Vibrotactile Guidance for Drumming Learning: Method and Perceptual Assessment

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Abstract

In this paper, we introduce a haptic guidance system for learning how to play a drum using vibrotactile cues generated by multiple actuators embedded in a vibrotactile vest and ankle bands worn by the learner. A natural egocentric mapping of our system from the body site of vibrotactile stimulation to a target percussion instrument (PI) in a drum set enables intuitive guidance for striking movements. The current system also informs the learner of two levels of PI striking strength by varying both the intensity and duration of vibrotactile cues. An initial perceptual assessment of the system showed 95.0% of accuracy in delivering the information on the target PI (9 levels) and striking strength (2 levels). The experiment also allowed us to estimate the mental processing times of our guidance cues: 0.30 s for detection, 0.46 s for identification, and 0.15 s for decision. These results provide basic guidelines for designing vibrotactile guidance cues for a series of fast coordinated movements of multiple limbs.

Index Terms: H.5.2 [Information Interface and Presentation]: User Interfaces—Haptic I/O; K.3.1 [Computers and Education]: Computer Uses in Education—Computer-assisted instruction;

1 Introduction

The present study pertains to haptic guidance for learning coordinated discrete movements of multiple limbs using vibrotactile cueing. As a benchmark, we use drumming skills, which require fast, patterned, coordinated discrete movements of the two arms and two feet. This paper presents an initial design of our guidance system and reports the results of its perceptual assessment. Our guidance method relies on all of spatial, temporal, and intensity information coding schemes using vibrotactile cues that are generated by multiple tactors distributed on the learner's body.

1.1 Related Work

Early studies on haptic guidance attempted to facilitate motor learning by providing the force feedback that enables the learner to experience the ideal, desired movements during training. For example, Feygin et al. demonstrated that active force guidance can be beneficial for learning a 3D trajectory following task, particularly in timing-related aspects [4]. Grindlay argued that force guidance had better learning effectiveness than auditory guidance for a rhythmic drumming task in terms of movement velocity accuracy [5]. Lum et al. applied force guidance to the rehabilitation of stroke patients, and the patients regained their arm functions better than those who received a conventional human therapy [12].

However, there exist a considerably larger number of studies that reported no positive effects of force guidance on motor learning. It is presumably due to the facts that force guidance results in some differences in the task context between practice and the actual execution of the task and that the learner's attention level may decrease as the learner's dependency on guidance stimuli grows over the course of training [10]. Both factors lead to inefficient motor learning [15]. Approaches to improve upon these problems include progressive haptic guidance, which adaptively controls the intensity or frequency of guidance stimuli depending on the learner's performance [8, 3], and haptic disturbance, which makes the task more challenging in order to prompt the learner to pay more attention to training [10, 14, 9]. These new approaches resolve some disadvantages of the previous fixed-gain force guidance, but much more extensive research is required before understanding the ultimate benefits of force guidance. A comprehensive review on this topic can be found in [14, 15].

An alternative of force guidance is vibrotactile guidance, and it has been the subject of recent research. Vibrotactile guidance is not able to provide direct kinetic feedback unlike force guidance, but it does have several distinctive merits. Vibrotactile actuators are much more compact and inexpensive, so they can easily stimulate multiple body sites if embedded in a chair or a wearable interface. In this aspect, vibrotactile guidance has the potential for the effective delivery of movement instructions, particularly for complex coordinated movements between multiple limbs and joints.

Research on vibrotactile guidance has considered two classes of motor tasks, continuous and procedural. For continuous tasks, one popular approach is to present vibrotactile feedback to the body part to move to specify its movement direction. For this purpose, a direction coding scheme can be either attractive or repulsive; for example, a vibration produced by a tactor attached on the palm means to move the hand to the direction of the palm (attractive) or to the direction of the back of the hand (repulsive) [1]. The strength of the vibration can be fixed or proportional to the distance to the target position. Lieberman and Breazeal developed a vibrotactile sleeve with eight tactors that were distributed on the elbow and wrist and showed that repulsive vibrotactile guidance was effective in guiding complex arm motion trajectories in terms of position accuracy and learning rate [11]. Using similar hardware, Bark et al. [1] guided three arm motions (wiping, eating, and cutting) performed with a non-dominant hand, and they found no statistically significant differences in position error or in subjective measures between attractive and repulsive guidance mode. Vibrotactile guidance can also be effective for body posture guidance. Linden et al. applied repulsive vibrotactile guidance to the upper body and successfully helped young children learn the proper body posture and bowing motion of playing violin [17].

