Intuitiveness of Vibrotactile Speed Regulation Cues

JANI LYLKYKANGAS, VEIKKO SURAKKA, JUSSI RANTALA, and ROOPE RAISAMO, University of Tampere, Finland

Interpretations of vibrotactile stimulations were compared between two participant groups. In both groups, the task was to evaluate specifically designed tactile stimulations presented to the wrist or chest. Ascending, constant, and descending vibration frequency profiles of the stimuli represented information for three different speed regulation instructions: “accelerate your speed,” “keep your speed constant,” and “decelerate your speed,” respectively. The participants were treated differently so that one of the groups was first taught (i.e., primed) the meanings of the stimuli, whereas the other group was not taught (i.e., unprimed). The results showed that the stimuli were evaluated nearly equally in the primed and the unprimed groups. The best performing stimuli communicated the three intended meanings in the rate of 88% to 100% in the primed group and in the unprimed group in the rate of 71% to 83%. Both groups performed equally in evaluating “keep your speed constant” and “decelerate your speed” information. As the unprimed participants performed similarly to the primed participants, the results suggest that vibrotactile stimulation can be intuitively understood. The results suggest further that carefully designed vibrotactile stimulations could be functional in delivering easy-to-understand feedback on how to regulate the speed of movement, such as in physical exercise and rehabilitation applications.

Categories and Subject Descriptors: H.1.2 [Models and Principles]: User/Machine Systems—Human factors, human information processing; 5.2 [Information Interfaces and Presentation]: User Interfaces (D.2.2, H.1.2, I.3.6)—Haptic I/O; J7 [Computer Applications]: Computers in Other Systems—Consumer products

General Terms: Design, Experimentation, Human Factors

Additional Key Words and Phrases: Human-computer interaction, heart rate monitor, haptic feedback, iconic information, priming, intuitive decision making

ACM Reference Format:
DOI: http://dx.doi.org/10.1145/2536764.2536771

1. INTRODUCTION

Interaction with mobile devices relies mainly on auditory and visual feedback modalities, although it is known that cognitive processing of auditory and visual information in mobile situations can be problematic (e.g., Oulasvirta et al. [2005]). Problems regarding parallel processing of technology-mediated information and the environment stem from the limitations of the human mental capacity, which is emphasized in situations where divided attention is required (e.g., while moving in rough terrain or...
in traffic) [Lamble et al. 1999]. Especially in sports, visual and auditory attention often needs to be focused primarily on the environment and on the ongoing performance, and all intervening or competitive information from a mobile device may distract and expose both the user and the other people nearby to potential safety risks.

Utilizing the human sense of touch (i.e., haptic modality) as an information channel is a promising alternative to visual and auditory information in mobile and visually demanding situations [Raisamo et al. 2009]. Touch-based stimulation can convey the needed information while allowing the user to focus the vision and hearing exclusively on the surroundings and on the primary task, such as an ongoing workout. For example, Ho et al. [2005] found that reactions to vibrotactile warning signals presented to the torso were significantly faster and also somewhat more accurate as compared to warning signals presented in auditory and visual modality in a dual-task condition (i.e., while performing an attention-demanding visual task).

Haptic feedback that is informing about a status of mobile devices (e.g., alarm for an incoming phone call) is most commonly provided with vibrotactile actuators that vibrate the device and provide tactile sensations by activating mechanoreceptors in the user’s skin. In addition to mobile phones, some of the latest sports heart rate monitors are equipped with a vibration function as an alternative to auditory alarms. Although vibration can potentially grasp the exerciser’s attention effectively, privately, and in an unobtrusive way, a binary type (i.e., on/off) alarm is limited in the sense that it is incapable of conveying the actual meaning of the alarm signal. Therefore, after noticing the vibration, there is still a need to refer to visual information to confirm whether to slow down or to speed up the exercise.

With haptic stimulation, it is possible to provide richer information than just binary alarms. Brewster and Brown [2004] introduced tactile icons—structured, abstract messages that can be used for presenting information via the sense of touch. They suggested that distinguishable and identifiable iconic information can be encoded by manipulating, for example, frequency, amplitude, duration, rhythm, and spatial location of the haptic stimulation. Using a vibrotactile actuator of a mobile phone, Brown and Kaaresoja [2006] created nine two-dimensional tactile icons informing about the type of a phone alert (i.e., three different rhythms) and the priority of the alert (i.e., three different amplitude modulations within each rhythm). The results showed that the icons were recognized correctly with an accuracy of 72%.

Iconic haptic feedback has been investigated in physical training as well. Rovers and van Essen [2006] introduced a crosstrainer gym device with haptic features. The handles of the device were equipped with multiple vibrotactile actuators mediating iconic guidance information by stimulating the user’s palms. The icons were designed to inform the user of factors such as a heartbeat that is too low or too high. For example, an overly extensive workout was represented as a heartbeat signal consisting of a strong beat at the center of the palm and a weaker afterbeat at the lower palm. The results showed that the icons were noticeable during the exercise, but their interpretation required first referring to visual information to understand and eventually learn their meanings.

