Display of Simultaneous Vibrotactile Rhythms on the Fingertips and Forearm

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***Abstract*— In this paper, we present a dual-function body-mounted tactile display where haptic feedback is received by the forearm and augmented through optional feedback to the fingertips. We demonstrate that the device architecture allows signals to be interpreted by the forearm and the fingertip either simultaneously or separately, achieving signal transmission with the information capacity of hand-mounted device signals and the convenience of forearm mounted devices. We validate the utility of the device architecture in a study showing that simultaneous vibration feedback to the forearm and fingertips does not degrade user ability to identify vibrotactile rhythms. In this study, 12 participants identified simultaneous vibrotactile rhythms on: (1) the forearm, (2) the fingertips, and (3) both the forearm and fingertips simultaneously. User accuracy when given simultaneous haptic feedback to the fingertips and forearm was not significantly different than user accuracy for feedback to the fingertips only. The results show that user accuracy with feedback to the forearm only is higher than chance but statistically significantly lower than in conditions where the fingertips are involved.**

I. Introduction

We investigate the potential for a forearm-mounted haptic device whose active area is easily accessible by the fingertips of the opposing arm and, consequently, can deliver haptic feedback to two locations. Research has shown that different vibration stimuli to multiple fingers on the same hand and to fingers of different hands are optimally integrated [1]. However, little research has been done to investigate how haptic integration affects information transfer when the same signals are received simultaneously at two locations. We demonstrate that receiving vibrotactile rhythms on both the fingertips and the forearm simultaneously results in similar performance to receiving rhythms only to the fingertips. Vibration feedback was chosen because it is a well studied form of haptic feedback – its psychophysical properties are widely reported in the literature, e.g. [2]. We conduct a user study to assess the accuracy of a set of vibrotactile rhythms on just the forearm, just the fingertips, and on the forearm and fingertips simultaneously.

II. Tactile Display Design

A. Hardware

The system is composed of two vibrotactile actuators, a desktop platform for the actuators, and the electromechanical architecture. The two vibrotactile actuators are Haptuator Mark II voicecoil motors, shown in Fig. 1, that are controlled using signal outputs from a Sensoray 826 PCI card. In conditions where the forearm receives stimulus, the tactors are attached to the dorsal forearm using 0.5 in. by 3 in. double-sided tape (Fearless Tape). The placement of the actuators was standardized between participants and across conditions. In the condition where only the fingertips are used, the vibrotactile actuators are mounted, using double-sided tape, to a 0.01 in thick natural rubber that is grounded along its edges, to allow the actuators to move laterally similar to how they move on the surface of the skin. The actuators were calibrated to have a maximum acceleration of 19.6 m/s^2 or approximately 20 dB with respect to the vibration threshold for the fingertips in Bolanowski et al. [3] and approximately 4 dB with respect to the vibration threshold for the volar forearm interpolated from data in Morioka et al. [4].

B. Vibrotactile Rhythms

Based on previous literature and our own pilot testing, we developed a set of rhythmic temporal-spatial signals that are clear and easy for users to learn [5], [6]. Additional internal piloting showed that the easiest simultaneous signals to understand are differential signals. In our case, this corresponds to both actuators giving the same signal, until at some point, one of the actuators turns off. This observation inspired a set of pulsed signals, where each pulse lasts a total of 250 ms, is composed of a 187.5 ms sine wave played at 150 Hz, and is followed by a 62.5 ms period where no signal is played. There are four different signals: one pulse, two pulses, three pulses, and four pulses. When the signals are played on two actuators the total vocabulary numbers 16 signals (Fig. 2).

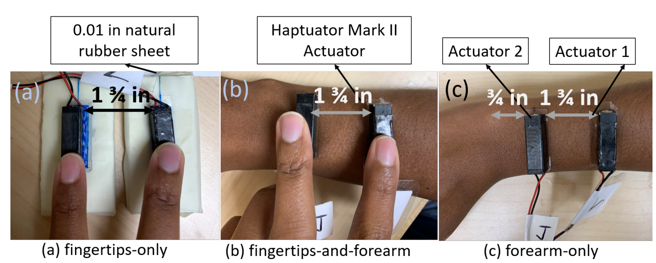

Fig. 1. The study was conducted with three conditions. Participants receive feedback to (a) the fingertips-only, (b) the fingertips-and-forearm, and (c) the forearm-only. The tactors are mounted to a 0.01 in natural rubber sheet in the fingertips-only condition, as shown in (a). Pairs of Haptuator Mark II actuators are shown in each image.