Vibrotactile guidance for procedural tasks is often called vibrotactile cueing. In this approach, every movement comprising the target task is represented by a unique, simple or patterned, vibrotactile stimulus (cue). During learning, the vibrotactile cues are presented to instruct the learner which movement should be performed. For example, to teach two two-measure-long piano phrases

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IEEE Haptics Symposium 2014
23-26 February, Houston, Tx, USA
978-1-4799-3131-6/14/$31.00 ©2014 IEEE

each composed of five piano keys, Huang et al. related the five piano keys to the five fingers in a one-to-one correspondence, then presented a series of short vibrotactile stimuli to the fingers in order to designate which key should be pressed when [7]. Similarly, Holland et al. presented short vibrotactile stimuli to the wrists and ankles to guide several drum rhythms [6]. They performed a subjective evaluation on their guidance system without objective performance assessment and stated that the vibrotactile cues were often unperceived by the learner due the impact that occurred at drum strikes. In addition, to instruct snowboarding movements such as leaning forward or turning left, Spelmezan et al. [16] designed a set of vibrotactile patterns generated by many tactors distributed over the entire body, and then searched a natural intuitive mapping from vibrotactile patterns to snowboarding movements through a series of human subjects experiments. For vibrotactile cueing, it is important to design vibrotactile cues and their mapping to the movements of a task in such a way that the learner's mental effort to recognize the cues and to subsequently determine the corresponding movements is minimized.

1.2 Drumming Learning and Our Guidance Scheme

A drum set is a musical instrument that gives the *groove* of music through the repetitive and rhythmic presentation of percussion sound patterns, i.e., drum beats. Playing all drum beats correctly and fluently is vital to good drumming, so learning of drum beats is the main content of drum lessons for novice drummers. Playing a drum beat involves a series of fast, single or multiple, drum strikes, and this requires a sequence of fast coordinated discrete movements of multiple limbs. Every strike must be executed on a correct PI with high accuracy in position, timing, and strength; even a small error in a drum strike can cause a substantial change in the overall perception of the drum beat.

For practice, novice players read musical notations on a drum music piece, interpret their meanings, and execute the designated actions. Even if the interpretation is correct, they make various errors in the execution because they lack a well-established motor program for drumming action. An instructor helps learners in various ways during drum lessons, and showing a *demonstration* of the desired play is the most effective method on transferring the interpretation-to-action model of the instructor to the learners. Therefore, for self-practice without instructors, other means that can present demonstrations of the desired play can be very helpful. To this end, sound-based methods are not promising because novice players find it difficult to identify a target PI from its sound, especially when multiple PIs are struck simultaneously. Visual methods, e.g., showing a demonstration video, may not help greatly because they require intensive visual processing for recognizing complex striking movements of multiple limbs from quickly changing video and matching them to those of a target drum beat. In contrast, vibrotactile guidance may be a viable approach in that it does not require visual attention and is effective in demonstrating the desired movements of procedural tasks.

Our initial design of vibrotactile guidance assumes beginner-level learners of drum playing. Beginner-level drum playing involves up to nine striking positions, one for each PI (see Figure 1a), and two discrete levels of striking strength, weak and strong. Playing speed is relatively slow, but still challenging (around 60 BPM; 0.5 s between strikes for 8-beat rhythms).

In our vibrotactile guidance system, striking position is instructed by the body site stimulated by vibrotactile stimuli. The trunk and ankles, which are relatively stationary during drumming, are used to avoid masking between vibrotactile stimuli during active motion [13], and the exact stimulation positions are selected to preserve the egocentric orientation from the body sites to the PIs. Striking strength is mapped to the stimulus strength and duration using redundant coding. All vibrotactile stimuli are sufficiently short (< 0.2 s) so that our guidance system is applicable to beginner-level playing speeds. Further details are provided in the rest of this paper.

