

Enhancing Mobile Phones for People With Visual Impairments Through Haptic Icons: The Effect of Learning Processes

Pedro María Galdón MSc ^a, R. Ignacio Madrid PhD ^b, Ernesto J. de la Rubia-Cuestas MSc ^a, Antonio Diaz-Estrella PhD ^a & Lourdes Gonzalez MSc ^b

^a Department of Electronic Technology, University of Malaga, Campus de Teatinos, Malaga, Spain; ^b Technosite (ONCE Foundation for People with Disabilities), Madrid, Spain

*Address correspondence to: Pedro María Galdón, Department of Electronic Technology, University of Malaga, Campus de Teatinos, Malaga, Spain. Email: pedro.m.galdon@gmail.com

Abstract

We report the results of a study on the learnability of haptic icons used in a system for incoming-call identification in mobile phones. The aim was to explore the feasibility of using haptic icons to create new assistive technologies for people with visual impairments. We compared the performance and satisfaction of users with different visual capacities (visually impaired vs. sighted) and using different learning processes (unimodal vs. multimodal). A better recognition rate and user experience were observed for the visually impaired than for sighted users and for multimodal rather than unimodal learning processes.

Keywords: learnability, mobile phones, haptic icons, tactile, touch, assistive technology

Introduction

Research on haptics for mobile phones during the last decade suggests that vibrotactile stimuli could be used to transmit complex information. In addition to a vibration warning the user of an incoming SMS, the type, priority/urgency, and the sender of the message could also be identified (Brown & Kaaresoja, 2006; Hoggan, & Brewster, 2007). Recently, high resolution haptic feedback systems for mobile phones have become mainstream, allowing for the transmission of rich information through the haptic channel (IMMERSION, 2010). However, most vibrotactile stimuli used thus far in typical mobile phones transmit much simpler information, such as alerts.

Adding complex vibrotactile stimuli to typical mobile phones has several advantages, such as increased intimacy, enhanced user experience, and reduced interruptions of other tasks that require the intensive use of hearing and sight (e.g., using a computer or attending a conference). Moreover, these stimuli can replace audio feedback when loud environmental conditions (e.g., a concert) render audio signals ineffective (Hoggan, Crossan, Brewster, & Kaaresoja, 2009). Finally, specific groups of users, such as the deaf or visually impaired (VI), could especially benefit because they can use mobile phones and applications, such as assistive technologies, to improve communication through touch to compensate for deficiencies in other senses (Rantala et al., 2009).

To communicate complex information, vibrotactile stimuli need to be associated with specific meanings. These meaningful tactile stimuli are called Tactons (where the key

aspect is that the stimuli are built using a coded approach; Brewster & Brown, 2004) or haptic icons (in which a metaphorical approach is adopted to establish the association; MacLean & Enriquez, 2003).

Different applications of haptic icons have been developed, including as a way to represent turn-taking to improve collaborative applications (Chan, MacLean, & McGrenere, 2008) and as a medium for transmitting emotions in instant messaging (Rovers & Van Essen, 2004).

A potential limitation for the use of haptic icons is related to the constraints of the human cognitive system (Gallace, Tan, & Spence, 2007). For haptic icons to be usable, their design should allow information-processing limitations to be clearly perceived and their meaning easily learned (Ternes & MacLean, 2008).

In this study, a mobile device that uses haptic icons for incoming-call identification was utilized to investigate haptic icons and to determine whether this functionality can benefit VI users.

Design of Haptic Icons in Mobile Phones

Methods for designing haptic icons are currently being developed. Currently, there are existing guidelines that facilitate the creation of stimuli that can easily be recognized and memorized by the user (MacLean, 2008; Van Erp et al., 2010).

Frequency, amplitude, duration, and location are the main parameters of vibration that can be manipulated (Jones, Kunkel, & Piatetski, 2009). An additional parameter of vibration is rhythm; groups of pulses of different durations and amplitudes can be combined to create rhythmic units (Brown, Brewster, & Purchase, 2005). Ternes and MacLean (2008) systematically used rhythm to obtain a set of haptic icons, which were organized to facilitate their association with other meanings. In addition to rhythm, other musical techniques have been applied to create sets of haptic icons that are easy for the user to recognize and distinguish. For example, by progressively increasing the amplitude of a signal, a musical crescendo (i.e., increase in volume over time) can be emulated (Brown & Brewster, 2006). Swerdfeger, Fernquist, Hazelton, and MacLean (2009) suggested that haptic icons could be extended in expressivity through the use of melody (i.e., stimuli that vary in rhythm, frequency, and amplitude).

In summary, different musical techniques are useful for obtaining sets of identifiable haptic icons that are distinguishable from one another.