Enriquez and MacLean [2008] found that vibrotactile icons (e.g., for going faster and slower) can be learned and recalled after a 2-week delay with 80% accuracy regardless of whether their meanings were purely arbitrarily chosen or self-chosen by the participants. Even then, it would seem probable that using arbitrarily or subjectively predefined haptic icons in commercial products holds some concerns. This is because, in all likelihood, many end-users would not interpret the meanings of the icons in a way that the designer has originally intended.

In conclusion, there is evidence that haptic stimulation can complement or even substitute visual and auditory feedback, not only for alarming purposes but also in mediating the needed information with relatively high recognition accuracies. We note, however, that in all of the noted studies, the participants were provided with guidance or a chance to first learn the meanings of the iconic...
stimulations. This type of individual priming is, of course, impossible when considering the everyday use of haptic icons in consumer devices. It is also known that most typically, people want to learn to use new devices and applications first based on their intuition, and manuals are often referred to only when anything else does not seem to solve the problem [Rettig 1991]. Hence, it would be ideal if haptic information could be interpreted intuitively so that the device could be introduced “out of the box” without any extensive learning or adjustments of its functions. Motivated by the reasons mentioned earlier, we started investigating possibilities of providing simple and easily interpretable haptic information for the needs of mobile users. The aim of an initial experiment [Lylykangas et al. 2009] was to study whether three types of iconic speed regulation cues could be recognized in an intuitive manner—that is, without a priori teaching or coaching. The vibrotactile stimuli were varied, for example, by a vibration frequency profile to investigate if stimuli with ascending, constant, and descending vibration frequency profiles could be associated naturally and analogously with information cueing to accelerate the speed, to keep the speed constant, and to decelerate the speed, respectively. The wrist and chest were chosen for the stimulus locations because the main components of the most heart rate monitors—a wrist unit and a chest strap—could serve as natural platforms for embedding haptic technology and enabled permanent contact to the skin. The results showed that the stimuli were predominantly perceived in congruence with the three different vibration frequency profiles in both body locations. The best recognized ascending, descending, and constant frequency stimuli represented “accelerate your speed,” “decelerate your speed,” and “keep your speed constant” information in accuracies of 88%, 79%, and 100%, respectively. The results indicated promisingly that it could be possible to provide interpretable information via the sense of touch to guide the user’s performance without any teaching. In this respect, it seemed that conveying speed regulation information with haptic icons might really be intuitive.

The present aim was to further test the learnability and, particularly, the possible intuitiveness of the three types of haptic speed regulation cues. Intuitiveness is frequently referred to as an important factor in human-technology interaction [Naumann et al. 2007], but controlled experimental research in this area seems to be virtually nonexistent. We decided to put intuition to the test by comparing a condition where participants were primed by first teaching the intended meaning of the stimulation against one where participants were unprimed (i.e., not taught). By comparing the response rates between these two groups, it would be possible to get a better understanding of the actual intuitiveness of the associations in the decision making.

Because this was the first test of this type of experimental design, we decided to conduct the initial study in laboratory settings with immobile participants in order to minimize the effects of uncontrolled variables to the results. Knowing that physical movement can attenuate the recognition accuracy of low-amplitude vibrotactile stimuli [Pakkanen et al. 2008; Post et al. 1994], we used relatively high stimulus amplitude to ensure that the stimulations could be functional in future studies with mobile participants. Karuei et al. [2011] found that negative effects of movement artifacts on vibration perception can be compensated by sufficient stimulus intensity and appropriate body location. There are several examples showing that vibrotactile displays can provide guidance information during physical movement in various sports, such as snowboarding [Spelmezan et al. 2009], rowing [Van Erp et al. 2006], and swimming [Bächlin et al. 2009].

Tactile stimulation has been found to be associated with human emotions [Salminen et al. 2008]; therefore, we also measured the emotion-related subjective experiences evoked by the stimuli. Earlier research has shown that the use of dimensional affective space can be effective in tracking down experiences evoked by visual and auditory stimulations [Bradley and Lang 1994, 2000]. Because haptic stimuli in mobile situations should be clearly noticeable, yet preferably not irritating, subjective ratings on arousability and pleasantness of the stimuli were collected.
Based on the results of our earlier study [Lylykangas et al. 2009], it was expected that responses are mostly given in congruence with the vibration frequency profile of the stimuli regardless of the experimental condition (i.e., primed or unprimed group).

2. METHOD

2.1 Participants

Twenty-four volunteers took part in the experiment after signing informed consent forms. Twelve of the participants were female (mean age 29 years, age range 19–57 years) and 12 were male (mean age 23 years, age range 19–30 years). The participants were students of the University of Tampere. They all were naïve with respect to the purpose of the experiment and reported having a normal or corrected-to-normal vision and normal sense of touch. By self-reports, 23 participants were right-handed and 1 participant was left-handed.