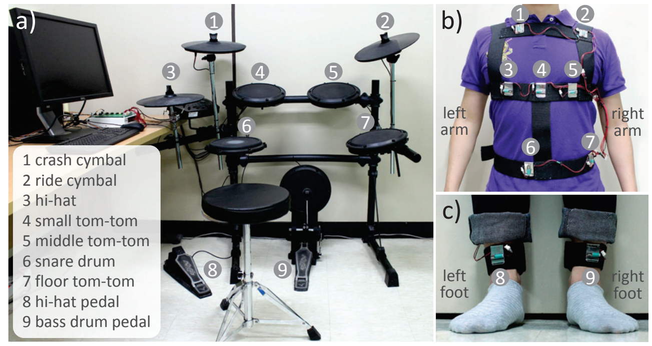

Figure 1: (a) Hardware for vibrotactile drumming guidance. (b), (c) Vbrotactile vest and ankle bands (mirror images). Relationships between PIs and body sites are denoted by numbers.

2 System and Vibrotactile Guidance

Our haptic drumming guidance system is shown in Figure 1a. The key component is an electric drum set (Model DD506; Medeli Electronics, Hong Kong). If a player strikes a PI in the drum set, the target PI and strength of that stroke is measured and sent to a computer that renders visual and haptic stimuli. Visual scenes are displayed by a 24-inch LCD monitor, and haptic guidance is provided by a custom-made vibrotactile vest and ankle bands.

The vibrotactile vest and ankle bands are made of elastic rubber bands to which bar-type ERM motors (tactors; $\phi 7.0 \times$ L25.0 mm, 5 g; Sejoo Electronics, Korea) are fastened. Seven tactors are attached to the vest using metal clips (W25 $\times$ H50 mm), and one tactor is attached to each ankle band in the same way. The use of clips allows us to adjust tactor positions to individual learners. It is also helpful to maintain stable contacts between the tactors and the learner's body. The placement of the tactors is shown in Figure 1b for the vest and Figure 1c for the ankle bands.

Haptic guidance delivers the three main elements (target PI, strength, and timing) of a drum strike by a vibrotactile cue. The target PI of the strike is designated by a stimulated body site. For this, each PI of the drum set is mapped to the body site that is near to the PI and also relatively stationary during drumming. This mapping is illustrated for the vest in Figure 1a and 1b. This design preserves the egocentric orientation in the transverse plane from each body site to the target PI, while reflecting correspondence in their relative heights. The mapping for the two ankle bands is also depicted in Figure 1a and 1c. Here, vibrotactile cues stimulate the proximal frontal part of each ankle to prevent any hindrance during pedaling movements while matching the egocentric orientations between the stimulation sites and the target PIs. The exact stimulation locations were determined by a series of pilot tests so that absolute identification of vibrotactile cues produced by individual tactors could have nearly perfect accuracy.

We also transmit two levels of PI striking strength (weak or strong) using two different vibration strengths. Considering the dependence of vibrotactile magnitude perception on body site, input voltage to each tactor has been adjusted so that the vibrations of the same strength level are perceived to be of the same or at least very similar intensities at all the nine body sites. Tactors at the epigastrium (no. 4 in Figure 1b) or umbilical region (no. 6) use higher-range input, those at the upper thorax (no. 1 and 2) or right lumbar region (no. 7) use lower-range input, and the other tactors (no. 3 5, 8, and 9) use middle-range input. Their input ranges are 1.2–1.8 V for weak vibrations, and 2.8–3.5 V for strong ones.

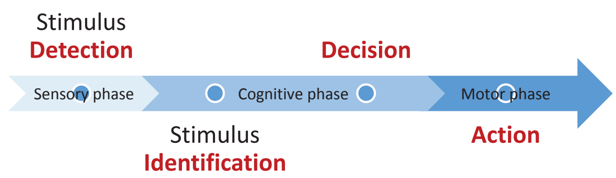

Figure 2: Four processing stages of stimulus-response task.

Striking timing is presented by the stimulation timing of vibrotactile cues. To guide the timing precisely while preventing overlaps between consecutive cues, short but clearly perceptible vibrotactile stimuli are required. In the present study, we use 100-ms long vibration signals for weak cues and 150-ms signals for strong cues, which result in actual vibration durations of about 94 ms and 199 ms (threshold 1 G), respectively. Strong cues have longer durations for better identification performance (redundant coding).