Learnability of Haptic Icons

Most auditory and graphic icons have already been integrated into human-computer interfaces, and their meanings are now easily recognized and identified by users. However, icons are not inherently meaningful and users must learn the link between the stimulus and its meaning, which can range from representational to abstract. Some icons are purely representational, linking objects and their meanings. For example, the sound of paper being crumpled indicates a draft file. Other icons are abstract without intrinsic meanings but are associated with arbitrary relationships (e.g., Windows error sounds; Stephan, Smith, Martin, Parker, & McAnally, 2006). Therefore, learnability is one of the most important aspects of the implementation of haptic icons. In fact, understanding how

to support users in learning the meaning of a set of haptic icons is currently an important issue in haptic research (MacLean, 2008; MacLean & Hayward, 2008). Enriquez and MacLean (2008) recommended a three-stage approximation. In the first stage, *self-guided learning*, users learn the associations between haptic stimuli and their meanings. The second stage, *reinforcement*, presents the haptic stimuli to the user, who must recognize the associated meanings and receive feedback on their correct or incorrect answers. The third stage is *test*, where users perform the same task as in the reinforcement stage but without receiving feedback as reinforcement.

In the self-guided learning stage, haptic stimuli are presented concurrently with a representation of their meaning. This representation can be communicated through a textual, audio, and/or graphical description. In a study by Swerdfeger (2009), a unimodal learning process was used, in which a textual description was displayed on a screen next to a button that could be pressed to launch the associated haptic stimulus. A different way of communicating the meaning of haptic stimuli is by the VibeTonz® demo by IMMERSION, which uses a multimodal application that combines graphic icons and textual labels to represent haptic icons.

Which types of learning processes are more effective for improving the acquisition of stimulus-meaning associations? Although the effects of haptic icon learnability for unimodal versus multimodal presentations have not been compared, a multimodal learning process has been hypothesized to be advantageous. This claim is supported by several learning theories (e.g., dual coding theory [Paivio, 1986] or the multimedia learning theory [Moreno & Mayer, 1999]).

Haptic Abilities of Visually Impaired People

The aim of this study was to test the idea that haptic icons in mobile devices can be especially beneficial for VI users. Because VI users cannot rely on visual modalities, haptic interfaces can provide them with an alternative form of sensory information.

Indeed, several applications that use haptic icons to communicate information have already been developed for VI users, including an assistive technology that conveys facial expressions through haptic icons (Krishna, Bala, McDaniel, McGuire, & Panchanathan, 2010; Réhman & Liu, 2010). A second example is a mobile guide for assessing orientation and avoiding obstacles in museums. Eleven blind users participated in this study, confirming the feasibility of this application (Ghiani, Leporini, & Paternò, 2009).

In addition to the feasibility of using haptic information, cognitive-processing differences appear to allow VI persons to outperform sighted persons when using the haptic modality (Heller, 2000). From a neurophysiological point of view, some authors have provided empirical evidence suggesting that people who lack the ability to see can compensate for this impairment with enhancements in their other senses, also known as sensory compensation (Cohen et al., 1997). For example, major sensory differences have been identified between VI and sighted persons with respect to the tactile sensory threshold (Lai & Chen, 2006).

Moreover, differences in haptic performance go beyond perception and are related to higher cognitive abilities, such as memory. Some studies have shown that VI persons have better memorization skills and exhibit better performance at haptic tasks than sighted

people (Gallace & Spence, 2009; Waraich & D'Angiulli, 2002). Using a specific haptic test battery, Ballesteros, Bardisa, Millar, and Reales (2005) showed that blind school children ranging from 3 to 16 years of age had an advantage over their sighted counterparts with respect to several haptic cognitive abilities.

In summary, even though no specific studies comparing the learnability of haptic icons in people with differences in their visual capacity have been conducted, the evidence reviewed here suggests that VI users could outperform sighted users when learning the meaning of haptic icons in mobile devices.

Aims of the Present Study

In this study, a mobile application was designed to allow users to learn the association between a set of vibrotactile stimuli and contact groups in an address book. The aim of the experiment was to test the feasibility of using haptic icons as an assistive technology for people with visual impairments. Moreover, we aimed to identify a procedure that can be used to learn the meaning of haptic icons.

Based on the literature reviewed, our hypotheses were as follows:

1. VI users will exhibit better recall of the meaning of haptic icons compared to sighted users through both unimodal and multimodal learning processes.
2. Including graphic icons together with vibrotactile stimuli during learning (i.e., multimodal learning process) will improve the learnability of sighted users compared to only showing the haptic icons (i.e., unimodal learning process). Providing a multimodal alternative to VI users through audio descriptions of the presented graphic icons will also improve learning.

Methods

Participants

Twenty-four participants (10 VI users and 14 fully sighted non-VI users) between the ages of 23 and 39 participated in the experiment. Of the 10 VI participants, 8 were completely blind (i.e., acquired blindness at least 10 years before this study) and 2 were near total-blind individuals (very low vision). All VI participants were screen-reader users (i.e., they accessed computers using audio description software such as JAWS®). None of the participants had previous experience with the mobile phone used in the experiment or other devices that provide rich vibrotactile feedback.

Design

This study followed a 2 x 2 design, with the user's visual capacity (VI vs. non-VI) and the learning process (unimodal vs. multimodal) as independent variables. The learning times at each stage, the recognition rate of the haptic icons and the responses to different items in a usability questionnaire were the dependent variables. See the Procedure section for a description of the procedure.