2.2 Apparatus

Experimental hardware was identical to our previous study [Lylykangas et al. 2009]. Two Engineering Acoustic Inc. C2 voice coil actuators were used to present vibrotactile stimulations through a sound card of a personal computer. The diameters of the actuator and its vibrating skin contactor area were 3.05cm (1.2in) and 0.76cm (0.3in), respectively. Stimuli were amplified with a Stage Line® STA 1508 audio amplifier. The actuators were attached to a soft textile wristband and to a Polar® WearLink™ chest strap (Figure 1).

E-Prime® 2.0 Professional experiment generator software [Schneider et al. 2002] was used for controlling the stimulus presentation and data collection. Responses were given using a computer keyboard. The buttons for “accelerate your speed,” “keep your speed constant,” and “decelerate your speed” responses were set in a vertical layout and labeled with an arrow pointing upward, sideward, and downward, respectively. An experiment initiation button was located on the left side of the middle button. In addition, nine response buttons for giving emotional ratings were set in horizontal layout and labeled from −4 to +4.

2.3 Stimuli

A subset of 18 stimuli was selected from the previous study [Lylykangas et al. 2009]. The stimuli were varied by $3 \times$ frequency profile, $3 \times$ duration, and $2 \times$ stimulus location. The frequency profiles of the stimuli (Figure 2) were created in the following way: (a) for ascending stimuli, the frequency was modulated linearly from 50 to 300Hz; (b) the frequency for the constant stimuli was kept at 100Hz; and (c) the frequency for the descending stimuli was modulated linearly from 300 to 50Hz.
Intuiveness of Vibrotactile Speed Regulation Cues

2.4 Procedure

After introducing the laboratory and the equipment, the participant was seated and the actuators were attached on top of the wrist of the nondominant hand and to the chest (Figure 1). The actuator in the chest strap was located in the sagittal plane of the thorax. In order to avoid vibration resonance with the skeleton, the actuator was attached below the breastbone. Because the chest strap was originally from a heart rate monitor, the participant was informed that the heart rate data was not measured during the experiment. The nondominant hand was laid on a soft armrest, and the other hand was put next to the response buttons. The participant was instructed to hold the nondominant hand still and to keep the gaze on the display during the experiment. To block the mechanical sound of the actuators, the participant listened to pink noise via a hearing protector headset at a comfortable sound level.

The experiment consisted of two experimental conditions. In the primed condition, the participants (six females and six males) were first trained to learn the meanings of the stimuli. In the unprimed condition, the participants (six females and six males) were not taught the meaning of the stimuli. Both conditions included three sessions: (1) priming/familiarization, (2) recognition, and (3) rating. The order of the sessions was fixed. The rating session consisted of two subsessions: pleasantness rating and arousability rating. The order of the subsessions was counterbalanced so that half of the participants started with pleasantness rating and then continued with arousability rating. The other half performed the subsessions in reversed order. Each of the sessions and subsessions consisted of two separate blocks. In one block, the stimuli were presented to the wrist; in the other block, they were presented to the chest. The order of the blocks within each session and subsession was counterbalanced.

The participant was allowed to take a short break between the sessions, subsessions, and blocks. Finally, there was a structured postexperimental interview, where questions were asked to get additional information on the easiness/difficulty of the recognition task and on the used response strategies. The two stimulus locations were also ranked in terms of touch sensitivity and preference. The experiment

Fig. 2. Vibration frequency profiles of (a) ascending, (b) constant, and (c) descending stimuli.

175Hz; and (c) for descending stimuli, the frequency was modulated linearly from 300 to 50Hz. Three different durations of the stimuli were 500, 1750, and 3000 ms, which provided clearly distinguishable stimulations. The stimuli were built upon sine waveform based on C2 actuator recommendations (http://www.eaiinfo.com/). The amplitude and phase of the signal were not manipulated.

Audacity® audio editor and recorder software version 1.2.6 (http://audacity.sourceforge.net/) and Pure Data real-time audio synthesizer software version 0.40.3 (http://puredata.info/) were used in creating the stimuli. All of the stimuli were 16-bit mono Windows Waveform (WAV) audio files with a 44.1kHz sampling frequency. Stimulus amplitude was adjusted to 1.49V (AC) for both wrist and chest by measuring the voltage from the amplifier outputs with a Fluke® 87V True RMS multimeter while the actuators were playing a constant 250Hz sine wave calibration stimulus.
finished with a debriefing, in which the participants were explained the purpose of the experiment. It took an average of 1 hour to conduct the whole experiment.