3 Experiment

The long-term goal of our research is to develop methods that can help novice drum players learn playing of drumming sequences by providing guidance on the target, strength, and timing of each PI strike using vibrotactile cues. The first priority for effective guidance is with ensuring that learners can correctly recognize the information embedded in vibrotactile cues. The time required for recognition is also of importance because it determines the limit of drumming speed to which vibrotactile guidance is applicable. For these reasons, our first perceptual evaluation was concerned with the accuracy and temporal requirement of our guidance design. We also assumed the simplest scenario in which a single vibrotactile cue is presented at a time and the learner responds to the cue.

To respond to a guidance stimulus, a user goes through four mental processing stages: detection, identification, decision, and action (Figure 2). When a vibrotactile cue is presented, the user first detects the stimulus, and then identifies its properties such as location and strength. Based on this information, the user understands the meanings (e.g., striking target and strength) of the cue and make a decision of what to do, and then finally performs the action. All of these four stages affect the performance of a sensorimotor task, so understanding their respective effects can be a cornerstone for the design of optimal vibrotactile guidance methods. To this end, our experiment tested three conditions: (1) simple detection of vibrotactile cues, (2) absolute identification of the vibrotactile cues, and (3) selection of PIs in a drum set according to the vibrotactile cues. By comparing the performance in the three conditions, we could estimate the effects of the four processing stages in terms of accuracy and time.

3.1 Participants

We recruited 12 male university students (aged 19–28 years; mean 21.0) for the experiment. They reported that they had no known sensorimotor disorders, had no experience of playing drum sets, and were naive to this kind of experiments. The participants were paid 10,000 KRW ($\simeq$ 9.2 USD) after completing the experiment.

3.2 Task

On each experimental trial, nine targets were displayed on the screen as gray circles (outer diameter 10 mm, inner diameter 5 mm; see Figure 3). The targets had a one-to-one correspondence to the body sites for stimulation (and also to the PIs of a drum set), and the positions of the targets were determined to be consistent with the stimulated body locations. The task of the participants was to perceive a vibrotactile cue presented by one of the tactors in the vest or ankle bands and then enter its perceived location and strength to the computer using a mouse. The participants were instructed to indicate the location of each vibrotactile cue by selecting the corresponding circle out of the nine circles displayed on the screen and its strength by pressing a left button on the mouse for weak stimuli and a right button for strong stimuli.

The above response input method was designed taking the context of the present study into account. In pilot experiments, we found that striking a PI with high positional accuracy while controlling its strength is very difficult for novice participants. This means that using the actual drum set to collect participants' responses is subject to a large amount of motor errors, thereby preventing us from looking into the true information transmission performance of our vibrotactile guidance design. For this reason, we needed to use the most reliable means for response collection, and our solution was using the most familiar interface (the mouse) to participants.

3.3 Experimental Conditions

The experiment consisted of three conditions that differed in the mental processing stages involved for a systematic assessment of our vibrotactile guidance design. This was done by providing different levels of visual information.

Condition DA (Detection and Action) was to measure the performance for the detection of a vibrotactile cue and subsequent action. In this condition, the location and strength of the correct answer was provided visually before a vibrotactile cue was presented. For this, the target circle was filled with a red inner circle with different diameters (small for weak stimuli and large for strong stimuli), as shown in Figure 3a. Then, randomly after 1–3 s, a vibrotactile stimulus was provided, and the participant was asked to make an answer immediately after perceiving the stimulus. The visual guidance lasted until the participant finished entering the response. In this condition, the necessity for identification and decision making is removed or at least minimized.

Condition DIA (Detection, Identification, and Action) did not provide the visual guidance used in Condition DA. Instead, a mirror drawing of a human body was displayed on the background, as shown in Figure 3b. Hence, the participant had to identify the location and strength of each vibrotactile cue. The mirror serves as a reference as to the associative mapping between the stimulated body sites and the target locations, making involvement of the decision stage unnecessary or minimal. No references for vibration strength were given because participants could learn very quickly the stimulus-response mapping for strength that used the left-right buttons of the mouse.