In the unimodal condition, each contact group name was shown together with the haptic icon for memorization during the self-guided learning and reinforcement stages. In the multimodal condition, a graphic icon was added next to the contact group name. The graphic icons were replaced by their audio descriptions (e.g., "a flying bee") to provide a

multimodal alternative for VI users. Although these two multimodal representations (graphic + haptic vs. audio + haptic) may be not completely equivalent, they were determined to foster the ecological validity of this research.

Stimuli and Apparatus

Design of the Haptic and Graphic Icons

Eight categories of frequent contacts were defined. For each category, a set of corresponding vibrotactile patterns and a picture were designed (see Table 1).

IMMERSION VibeTonz® Studio was used to create the vibrotactile patterns. Two criteria were used during the design process. First, the parameters of rhythm, intensity, and duration suggested by Brown and Kaaresoja (2006) were used as a reference. Rhythm appeared to be the most decisive factor for learnability (95% of pattern recognition). Second, popular haptic rhythms that could metaphorically represent each contact group (e.g., a heartbeat represents the contact group “couple”) were chosen. For each metaphor, a previous screening with sighted users was conducted to ensure that the meaning was clear to them. Unfortunately, it was not possible to collaborate with blind users at this stage. It should be noted that some of the selected metaphors were relevant for the Spanish culture and may have a different meaning or no meaning in other cultures. However, even if the metaphors are not culturally meaningful, users may be able to find their own mnemonics. For example, Enriquez and MacLean (2008) compared arbitrary and user-chosen associations and found similarly high performance with both design approaches. A set of pictures was also designed to visually represent vibrotactile patterns in the multimodal condition, with a direct relationship between the vibrotactile stimuli and visual items (e.g., a picture of a flying bee was associated with the vibration representing a buzz).

Hardware and Software

The Samsung SGH-i718 mobile phone, which was recommended by IMMERSION to be used with VibeTonz® Studio, was used as the hardware in this experiment. A learning application was developed in Microsoft Visual Studio® 2005 using C#. The function of this application was to identify incoming calls through touch using a three-stage learning approach (see the Procedure section).

Users were able to learn the association between the designed set of vibrotactile stimuli and the contact groups that they represented. The software also provided speech synthesis output for VI users, reading aloud text labels, picture descriptions, and feedback notifications. This output is the most natural way VI individuals use computers and other devices, such as websites and software that follow the World Wide Web Consortium’s accessibility guidelines (e.g. Caldwell, Cooper, Reid & Vanderheiden, 2008) to allow screen readers to also have an audio description of pictures and other visual objects.

The application was also provided with an event log that registered the history of the user’s actions and response time at each stage.

Procedure

At the beginning of the session, the participants were asked to memorize the association between each vibrotactile stimulus and its corresponding contact group. The underlying metaphor or the rationale for the association was not explained to them. To measure learnability, we adopted the common three-stage approach of measuring identification accuracy after a limited amount of practice (MacLean, 2008; Ryu, Chun, Park, Choi, & Han, 2010): self-guided learning, reinforcement, and test (Enriquez & MacLean, 2008). No time limits for completing the procedure were set. Figure 1 shows the first screen during each of these stages.

The self-guided learning stage presented eight haptic icons to the user for memorization in either a unimodal or multimodal condition. On each screen during this stage, four items were shown, and after clicking on each one, the user could perceive the corresponding haptic icon. To control for practice effects, each haptic icon could only be perceived twice during this stage.

The reinforcement stage consisted of eight screens (one per haptic icon). A button was displayed on each screen with the sample, which reproduced the vibrotactile stimulus for each of the eight haptic icons when pressed. Three alternative responses were shown and users were asked to select which contact group they thought was associated with the reproduced haptic icon. Once the participants selected an option, the application gave them feedback both graphically and verbally, indicating whether the reply was correct or incorrect.

Table 1. Description of the set of haptic icons.

Vibrotactile patterns+	Description	Picture	Assigned to
	The buzzing of a bee		Friends
	The sound of a drum		Customers
	"We will rock you"*		School
	Supporters' claps (football match)		Mates
	Typical gypsy claps		Family
	Football referee's whistle (end of match)		Bosses
	A heartbeat		Couple
	Someone rhythmically knocking at a Door		Neighbors

+ Mean duration was 4.06 s. * The chords at the beginning of the Queens's song "We will rock you" (typical supporters' anthem during a basketball match).