2.4.1 Session 1: Priming/Familiarization. The objective of the first session was to create two experimental treatments: a condition with primed participants and a condition with unprimed participants. In the primed condition, the purpose of the session was to teach the participants the intended meanings of the stimuli. They were first told that ascending, constant, and descending vibration frequency meant speed acceleration, constant speed, and speed deceleration, respectively, and that the stimulus duration did not make any difference in this respect. The task was to sit still, feel the stimulations, and learn their meanings. The participants would see a text in the screen that indicated the meaning of the stimuli before and after each stimulus presentation (e.g., “The upcoming stimulus means: Accelerate your speed” and “The stimulus meant: Accelerate your speed”). In the unprimed condition, the purpose of the session was to allow the participants to familiarize themselves with feeling the vibrotactile stimuli in the two body sites and to initiate them into the stimulus space used in the experiment. They were instructed simply to sit still and feel the stimuli. In both conditions, participants started the session by pressing the experiment initiation button. Then the nine wrist stimuli and the nine chest stimuli were presented in separate blocks sequentially in a random order with an interstimulus interval of 3500ms. The response buttons were covered in both conditions to prevent hints to the experimental task in the upcoming session.

2.4.2 Session 2: Recognition. In the beginning, the experimenter uncovered the response buttons. At this point, the actual meaning of the experiment was revealed and explained to the participants. They were instructed to imagine that the computer was giving them instructions to either accelerate their speed, keep their speed constant, or decelerate their speed by using the stimuli presented in the previous session. The primed group was instructed to respond as quickly and as accurately as possible according to what was taught in the previous session. However, according to Kahneman’s [2003] characterization of intuition being thoughts and preferences that come to mind quickly, spontaneously, and effortlessly under appropriate circumstances, the unprimed group was instructed to respond as quickly as possible by relying on the first impression. Otherwise, the procedures in the primed and unprimed groups were identical. First, the participant performed three practice trials in order to rehearse the response technique. In the practice session, three 1000ms-long practice stimuli (constant 50, 175, and 300Hz square wave vibration) were presented one at a time in random order. In contrast to the experimental stimuli, the training stimuli were presented simultaneously to the wrist and chest. The practice stimuli were not presented in the actual experiment. After the practice trials, the experimenter left the room and the participant initiated the first trial by pushing the experiment initiation button. In a trial, a “Next stimulus” text appeared on the display for 1500ms. Then, the text disappeared and a fixation point (+) appeared on the center of the display for 1500ms. The display was blank for 500ms before the stimulus onset and during the stimulus presentation. Immediately after the stimulus offset, the response options appeared on the display, and the participant was able to answer. The uppermost button was to be pushed for an “accelerate your speed” response, the middle button was to be pushed for a “keep your speed constant” response, and the lowest button was to be pushed for a “decelerate your speed” response. After the response, there was a 500ms interval and then a new trial was initiated automatically. Response times were calculated from the stimulus offset. Each of the nine wrist stimuli and nine chest stimuli were presented twice in a random order in separate blocks, resulting in a total of 36 trials in the session.

2.4.3 Session 3: Rating. The task in the third session was to rate the stimuli using two emotion-related nine-point bipolar scales varying from −4 to +4. The procedure was the same in the primed
and the unprimed conditions. Ratings were asked for the scale of pleasantness of a stimulus (i.e., how unpleasant or pleasant the stimulus felt), varying from unpleasant to pleasant, and for the scale of arousability of a stimulus (i.e., how relaxed or aroused the participant felt during the stimulus), varying from relaxed to aroused. On both scales, 0 represented a neutral experience (i.e., neither unpleasant nor pleasant, and neither relaxed nor aroused). Ratings were given using the keyboard. In the beginning of both pleasantness and arousability ratings, the participant performed three practice trials in order to rehearse the rating procedure. Three practice stimuli not included in the actual experiment were rated one at a time. The practice stimuli were presented simultaneously to the wrist and chest. After the practice trials, the experimenter left the room and the participant was allowed to start rating the experimental stimuli. The participant initiated a trial by pushing a space bar on the keyboard. Then, a fixation point appeared on the center of the display for 1500ms. The display was blank for 1500ms before the stimulus onset and during the stimulus presentation. Immediately after the stimulus offset, the rating scale appeared on the display, and the participant was able to respond. After giving the response, there was a 500ms interval and then the participant could initiate a new trial. Each of the 18 stimuli was presented once for both the pleasantness and the arousability rating scales in separate blocks in a random order. Thus, there were a total of 36 trials in the session.

2.5 Data Analysis
The data of the average response percentages in the second session were analyzed using a four-way mixed model Analysis of Variance (ANOVA) with experimental condition (i.e., primed and unprimed group) as a between-subjects factor, and stimulus properties (i.e., frequency profile, location, and duration) as within-subjects factors. The analysis was conducted separately for each of the three response options.

Response times in the second session were analyzed with a two-way mixed model ANOVA with experimental condition as a between-subjects factor and stimulus location as a within-subjects factor. The main interest was to study the possible effects of these two factors; therefore, response times were averaged over the frequency profiles and stimulus durations to simplify the analysis. In addition, data were averaged over the three response options in order to avoid a bias caused by the fixed order of the response buttons. Response time analysis included both congruent and incongruent responses.