Condition DICA (Detection, Identification, deCision, and Action) was designed to involve all the four mental processes. This condition is the same as Condition DIA, except that the background mirror image of a human body was replaced with a drawing of a drum set (Figure 3c). Each PI of the drum set included a target circle associated with the body site of vibrotactile stimulation. This spatial relationship was informed to the participant prior to the experiment, and the participant was instructed to select the corresponding PI for a given vibrotactile cue. The latter requires understanding the meanings of the cue and making a decision of which PI to strike with which strength.

In all the experimental conditions, the positions of the target circles were the same, ensuring the movement requirement of selecting each target remained identical throughout the experiment.

3.4 Procedures

The main experiment consisted of three sessions, each for one of the three experimental conditions, and each session was composed of 180 trials (9 location $\times$ 2 strengths $\times$ 10 repetitions). Each participant completed all the three experimental sessions in a within-subjects design. The session order was fully balanced across the

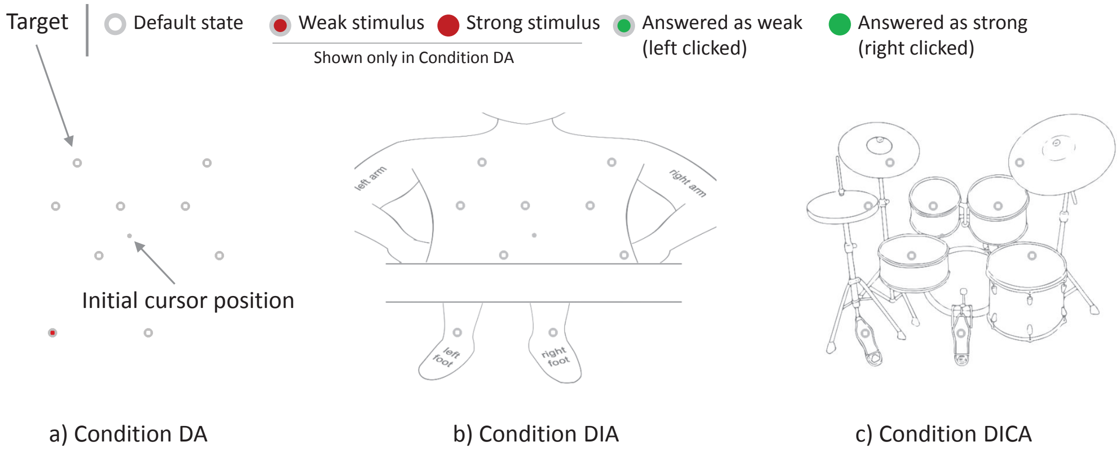

Figure 3: Visual scenes provided for each experiment condition.

participants, and the order of trials was randomized for each session and each participant.

Before the experiment, the participant was informed of the experimental task and procedures, and then signed on a written consent form. Then the participant wore the vibration vest and ankle bands and went through a short training session to become accustomed to the system. The participants also wore earplugs to mask any effects of ambient noise and the sound produced by the tactors.

In each trial of the main sessions, the mouse cursor was initially located at the center of the screen (a small gray point in Figure 3). If the participant selected the target following the procedure described in Section 3.3, the selected target turned green for 500 ms for confirmation. Then the trial ended, and the mouse cursor was returned to its initial state. For Condition DA, visual guidance for the next trial was given immediately after the end of the trial. The next trial started randomly after 1–3 s.

To avoid fatigue, the participant was required to have a break for 5 min between the experimental sessions and also could take a rest whenever necessary. The experimental procedures took about 1 hr.

3.5 Performance Measures

In each trial, response correctness and response time were recorded. A response was incorrect if the selected circle did not match the target circle or the pressed mouse button was not the same as the target button, both indicated by the vibrotactile cue. The response time was defined as the time difference from the instant (t_{init}) at which the vibrotactile cue generation was initiated to the instant (t_{resp}) at which the participant's response using the mouse was detected, both by the experimental program. We also measured action time, which is part of the response time spent to move the cursor to the target circle and to enter a response. The action time was defined as the time difference from the instant (t_{act}) at which the cursor movement (threshold 2.5 mm) was detected by the experimental program to the instant of response detection.