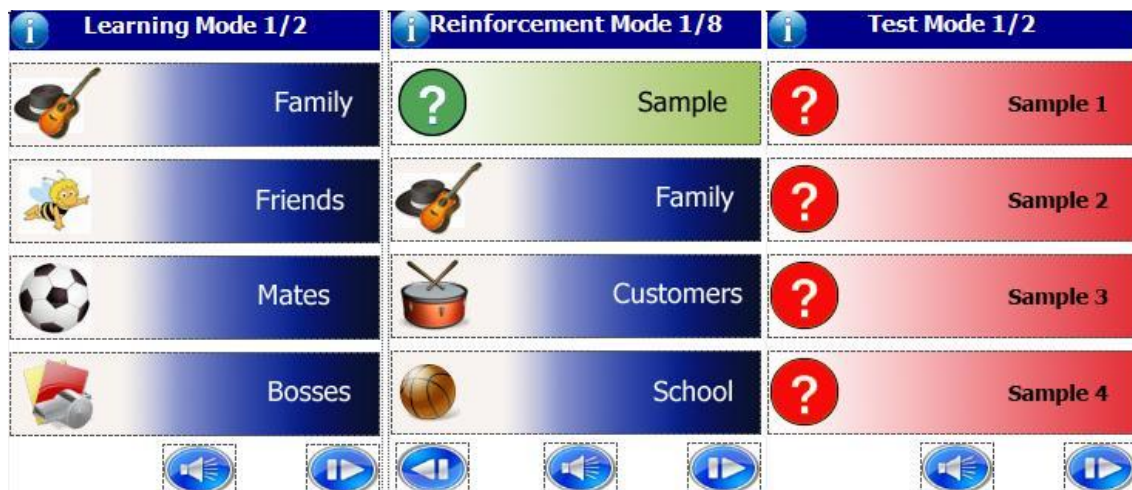


Fig. 1. Self-learning, reinforcement, and test screens (multimodal) (color figure available online).

After completing the reinforcement stage, users performed a test that indicated the ease of discrimination and recall of the eight haptic icons. Four buttons corresponding to four samples were shown on this screen. When users clicked on each of these samples, a vibratory pattern corresponding to one of the eight haptic icons was reproduced. Then, users had to choose the correct responses from three possibilities (chance was set to 33%). Three different versions of the test were provided (labeled A, B, and C) in which the order of appearance of each haptic icon was randomized. To minimize ordering effects, each third of the participants completed each test in the experiment in its entirety.

After the experiment was completed, all participants were required to fill out a usability questionnaire composed of six usability items. Three of the items were adapted from well-established usability surveys such as System Usability Scale (SUS) or Computer System Usability Questionnaire (CSUQ) (Tullis & Albert, 2008; see section 6.4). The remaining three items focused on the key aspects for improving the learnability of haptic icons: perceptiveness, distinctiveness, and recognizability (Swerdfeger, 2009). The participants rated each item using a Likert-type scale (see Table 2).

Table 2. Usability questionnaire.

Questions
1. The intensities of the haptic icons were clearly perceived
2. The haptic icons were distinguishable from each other
3. I was able to recognize the meaning of each haptic icon
4. I would use haptic icons to identify contacts if I had this feature on my own mobile phone
5. It was difficult to learn the meaning of the haptic icons
6. I felt comfortable using the application

Note. Likert-type scale from 1 (totally disagree) to 4 (totally agree).

Results

In this section, we present the main findings of the experiment, stressing the statistically significant results ($p < 0.05$).

Learning Times

The average total time that the application was used was 533 seconds ($MIN = 334$, $MAX = 826$). Analysis of variance (ANOVA) results confirmed differences between the total learning time required by VI and non-VI users ($F(1,20) = 4.56$, $p < 0.05$, $\eta p^2 = 0.40$) and for the unimodal and multimodal conditions ($F(1,20) = 16.50$, $p < 0.001$, $\eta p^2 = 0.11$). Further per stage analyses showed that the differences were mainly due to performance during the self-guided learning stage: VI participants needed more time ($M = 264.80$) than non-VI participants ($M = 156.14$) to complete the self-learning process ($F(1,20) = 27.82$, $p < 0.001$, $\eta p^2 = 0.26$), and this stage also took less time to be completed in the unimodal ($M = 130.25$) than in the multimodal ($M = 272.58$) condition ($F(1,20) = 52.70$, $p < 0.001$, $\eta p^2 = 0.50$). No significant differences (all $p > 0.05$) were observed in the reinforcement stage. Only the learning process showed significant differences ($F(1,20) = 6.10$, $p < 0.05$, $\eta p^2 = 0.21$) in the test stage, with a higher time for the unimodal ($M = 200.04$) than for the multimodal condition ($M = 121.30$).

These results were expected due to the different requirements in each condition. A summary of the data is found in Table 3.

TABLE 3. Time of use in each stage

Stage	Unimodal		Multimodal		All (n=24)
	Non-VI (n=7)	VI (n=5)	Non-VI (n=7)	VI (n=5)	
Self-guided L.	103	168.4	209.29	361.20	202
Reinforcement	154.57	155.20	184	174.20	173.52
Test	162.29	237.80	126	116.60	157.92
TOTAL	419.86	561.40	519.29	652.00	

Recognition Rates

Two-way ANOVA of the percentage of haptic icons recognized during the test stage showed significant differences in both the participants' visual capacity ($F(1,20) = 15.78$, $p < 0.001$, $\eta p^2 = 0.31$) and learning process ($F(1,20) = 12.51$, $p < 0.005$, $\eta p^2 = 0.24$). The VI participants recognized the meaning of a higher percentage of haptic icons during the test phase ($M = 91.2$) than the non-VI participants ($M = 65.12$). The percentage of recognition was higher for the multimodal ($M = 89.87$) than for the unimodal ($M = 66.62$) condition (Figure 2).