The main scope of the emotional ratings in the third session was to study possible effects of gender, frequency profile, and stimulus location. Thus, to avoid overly complex analysis, the data were averaged over the experimental conditions and stimulus durations. A three-way mixed model ANOVA with gender as a between-subjects factor and frequency profile and location as within-subjects factors was used for the analysis.

Greenhouse-Geisser–corrected degrees of freedom were used to validate the $F$ statistic, if the sphericity assumption of the data was violated. Bonferroni-corrected $t$-tests were used for pairwise post hoc tests.

3. RESULTS
Figure 3 shows the mean responses and Standard Error of the Means (SEMs) in the second session. Figures 4 and 5 present the mean responses and SEMs of the emotional ratings of pleasantness and arousability in the third session.

3.1 “Accelerate Your Speed” Responses
For the “accelerate your speed” responses (Figure 3(a)), a four-way $2 \times 3 \times 2 \times 3$ (experimental condition $\times$ frequency profile $\times$ location $\times$ duration) mixed model ANOVA showed a statistically significant
Fig. 3. Mean percentages and SEMs of (a) “Accelerate your speed” responses, (b) “Keep your speed constant” responses, and (c) “Decelerate your speed” responses for wrist and chest stimuli by experimental condition, stimulus duration, and frequency profile. The grey area indicates the range of the chance level. C, congruent stimuli; I, incongruent stimuli.

Fig. 4. Mean pleasantness ratings and SEMs of wrist stimuli (left) and chest stimuli (right) by gender and frequency profile.

Fig. 5. Mean arousability ratings and SEMs of wrist stimuli (left) and chest stimuli (right) by gender and frequency profile.
main effect of frequency profile $[F(2, 44) = 113.2, p < 0.001]$ and two-way interactions between frequency profile and experimental condition $[F(2, 44) = 5.1, p \leq 0.01]$, frequency profile and location $[F(1.6, 35.2) = 4.3, p < 0.05]$, and frequency profile and duration $[F(2.4, 53.6) = 7.56, p \leq 0.001]$. Main effects of experimental condition, duration and location, and other interactions of the main effects were not statistically significant.

Post hoc pairwise comparisons showed that the mean rate of “accelerate your speed” responses given to congruent (i.e., ascending frequency) stimuli (83.3%) was significantly higher as compared to incongruent (i.e., constant and descending frequency) stimuli, but they differed significantly for congruent responses as compared to 1750 and 3000ms stimuli.

In order to analyze the interaction between frequency profile and experimental condition in more detail, three separate one-way ANOVAs (i.e., one for each frequency profile with experimental condition as an independent between-subjects factor) were conducted. The analyses showed that the interaction was due to the fact that response rates between primed and unprimed participants were similar for incongruent (i.e., constant and descending frequency) stimuli, but they differed significantly for congruent (i.e., ascending frequency) stimuli $[F(2, 22) = 12.7, p < 0.01]$. In Figure 3(a), it can be seen that primed participants gave “accelerate your speed” responses for ascending frequency stimuli more frequently than unprimed participants $[MD = 25.0\%]$.

The interaction between frequency profile and location came from the fact that response rates of wrist and chest stimuli were similar, except for descending frequency stimuli, where response rates were slightly, although not significantly, higher in the chest than in the wrist $[MD = 10.4\%, p = 0.079]$. The reason for the interaction between frequency profile and duration can be seen in Figure 3(a), which shows that response rates of 500ms stimuli were lower in congruent responses and higher in incongruent responses as compared to 1750 and 3000ms stimuli.

### 3.2 “Keep Your Speed Constant” Responses

For the “keep your speed constant” responses (Figure 3(b)), a four-way $2 \times 3 \times 2 \times 3$ (experimental condition $\times$ frequency profile $\times$ location $\times$ duration) mixed model ANOVA showed a statistically significant main effect of frequency profile $[F(1.4, 29.9) = 198.7, p < 0.001]$. Two-way interactions were found between frequency profile and experimental condition $[F(1.4, 29.9) = 6.1, p < 0.05]$ and frequency profile and duration $[F(2.7, 60.1) = 10.2, p < 0.001]$. Main effects of experimental condition, duration and location, and other interactions of the main effects were not statistically significant.

Post hoc pairwise comparisons showed that the rate of “keep your speed constant” responses given to congruent (i.e., constant frequency) stimuli (78.8%) was significantly higher as compared to incongruent (i.e., ascending frequency $[MD = 71.9\%, p < 0.001]$ and descending frequency $[MD = 64.2\%, p < 0.001]$) stimuli.

To analyze the interaction between frequency profile and experimental condition, three separate one-way ANOVAs (i.e., one for each frequency profile with experimental condition as an independent between-subjects factor) were performed. The analyses showed that the interaction was due to the fact that response rates between primed and unprimed participants were similar for congruent (i.e., constant frequency) stimuli but differed significantly for incongruent stimuli. Unprimed participants gave “keep your speed constant” responses more frequently to ascending and descending frequency stimuli than primed participants $[MD = 9.8\%, p < 0.05$ and $MD = 13.9\%, p < 0.05$, respectively].