In the experiment, each participant repeated 10 trials for each experimental combination of condition, location, and strength. These measurement data were used to compute three performance measures, the ratio of incorrect responses (miss ratio; MR), the mean response time (RT), and the mean action time (AT), as follows:

$$
\begin{aligned}
MR &= 1 - \frac{1}{10}\sum_{n=1}^{10} c(n), \\
& \quad c(n) = \begin{cases} 1 \text{ if the } n\text{-th response was correct} \\ 0 \text{ otherwise} \end{cases}, \\
RT &= \frac{1}{10}\sum_{n=1}^{10}\left(t_{resp}(n) - t_{init}(n)\right), \\
AT &= \frac{1}{10}\sum_{n=1}^{10}\left(t_{resp}(n) - t_{act}(n)\right). \qquad (1)
\end{aligned}
$$

To respond to a vibrotactile cue, the participant went through some or all of the four processing stages depending on the experimental condition, and each stage would have taken some processing time and caused some portion of response errors. Our design of the three experimental conditions allows us to estimate the respective effects of the four stages by comparing the performance measures between the conditions, assuming the operation of each stage is unaffected by the inclusion or omission of other stages. To specify the exact equations for this, we first define the following symbols: D: Detection, I: Identification, C: deCision, A: Action; MR^x: MR of a processing stage x; RT^x: RT of a processing stage x; MR_y: MR measured in Condition y; RT_y: RT measured in Condition y; AT_y: AT measured in Condition y. Then,

$$
\begin{aligned}
MR^A + MR^D &= MR_{DA}, \\
MR^I &= MR_{DIA} - MR_{DA}, \\
MR^C &= MR_{DICA} - MR_{DIA}, \\
RT^A &= AT_{DA}, \\
RT^D &= RT_{DA} - RT_A, \\
RT^I &= RT_{DIA} - RT_{DA}, \\
RT^C &= RT_{DICA} - RT_{DIA}. \qquad (2)
\end{aligned}
$$

These values were computed for each participant and each experimental combination and then used for the analysis of results.

4 Results and Discussion

4.1 Miss Ratio

The mean MR for the three experimental conditions are shown in Figure 4. The participants showed nearly no misses (mean $MR_{DA} = 0.65\%$) for Condition DA, owing the additional visual instruction that guided the participants to make correct answers. Condition DIA and DICA showed similar miss ratios (mean $MR_{DIA} = 4.54\%$; mean $MR_{DICA} = 5.00\%$). The high accuracy of Condition DICA seems sufficient for our purpose, particularly considering the large number (18) of vibrotactile cues and the minimal pre-training given to the participants. It should be addressed that the accuracy could have been overestimated to some extent because

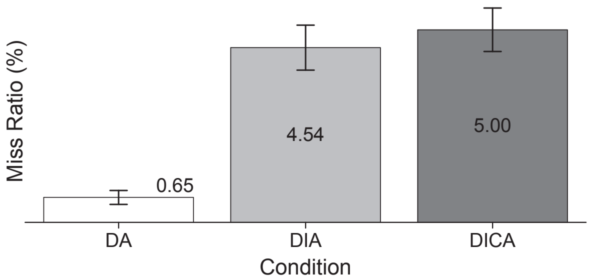

Figure 4: Means and standard errors of miss ratio.

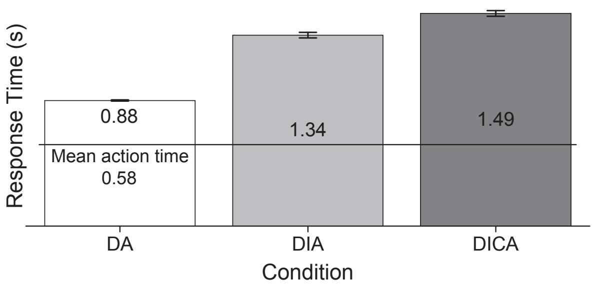

Figure 5: Mean response times with standard errors. A long horizontal line represents the grand mean of action time.