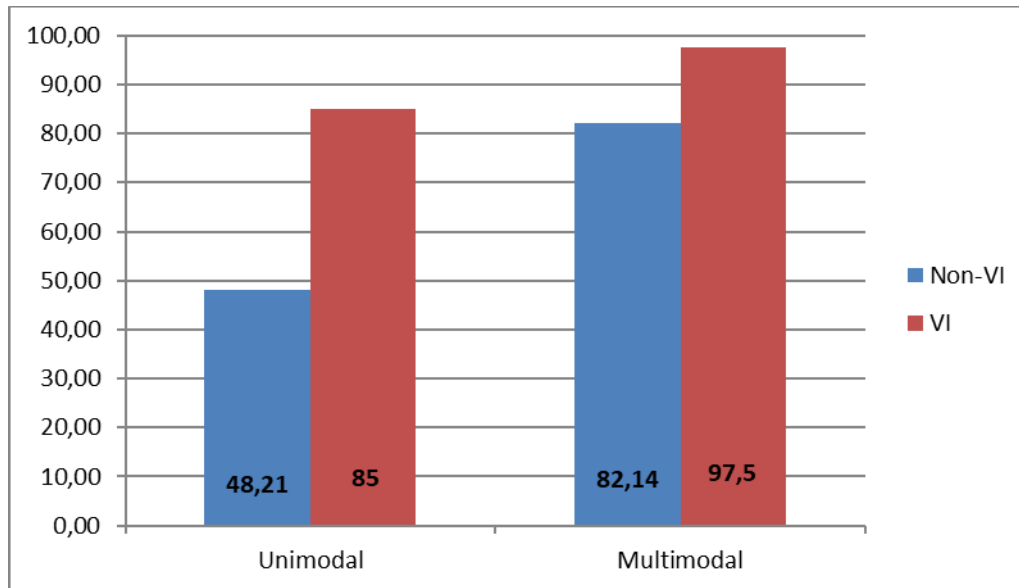


Fig. 2. Percentage of icons recognized for each group of participants during the test stage (color figure available online).

To gain insight into the dynamics of the learning processes, the recognition rates during the test and reinforcement stages were compared for each condition (Figure 3). The results indicated that recognition only improved significantly for the non-VI group with the multimodal condition ($F(1,20) = 10.32, p < 0.05, \eta p^2 = 0.21$). The absence of effects for the VI group may be due to a ceiling effect because they scored near the maximum.

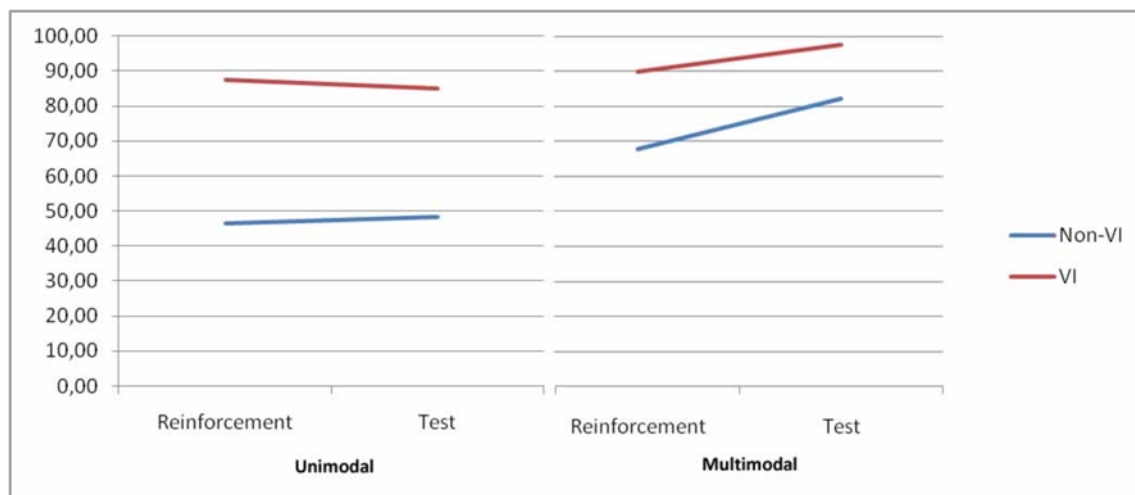


Fig. 3. Comparison of the percentage of recognition during the reinforcement and test stages (color figure available online).

The recognition rate for each individual haptic icon during the test was moderately high when all participants were considered (67%–92% with a total mean of 75.5%). Significant differences were observed in the recognition rate between the “couple” and “customers” and between the “couple” and “bosses” haptic icons ($t_{23} = 2.19, p < 0.05, d = 0.65$). Lower recognition rates were found for sighted users in the unimodal condition (between 14% and 86%), but the recognition rates were higher for VI users in the multimodal condition (between 80% and 100%). The results are summarized in Table 4.