The explanation for the interaction between frequency profile and duration can be seen in Figure 3(b) where response rates of 500ms stimuli is lower in congruent responses and higher in incongruent responses as compared to 1750 and 3000ms stimuli.
3.3 “Decelerate Your Speed” Responses

For the “decelerate your speed” responses (Figure 3(c)), a four-way $2 \times 2 \times 2 \times 3$ (experimental condition \times frequency profile \times location \times duration) mixed model ANOVA showed a statistically significant main effect of frequency profile $[F(1.5, 33.9) = 40.8, p < 0.001]$ and stimulus duration $[F(1.4, 30.3) = 4.6, p < 0.05]$. A three-way interaction was found between experimental condition, frequency profile, and duration $[F(4, 88) = 2.6, p < 0.05]$. Two-way interactions were found between frequency profile and location $[F(1.5, 32.1) = 9.7, p < 0.001]$ and frequency profile and duration $[F(4, 88) = 10.9, p < 0.001]$. Main effects of experimental condition, location, and other interactions of the main effects were not statistically significant.

Post hoc pairwise comparisons showed that the rate of “decelerate your speed” responses to congruent (i.e., descending frequency) stimuli (57.3%) was significantly higher as compared to incongruent (i.e., ascending frequency $[MD = 47.6\%, p < 0.001]$ and constant frequency $[MD = 44.4\%, p < 0.001]$) stimuli. Despite the main effect of stimulus duration, pairwise comparisons did not reveal significant differences between the durations.

To investigate the three-way interaction between experimental condition, frequency profile, and duration, two-way $3 \times 3$ (frequency profile \times duration) ANOVAs were performed separately for primed and unprimed groups. The results showed that the interaction resulted from the fact that frequency profile interacted with duration in the primed group $[F(2.3, 25.3) = 12.9, p < 0.001]$ but not in the unprimed group. Figure 3(c) shows that response rate of 500ms stimuli in the primed group fluctuated in response to frequency profile; thus, in ascending, constant, and descending frequency, it was either equal, lower, or higher, respectively, in relation to 1750- and 3000ms stimuli.

The interaction between frequency profile and location was due to the fact that congruent responses were given more often for the wrist than chest stimuli $[F(1, 23) = 7.0, p < 0.05]$, but incongruent responses to constant frequency stimuli were given more frequently when presented to the chest than the wrist $[F(1, 23) = 6.4, p < 0.05]$. The explanation for the interaction between frequency profile and duration can be seen in Figure 3(c), which shows that response rates of 500ms stimuli were lower in congruent responses as compared to 1750 and 3000ms stimuli, but in incongruent responses, the response rates were similar for the three stimulus durations.

3.4 Response Times

The grand mean of the response times in the second session was 1597ms. A two-way $2 \times 2$ (experimental condition \times stimulus location) mixed model ANOVA showed a statistically significant main effect of stimulus location $[F(1, 20) = 12.1, p < 0.01]$. The main effect of experimental condition and the interaction of the main effects were not statistically significant. Post hoc pairwise comparisons showed that the mean response time to wrist stimuli (1463ms) was significantly faster as compared to the responses given to chest stimuli $[MD = 269ms]$.

3.5 Pleasantness Ratings

For the ratings of stimulus pleasantness (Figure 4), a three-way $2 \times 3 \times 2$ (gender \times frequency profile \times location) mixed model ANOVA showed a statistically significant main effect of frequency profile $[F(2.44) = 17.2, p < 0.001]$ and a significant two-way interaction effect between gender and frequency profile $[F(2.44) = 5.3, p < 0.05]$. The main effects of gender and location were not statistically significant, and there were no other statistically significant interactions of the main effects. Post hoc pairwise comparisons showed that constant frequency stimuli were rated as more pleasant than ascending frequency stimuli $[MD = 0.7, p < 0.05]$ and descending frequency stimuli $[MD = 1.3, p < 0.001]$. In
addition, ascending frequency stimuli were rated as more pleasant than descending frequency stimuli \([MD = 0.5, p < 0.05]\).

The interaction between gender and frequency profile was analyzed in more detail with two separate one-way ANOVAs (i.e., one for both genders with frequency profile as an independent within-subjects factor). The results showed that the interaction was due to the fact that frequency profile had a statistically significant effect for females’ responses \([F(2, 22) = 24.8, p < 0.001]\) but not for males’ responses. Post hoc pairwise comparisons showed that females rated constant frequency stimuli as significantly more pleasant than ascending frequency stimuli \([MD = 1.4, p \leq 0.01]\) and descending frequency stimuli \([MD = 1.8, p < 0.001]\).