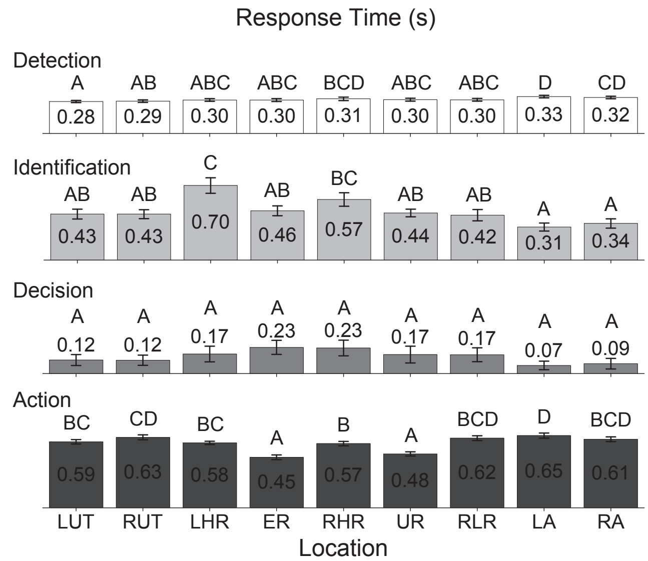

Figure 6: Mean response time for each process and body site (LUT/RUT: left/right upper thorax; LHR/RHR: left/right hypochondriac region; ER: epigastric region; UR: umbilical region; RLR: right lumbar region; LA/RA: left/right ankle). Alphabets denote SNK test results.

the experiment used the monitor and the mouse interface, not a real drum set and drum sticks. In actual drumming guidance, the learners would produce more errors due to the higher cognitive load and imprecise motor control caused by the learner's unfamiliarity to the drumming task.

According to one-way ANOVA, the effects of the mental processes on MR were significantly different ($F_{2,22} = 7.39$, $p = 0.0035$). A following SNK test revealed that the identification process had a statistically greater MR (mean $MR^I = 3.89\%$) than the decision process (mean $MR^C = 0.46\%$) and the detection and action process (mean $MR^D + MR^A = 0.65\%$). This result indicates that the identification process in which the participants recognized the stimulated body site and stimulus strength caused the most response errors, while the other processes were relatively straightforward.

Incorrect responses were made mostly by responding to the strength incorrectly (3.01% out of 5.00%), followed by the misses caused by selecting a wrong target (1.76%). Only few (0.23%) of them were incorrect for both target and strength. Thus, we expect that the accuracy of our vibrotactile guidance design can be further improved by adjusting the strength levels of the vibrotactile cues.

4.2 Response Time

Figure 5 shows the mean RTs for the three experimental conditions. The RT of the participants was the shortest for Condition DA (mean $RT_{DA} = 0.88$ s), due to the relatively small mental processing requirements. Their RT was increased greatly for Condition DIA (mean $RT_{DIA} = 1.34$ s), and the largest for Condition DICA (mean $RT_{DICA} = 1.49$ s). The mean action time for Condition DA (mean AT_{DA}) was 0.58 s.

By comparing the RTs for the three conditions and AT_{DA}, we can estimate that the participants used about 0.30 s on average to detect a vibrotactile cue (mean RT^D), 0.46 s to identify the vibrotactile cue (mean RT^I), 0.15 s to understand the cue and make a decision for action (mean RT^C), and finally 0.58 s to enter a response (mean RT^A). The temporal requirements of the four processing stages were significantly different ($F_{3,33} = 17.51$, $p < 0.001$). Excluding RT^A, which was determined by the response input method, the identification process required the most processing time, demanding more improvements in guidance cue design. The decision process took the least time with a very small value, which means that our mapping from the location and strength of a vibrotactile cue to the target PI and striking strength was intuitive to the participants. Overall, the results indicate that for informative guidance, at least 0.9 s of time should be provided to the learner for each vibrotactile cue to allow the learner to detect and identify the cue and to make a corresponding decision.

4.3 Effects of Body Site

The stimulus location inflicted no significant differences to $MR^D + MR^A$ ($F_{8,88} = 0.86$, $p = 0.551$), MR^I ($F_{8,88} = 1.13$, $p = 0.351$), and MR^C ($F_{8,88} = 0.87$, $p = 0.544$). This indicates that the response accuracy was independent from the stimulated body site.