TABLE 4 .Recognition rate for each haptic icon

Icon Name	Unimodal		Multimodal		All (n=24)
	Non-VI (n=7)	VI (n=5)	Non-VI (n=7)	VI (n=5)	
Friends	43%	100%	80%	71%	71%
Customers	14%	80%	100%	86%	67%
School	43%	80%	100%	86%	75%
Mates	57%	60%	100%	86%	75%
Family	64%	100%	100%	86%	79%
Bosses	57%	80%	100%	43%	67%
Couple	86%	100%	100%	86%	92%
Neighbors	43%	80%	100%	100%	79%
Mean	51%	85%	97.5%	80.5%	76%

Subjective Questionnaire

The results of the subjective questionnaire responses showed that the participants positively assessed the use of haptic icons and the learning procedure (see Table 5).

TABLE 5. Usability questionnaire results

Q.	Unimodal		Multimodal		All
	VI	Non-VI	VI	Non-VI	
1	3.60	3.57	3.60	3.43	3.54
2	3.80	2.57	3.60	3.00	3.17
3	3.00	2.57	3.80	3.14	3.08
4	3.80	3.57	3.80	3.71	3.71
5	1.60	3.00	1.40	2.00	2.08
6	3.40	3.57	4.00	3.86	3.71

Interestingly, the VI participants perceived the haptic icons as being more distinguishable from each other (*Mann-Whitney U* = 16.5, $p < 0.0005$) and learning the meaning of the icons was less difficult for them (*Mann-Whitney U* = 25, $p < 0.001$) than for the non-VI participants.

The participants assigned to the multimodal condition felt more comfortable than those assigned to the unimodal condition (*Mann-Whitney U* = 42, $p < 0.05$).

Discussion

The learnability of a set of haptic icons for incoming-call identification in mobile phones was tested in this study. The learning application used can be completed in an average time of less than 9 minutes. The time needed to accomplish the learning procedure varied between the groups due to the differences in the treatment conditions, but a higher

execution time did not negatively affect the participants' engagement. The two hypotheses of this study were confirmed, and their implications are discussed below.

Recall of VI Participants

Previous studies have claimed that implementing haptic information in mobile devices and other technologies is a feasible way of providing assistive technologies to people with visual impairments (Ghiani et al., 2009; Krishna et al., 2010). We hypothesized that visually impaired users may be able to learn haptic icons better than sighted users.

The VI participants did learn better and faster (nearly 90% of the haptic icons recognized during the reinforcement stage) and their subjective ratings showed that the haptic icons are more distinguishable and easier to learn for them than for sighted participants using both the unimodal and multimodal learning strategies.

Thus, these data support the use of haptic icons in mobile phones by this specific group of participants.

Effect of Different Learning Processes

The unimodal condition was not the easiest way to learn the association between a vibrotactile stimulus and a contact group, which demonstrated a lower recognition rate both for VI users and sighted users in particular. The unimodal process was also considered to be less comfortable. Therefore, a multimodal learning process improves the learnability of haptic icons, at least in this context.

The participants appeared to benefit from practice through the association created with the graphic icons (or audiodescriptions) during the reinforcement stage. Indeed, the multimodal process reflected an improvement in learning that was not reflected by the unimodal process. Differences found within the set also suggested that some associations are more difficult to learn (e.g., "bosses" and "customers"), while others can be learned without effort (e.g., "couple").

Conclusions, Limitations, and Future Work

In this study, haptic icons used for incoming-call identification in a commercial mobile phone were easier to learn with a brief multimodal learning process. Visually impaired users were found to learn the meaning of haptic icons effortlessly and obtain a better recognition rate than sighted users. They also benefited from multimodality with audio descriptions as an alternative to graphic icons.

However, the current study presents some limitations that should be addressed in future work:

- Recognition was not assessed while the user was concentrating on other tasks (such as walking, running, talking, or reading), which represents the common state that users experience when their mobile phones vibrate (Chan, MacLean & McGrenere, 2005).
- Users' short-term recall was tested in this study, and an appropriate recognition rate was reached after a limited amount of practice, which is the first indicator of good learnability. However, it is also necessary to evaluate memory retention and

learning in the long term, as in other studies (Hoggan & Brewster, 2010; Swerdfeger, 2009).

- In this study, a predefined set of meanings (e.g., contact groups) was assigned to a set of vibrotactile stimuli with specific characteristics (e.g., popular rhythms). The differences found between items suggest that the recognition rate could vary depending on factors such as the association strength of the metaphors used or the distinctiveness of the meanings to be represented. Future studies should perform comparative tests in which meanings are assigned randomly or users are allowed to select their own associations. Moreover, it will be very valuable to allow blind people to participate in the design of the haptic icons.
- Finally, some of the participants' characteristics such as age, cultural background, tactile training, or proficiency with mobile devices may also limit the generalizability of the results. For example, the participants in this study were relatively young (between ages 23 and 39 years), and differences in haptic sensitivity and learning ability are expected to increase with age. Moreover, because this study was conducted in the context of a Spanish culture, we may expect some differences in other cultures not only because of the different meanings of the metaphors selected but also because of the different perspectives on the use of tactile interfaces. Therefore, future research should also include an extended range of participants.