### 3.6 Arousability Ratings

For the ratings of stimulus arousability (Figure 5), a three-way \(2 \times 3 \times 2\) (gender \(\times\) frequency profile \(\times\) location) mixed model ANOVA showed a statistically significant main effect of frequency profile \([F(2, 44) = 56.3, p < 0.001]\) and location \([F(1, 22) = 6.9, p < 0.05]\). The main effect of gender and interactions of the main effects were not statistically significant.

Post hoc pairwise comparisons showed that both ascending and descending frequency stimuli were rated as significantly more arousing than constant frequency stimuli \([MD = 2.2, p < 0.001\) and \(MD = 2.6 p < 0.001\), respectively]. In addition, wrist stimuli were rated as significantly more arousing when compared to chest stimuli \([MD = 0.3, p < 0.05]\). The other pairwise comparisons were not statistically significant.

### 4. DISCUSSION

In general, the vibrotactile speed regulation stimuli were clearly intelligible for both primed and unprimed participants. Figure 3 showed that the average rates of congruently (i.e., according to our hypothesis) given responses were clearly above the 33% chance level, and incongruent responses were given at lower rates. At their best, the three different speed regulation cues could be evaluated congruently in the rates of 88% to 100% and 71% to 83% by primed and unprimed participants, respectively. To the best of our knowledge, these were the first results showing proof on behalf of intuitive judgments of vibrotactile iconic information by using a method where the performances of primed and unprimed participants were compared in a controlled experimental setup.

The hypothesis of the congruence between the vibration frequency profiles and the response options was mainly supported, because unprimed participants performed equally to primed participants in evaluating the stimuli with constant and descending frequency profiles congruently. Ascending frequency stimuli, however, were evaluated congruently (i.e., as “accelerate your speed” information) more frequently by primed than unprimed participants. Even then, as seen from Figure 3(a), the mean rate of congruent responses of unprimed participants for ascending frequency stimuli (83.3%) is commensurate with their congruent responses for constant and descending frequency stimuli. Considering that primed participants succeeded exceptionally well (i.e., in accuracy of 100% or close) in evaluating ascending frequency stimuli, the significant difference can be partly explained by the good performance of primed participants rather than by the low rate of congruent responses by unprimed participants. Taken together, the results of the unprimed participants replicated the significant findings of our previous experiment [Lylykangas et al. 2009]. Added to this, the predominantly coherent performance of both primed and unprimed participants in the present study gave evidence that the stimuli were intuitively associated to their intended meanings.

In postexperimental interviews, many participants criticized that evaluating the shortest (i.e., 500ms) stimuli was difficult. This opinion was supported by the significant interaction effects found between frequency profile and stimulus duration within each response option. Figures 3(a)–3(c) shows
that the 500ms stimuli were evaluated congruently to a lesser degree when compared to longer stimulus durations. Thereby, it seems that the 1750 and 3000ms stimuli would provide speed regulation information more efficiently than the 500ms stimuli.

Response times were similar between primed and unprimed groups. Both groups, however, responded significantly faster to wrist stimuli than to chest stimuli. The statistical analysis did not reveal a coherent result on the superiority of neither wrist nor chest stimulation; therefore, it seems unlikely that the difference of the response times was due to difficulty in perceiving the chest stimuli. One possible explanation can be related to results of Tipper et al. [1998], which show that visual perception on the haptically stimulated body site can facilitate reaction times as compared to a situation where the body site cannot be seen. Thus, faster response times in the wrist found in the present study could be related to the fact that the participants were able to see their wrist but not their chest during the stimulation.

Subjective ratings of the stimuli revealed that constant frequency stimuli were generally evaluated as more pleasant than stimuli with ascending and descending frequencies. Further, the ratings of arousal showed that constant frequency stimuli were rated as less arousing than the other frequency profiles. Thinking from the application point of view, this result suggests that constant vibration frequency stimulation could function nicely in informing nonarousingly that “you are doing fine—keep your speed constant.” The other two frequency profiles rated as more arousing would also function well by first alerting that one needs to make a change and then informing whether one should accelerate or decelerate the speed.

Although the pleasantness of wrist and chest stimuli was rated in an equal way by both genders, postexperimental interviews (see the Appendix) revealed that females preferred wrist stimulation over chest stimulation almost unanimously. The wrist was preferred also by males but not as clearly as among females. The females’ greater favor of wrist stimuli could be due to gender difference in touch sensitivity, because females, more often than males, reported their chest area being more sensitive than their wrist. Therefore, some of them relayed the experience of chest stimuli as overly vigorous and thus unpleasant. Unlike females, however, the majority of males reported their wrist being more sensitive than their chest in feeling the stimuli. This result is in line with Karuei et al. [2011], who found differences in touch sensitivity between genders across different body sites. For example, they found that wrist stimuli were detected better by males than females. To sum the results of the interviews of the current study, the wrist was preferred over the chest in feeling the stimuli by both genders, yet males showed more interpersonal variation in their most preferred stimulus location. In subjective evaluations of Karuei et al. [2011], wrist stimulation was also found as a preferred body site for vibrational exercise cues.

