbeck, M.S., 2011. The use of simulated visual impairment to identify hospital design elements that contribute to wayfinding difficulties. Int. J. Ind. Ergon. 41, 447–458.
Sanders, M.M., McCormick, E.J., 1993. Human Factors in Engineering & Design. McGraw-Hill, NY.
Sato, K., Lim, Y., 2000. Physical interaction and multi-aspect representation for information intensive environments. In: Proceedings of the IEEE International Workshop on Robot and Human Interactive Communication, pp. 436–443.
Schrope, M., 2001. Simply sensational. New Sci. 2, 30–33.
Sears, A., Lin, M., Jacko, J., Xiao, Y., 2003. When Computers Fade: Pervasive Computing and Situationally Induced Impairments and Disabilities. In: Human-computer Interaction: Theory and Practice. Springer-Verlag, pp. 1298–1302.
Szalma, J.L., Hancock, P.A., 2011. Noise effects on human performance: a meta-analytic synthesis. Psychol. Bull. 137, 682–707.
Thompson, L.J., Chronicle, E.P., Collins, A.F., 2003. The role of pictorial convention in haptic picture perception. Perception 32, 887–893.
Van Erp, J.B.F., 2005. Presenting directions with a vibro-tactile torso display. Ergonomics 48, 302–313.
Weiser, M., 1991. The computer for the 21st century. Sci. Am. 265, 94–104.
Wickens, C.D., 1984. Processing Resources in Attention. Varieties of Attention. Academic Press, Orlando, FLA.
Widmaier, E., Raff, H., Strang, K., 2013. Vander's Human Physiology: the Mechanisms of Body Function. McGraw-Hill Education, NY.