Acknowledgments

This research was part of the Spanish project Interfaces de relación entre el entorno y las personas con discapacidad (INREDIS, <http://www.inredis.es>), led by Technosite and funded by Centro para el Desarrollo Tecnológico Industrial (CDTI, CENIT/INGENIO 2010). The opinions expressed in this paper are those of the authors and are not necessarily those of the project's partners or of CDTI.

References

- Ballesteros, S., Bardisa, D., Millar, S., & Reales, J. M. (2005). The haptic test battery: A new instrument to test tactual abilities in blind and visually impaired and sighted children. *The British Journal of Visual Impairment*, 23(1), 11–24.
- Brewster, S. A. & Brown, L. M. (2004). Non-visual information display using Tactons. In E. Dykstra-Erickson & M. Tscheligi (Eds.), *CHI 2004: Extended abstracts on Human factors in computing systems* (pp. 787–788). New York: ACM
- Brown, L. M. & Brewster, S.A. (2006). Tactile crescendos and sforzandos: Applying musical techniques to tactile icon design. In G. M. Olson & R. Jeffries (Eds.), *CHI 2004: Extended abstracts on Human factors in computing systems* (pp. 610–615). New York: ACM
- Brown, L. M., Brewster, S. A., & Purchase, H. C. (2005). A first investigation into the effectiveness of Tactons. In A. Bicchi & M. Bergamasco (Eds.), *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp.167–176). Washington, DC: IEEE.
- Brown, L. M. & Kaaresoja, T. (2006). Feel who's talking: Using tactons for mobile phone alerts. In R. Grinter, T. Rodden, P. Aoki, E. Cutrell, R. Jeffries & G. Olsen (Eds.),

Proceedings of the Conference on Human Factors in Computing Systems (pp. 604–609). New York: ACM.

Caldwell, B., Cooper, M., Reid, L. G., & Vanderheiden, G. (2008). Web content accessibility guidelines (WCAG) 2.0. W3C Recommendation. World Wide Web Consortium (W3C).

Chan, A., MacLean, K., & McGrenere, J. (2005). Learning and identifying haptic icons under workload. In A. Bicchi & M. Bergamasco (Eds.), *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 432–439). Washington, DC: IEEE.

Chan, A., MacLean, K. E. & McGrenere, J. (2008). Designing haptic icons to support collaborative turn-taking. *International Journal of Human Computer Studies*, 66(5), 333–355.

Cohen, L. G., Celnik, P., Pascual-Leone, A., Corwell, B., Falz, L., Dambrosia, J., . . . Hallett, M. (1997). Functional relevance of crossmodal plasticity in blind humans. *Nature*, 389, 180–183.

Enriquez, M., & MacLean, K. E. (2008). The role of choice in longitudinal recall of meaningful tactile signals. In J. Weisenberger, A. Okamura & K. MacLean (Eds.), *Proceedings of the IEEE Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems* (pp. 49–56). Washington, DC: IEEE.

Gallace, A., & Spence, C. (2009). The cognitive and neural correlates of tactile memory. *Psychological Bulletin*, 135(3), 380–406.

Gallace, A., Tan, H. Z., & Spence, C. (2007). The body surface as a communication system: The state of the art after 50 years. *Presence*, 16(6), 655–676.

Ghiani, G., Leporini, B., & Paternò, F. (2009). Vibrotactile feedback to aid blind users of mobile guides. *Journal of Visual Languages and Computing*, 20(5), 305–317.

Heller, M. A. (2000). *Touch, representation and blindness*. Oxford, UK: Oxford University Press.

Hoggan, E., & Brewster, S. A. (2007). Designing audio and tactile crossmodal icons for mobile devices. In D. W. Massaro, K. Takeda, D. Roy, & A. Potamianos (Eds.), *Proceedings of ACM International Conference on Multimodal Interfaces* (pp. 162–169). New York: ACM.

Hoggan, E., & Brewster, S. A. (2010). CrossTrainer: Testing the use of multimodal interfaces in situ. In E. D. Mynatt, D. Schoner, G. Fitzpatrick, S. E. Hudson, K. Edwards & T. Rodden (Eds.), *Proceedings of the 28th International Conference on Human Factors in Computing Systems, CHI 2010*, (pp. 333–342). Atlanta, GA: ACM.

Hoggan, E., Crossan, A., Brewster, S., & Kaaresoja, T. (2009). Audio or tactile feedback: Which modality when? In D. R. Olsen Jr., R. B. Arthur, K. Hinckley, M. Ringel Morris, S. E. Hudson & S. Greenberg (Eds.), *Proceedings of the 27th International Conference on Human Factors in Computing Systems* (pp. 2253–2256). New York: ACM.

This is an Accepted Manuscript of an article published by Taylor & Francis in *Assistive Technology: The Official Journal of RESNA* on 8 May 2013, available at: <http://dx.doi.org/10.1080/10400435.2012.715112>.