In conclusion, the current results demonstrated that vibrotactile cues can evoke coherent and intuitive associations for regulating behavior in a certain manner. A wearable heart rate monitor with carefully designed haptic signals would enable an inconspicuous medium capable of providing private information and guidance in an easily interpretable manner. This could serve as an alternative medium for both visual and auditory alarms, which can be cumbersome due to environmental or user-related reasons. For example, a noisy environment can prevent the user from hearing auditory signals. Auditory signals can also be awkward in social situations. Especially, information considered as private by its nature (e.g., heart rate and physical condition) may not be desirable to be shared in the presence of others. Visual signals can easily be neglected in high luminance conditions, and naturally, people with sensory impairments may not benefit from visual or auditory feedback at all.

Tactile information as an alternative to visual and auditory modalities could be appreciated among a variety of heart rate monitor users. In sports such as running and cross-country skiing, where upper limb coordination plays a central role, the stimuli introduced in the present study would not interfere
Intuitiveness of Vibrotactile Speed Regulation Cues

with the user's optimal hand trajectories, because one would not need to take glances at the display to interpret the alarms. Intuitive vibrotactile stimulations might be functional in home-based cardiac rehabilitation applications (e.g., Bidargaddi and Sarela [2008], Gay et al. [2009], and Su et al. [2010]) by informing the patient unobtrusively on safe strain levels and the status of the blood vascular system during light exercise, daily routines, and even in overnight monitoring. In comparison to visual and auditory information, simple and comprehensible haptic feedback signals especially could come up to the expectations of the technologically unoriented, weak-sighted, and hearing-impaired users. It is likely that the results could be applicable in other contexts as well, such as motion training, car driving, and gaming, in which haptic speed regulation cues could be beneficial in complementing or substituting audiovisual information in an intuitive manner.

In thinking of the ecological validity, there is evidence that wearable vibrotactile displays can provide users with perceivable and understandable information during physical exercise (e.g., Bachlin et al. [2009], Spelmezan et al. [2009], and Van Erp et al. [2006]). However, future work should include testing the stimuli suggested by our current results in mobile settings outside the laboratory. In fact, the perceptual cycle model by Neisser [1976] suggests that these stimuli might function even better in the actual speed regulation task than in the current laboratory setup. This is because in the present approach, the participants' information processing cycle was incomplete in the sense that the feedback on the correctness of the responses was missing from the information processing loop. In realistic settings, the speed regulation stimuli would be directly consequential in respect to the individual user's actions. In terms of Neisser's thinking, this would enable users to gradually build up an inner schema about the haptic code during the exercise. Following this, the schema could actually make it easier to recognize the stimuli.

The significant findings of the current research provide a fertile ground for future investigations with regard to intuitive decision making. For example, more diverse speed regulation information could potentially be designed using more rich variations of stimulus parameters. As one possibility, both short- and longer-term stimulation could be intuitively associated with quick and slow speed shift, respectively. In summary, the present results suggest that the use of carefully designed and tested haptic stimulation is a promising direction in which to proceed when developing future applications that aim at intuitive behavioral regulation.

APPENDIX. POSTEXPERIMENTAL INTERVIEWS

After the experiment, the majority of the primed participants (8/12) and nearly half of the unprimed participants (5/12) reported that the task of evaluating the meanings of the stimuli was easy rather than difficult. In proportion, two primed and five unprimed participants considered that the task was difficult. In both conditions, two participants thought that the task was neither easy nor difficult. The most frequent reason for the difficulties was related to the shortest (500ms) stimuli, which were considered problematic by nine primed and two unprimed participants.

Nearly all primed participants (11/12) reported the ability to respond according to the response logic introduced in the beginning of the experiment, regardless that many of them had some difficulties in evaluating the meaning of the shortest stimuli. Among the unprimed participants, the most prevalent response strategy was related mainly to frequency profile of the stimuli (10/12) according to what was hypothesized. One participant came up with response logic in which stimulus duration was the determinant for assessing the meanings, and one reported being unable to create any meaningful response strategy during the experiment.

Almost half of the females (5/12) stated that their chest was more sensitive in feeling the stimuli than the wrist. Another five females felt that their wrist was more sensitive than the chest. The majority
of the males (9/12) considered their wrist more sensitive than the chest, whereas only two males rated their chest as more sensitive than the wrist in feeling the stimuli. The rest did not feel a difference in the sensitivity of the wrist and chest locations.

Almost all females (11/12) preferred their wrist to the chest in feeling the stimuli. Only one female was fonder of the chest stimuli. With male participants, the preferences of feeling the stimuli were more evenly distributed between the locations, as seven voted for the wrist and five for the chest.

ACKNOWLEDGMENTS
We wish to thank Esa Tuulari for his contribution on ideating the experimental setup.

REFERENCES


Received December 2011; revised September 2012, March 2013, and May 2013; accepted May 2013