The response time of each mental process is shown in Figure 6 for different body sites. For detection, body site had a significant effect on RT^D ($F_{8,88} = 7.25$, $p < 0.001$). RT^D was generally increased with the distance from the stimulated body site to the central nervous system; the longest RT^Ds were measured on the ankles, while the shortest on the upper thorax, with the largest mean difference of 0.05 s. This implies that the neural transmission distance was a significant factor for RT^D. However, although the differences in RT^D were statistically significant, it is of little practical importance because of its small value with respect to the total response time RT_{DICA} (1.49 s on average).

As for identification, RT^I was under statistically significant influence of body site ($F_{8,88} = 8.29$, $p < 0.001$). The longest RT^Is were measured on the hypochondriac region, while the shortest were on the ankles, with the largest mean difference of 0.39 s. It seems that the identification process was hindered to some extent by the relatively dense positioning of the actuators at the upper abdomen, and we expect that this issue could be resolved by widening the distances among the actuators. The vibrotactile cues to the epigastrium showed less effect of the dense positioning on RT^I, and it is probably due to the directional sensitivity in vibration localization [2]. The effect of body site was only marginally significant for RT^C ($F_{8,88} = 1.75$, $p = 0.097$), which suggests that the decision process was relatively independent of body site. The time required to enter a response, RT^A, was determined by body site ($F_{8,88} = 34.19$, $p < 0.001$), reflecting the different distances from the initial mouse cursor position to the target circles.

In summary, body site had some significant influences on the response times, but not on the miss ratio. The plausible sources of the response time differences are neural transmission distance, actuator density, and the movement distance for each target.

4.4 Effects of Stimulus Strength

Stimulus strength caused a significant difference in $MR^D + MR^A$ ($F_{1,11} = 5.58$, $p = 0.038$), but this result is not robust because of the extremely small number of misses (0.65%) in the detection and action process. The effect of stimulus strength was not significant for MR^I ($F_{1,11} = 1.16$, $p = 0.305$) and MR^C ($F_{1,11} = 0.35$, $p = 0.567$). Stimulus strength also had no significant influences on the response times (RT^D: $F_{1,11} = 1.07$, $p = 0.328$; RT^I: $F_{1,11} = 0.34$, $p = 0.572$; RT^C: $F_{1,11} = 0.10$, $p = 0.754$; and RT^A: $F_{1,11} = 0.24$, $p = 0.637$), though the strong cues produced slightly shorter response times in all the processing stages. These results suggest that stimulus strength was not a significant factor for our stimulus-response task in terms of both miss ratio and response time.

5 Conclusions

In this paper, a guidance system for drumming learning was introduced. The system can instruct the learner how to play a drum using vibrotactile cues generated by nine tactors embedded in a vest or ankle bands worn by the learner. A natural egocentric mapping from the body site of vibrotactile stimulation to a target percussion instrument (PI) in a drum set and the redundant coding of striking strength with the strength and duration of vibrotactile stimuli enables intuitive and correct guidance for striking movements. In an initial perceptual assessment, our system showed 95.0% of accuracy in delivering the target PI (9 levels) and striking strength (2 levels). Our guidance cues required 0.91 s of mental processing time: 0.30 s for detection, 0.46 s for identification, and 0.15 s for decision. Dense tactor placement had increased the identification time significantly, and longer neural transmission distance had caused longer detection time. The accuracy of guidance did not significantly affected by body site or stimulus strength. These results provide basic guidelines for designing vibrotactile guidance cues for a series of fast coordinated movements of multiple limbs.

As an initial assessment, the present study assumed a simple scenario in which a single vibrotactile cue is presented at a time and the learner responds to the cue. For actual drumming guidance, a series of single or multiple vibrotactile cues that consists a drum beat needs to be presented and responded at a time. Due to the interaction between vibrotactile stimuli and the limited attention of the learner, successive or simultaneous presentation of multiple guidance cues can lead to lower accuracy and longer response time, which restricts the effectiveness of vibrotactile guidance. We plan to investigate this issue in our next work by conducting another experiment that assesses the effects of presentation of multiple guidance cues. Then, our vibrotactile guidance system will be evaluated for its effectiveness in drumming learning.

Acknowledgements

This work was supported in part by a Grant 2010-0019523, 2013R1A2A2A01016907, and 2011-0027994, all from NRF, and by an ITRC program (NIPA-2010-C1090-1011-0008) from NIPA, all funded by the Korean government.

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