- IMMERSION (2010). *Haptics White Paper: Improving the Mobile User Experience through Touch*. Retrieved March 10, 2011, from http://immersion.org/docs/Haptics_Improving-Mobile-UE_jun10v2.pdf
- Jones, L.A., Kunkel, J., & Piatetski, E. (2009). Vibrotactile pattern recognition on the arm and back. *Perception*, 38, 52–68.
- Krishna, S., Bala, S. McDaniel, T., McGuire, S., & Panchanathan, S. (2010). VibroGlove: An assistive technology aid for conveying facial expressions. In E. D. Mynatt, D. Schoner, G. Fitzpatrick, S. E. Hudson, W. K. Edwards & T. Rodden (Eds.), *Proceedings of the 28th of the International Conference on Human Factors in Computing Systems, CHI 2010, Extended Abstracts* (pp. 3637–3642). New York: ACM.
- Lai, H., & Chen, Y. (2006). A study on the blind's sensory ability. *International Journal of Industrial Ergonomics*, 36, 565–570.
- MacLean, K. E. (2008). Foundations of transparency in tactile information design. *IEEE Transactions on Haptics*, 1(2), 84–95.
- MacLean, K. E., & Enriquez, M. (2003). Perceptual design of haptic icons. In I. Oakley, S. O'Modhrain & F. Newell (Eds.), *Proceedings of EuroHaptics* (pp. 351–363). Washington, DC: IEEE.
- MacLean, K., & Hayward, V. (2008). Do-it-yourself haptics, part II: Interaction design. *IEEE Robotics and Automation*, 15(1), 104–119.
- Moreno, R., & Mayer, R. (1999). Cognitive principles of multimedia learning: The role of modality and contiguity. *Journal of Educational Psychology*, 91, 358–368.
- Paivio, A. (1986). *Mental representations: A dual coding approach*. New York: Oxford University Press.
- Rantala, J., Raisamo, R., Lylykangas, J., Surakka, V., Raisamo, J., Salminen, K., Pakkanen, T. & Hippula, A. (2009). Methods for presenting Braille characters on a mobile device with a touchscreen and tactile feedback. *IEEE Transactions on Haptics*, 2(1), 28–39.
- Rovers, A. F., & Van Essen, H. A. (2004). Design and evaluation of hapticons for enriched instant messaging. *Virtual Reality*, 9, 177–191.
- Réhman, S., & Liu, L. (2010). iFeeling: Vibrotactile rendering of human emotions on mobile phones. In X. Jiang, M. Ma & C. Chen (Eds.), *Mobile Multimedia Processing, Lecture Notes in Computer Science* (Vol. 5960, pp. 1–20). Berlin, Germany: Springer Verlag.
- Ryu, J., Chun, J., Park, G., Choi, S., & Han, S. H. (2010). Vibrotactile feedback for information delivery in the vehicle. *IEEE Transactions on Haptics*, 3(2), 138–149.
- Stephan, K. L., Smith, S. E., Martin, R. L., Parker, S. P. A., & McAnally, K. I. (2006). Learning and retention of associations between auditory icons and denotative referents: Implications for the design of auditory warnings. *Human Factors*, 48(2), 288–299.

This is an Accepted Manuscript of an article published by Taylor & Francis in *Assistive Technology: The Official Journal of RESNA* on 8 May 2013, available at: <http://dx.doi.org/10.1080/10400435.2012.715112>.

- Swerdfeger, B. (2009). *A first and second longitudinal study of haptic icon learnability: The impact of rhythm and melody*. (Unpublished MsC thesis.) University of British Columbia, Vancouver, Canada.
- Swerdfeger, B., Fernquist, J., Hazelton, T., & MacLean, K. E. (2009). Exploring melodic variance in rhythmic haptic stimulus design. In A. Gooch & M. Tory (Eds.), *Proceedings of Graphics Interface (GI_09)* (pp. 133–140). Toronto: ACM.
- Ternes, D., & MacLean, K. E. (2008). Designing large sets of haptic icons with rhythm. In M. Ferre (Ed.), *Proceedings of the 6th International Conference on Haptics: Perception, Devices and Scenarios, Lecture Notes in Computer Science* (Vol. 5024, pp. 199–208). Berlin, Germany: Springer Verlag.
- Tullis, T., & Albert, W. (2008). *Measuring the user experience: Collecting, analyzing, and presenting usability metrics*. San Francisco, CA: Morgan Kaufman.
- Van Erp, J. B. F., Kyung, K., Kassner, S., Carter, J., Brewster, S. A., Weber, G., & Andrew, I. (2010). Setting the standards for haptic and tactile interactions: ISO's work. In A. M. L. Kappers, J. B. F.
- van Erp, W. M. Bergmann Tiest & F. C. T. van der Helm (Eds.), *Haptics: Generating and Perceiving Tangible Sensations, International Conference, EuroHaptics 2010, Lecture Notes in Computer Science 6192* (pp. 353–358). Berlin, Germany: Springer Verlag.
- Waraich, P., & D'Angiulli, A. (2002). Enhanced tactile encoding and memory recognition in congenital blindness. *International Journal of Rehabilitation Research*, 25, 143–145.