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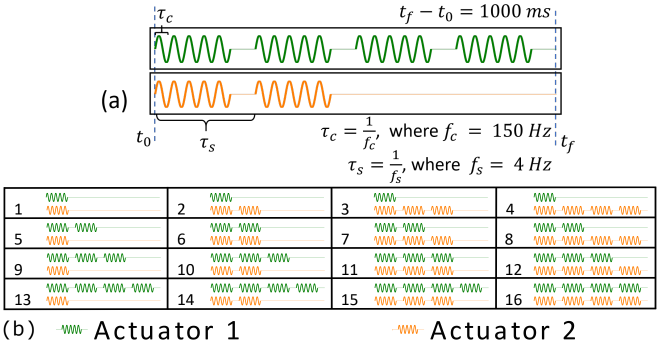

Fig. 2. (a) A magnified and labeled illustration of one example signal: Signal 14. The carrier frequency of the vibration signal, f_c, is 150 Hz. The pulse frequency, f_s, is 4Hz. The entire duration of pulse, $t_f - t_0$, is 1000 ms. (b) All 16 signals in the set played to the user.

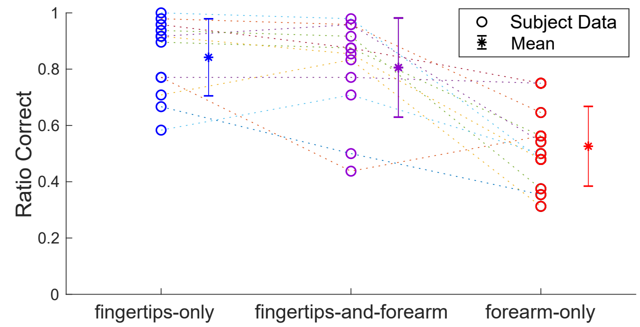

Fig. 3. Number of correct trials for each subject for each condition and the mean for each condition across subjects. The dashed lines connect the three conditions for a given subject. The forearm-only condition performed significantly worse than the other two conditions.

III. User Study

We performed a user study with 12 right-handed participants, 6 male and 6 female, aged 22-30, to determine their ability to identify the pairs of rhythms. The Stanford University Institutional Review Board approved the experimental protocol and all participants gave informed consent.

A. Methods

Users performed 48 trials in each of the conditions shown in Fig. 1. For every trial, the users felt the signal and selected a guess pattern for Actuator 1 and Actuator 2, respectively, on a simple GUI using their non-dominant hand. Users initiated the signal when they were prepared to receive the cue. For all trials, the users sat at a table and wore noise cancelling headphones playing brown noise to block sound produced by the voicecoil motors. Users did not look at the actuators during the experiment. In the fingertips-and-forearm condition, participants lightly rested their fingertips on the voicecoil motors to minimize any potential effects caused by normal forces on the actuators.

Users experienced a training session where they felt each of the four pulse patterns, twice in a random order, which allowed them to gain familiarity with the set of cues, but did not allow them to feel simultaneous cues. They received the training stimulus solely to the index finger of their dominant hand. The actuators were mounted in the desktop set-up for the entire training, as shown in Fig. 1(a). The users did not receive feedback on their performance during training. The users made an average of 93.8% correct guesses during the training, indicating that the rhythm cues are intuitive.

The order of the experimental conditions was pseudo-random, and balanced across the participant pool to mitigate ordering effects. Participants were given a break of three minutes between each condition as the apparatus was adjusted for the condition. For each condition, the users experienced each pair of signals three times in a randomized order. This amounts to 144 experimental trials per user. In total, we collected data from 12 participants for a total of 1728 trials.

IV. Results And Future Work

The mean ratio correct and standard deviation for the fingertip-only, fingertip-and-forearm, and forearm-only conditions are 0.84 ± 0.14, 0.81 ± 0.18, 0.53 ± 0.14, respectively (Fig. 3). In all conditions, the ratio correct is higher than chance (ratio correct of 0.063). The fingertip-only condition is statistically significantly greater than the forearm-only condition ($p < 0.001$). Similarly, the fingertip-and-forearm condition is significantly greater than the forearm-only condition ($p < 0.001$). However, the fingertip-only and the fingertip-and-forearm conditions are not statistically significantly different ($p > 0.5$). The user accuracy for signals sent to Actuator 1 were not statistically significantly different from the user accuracy of signals sent to Actuator 2 for any condition ($p > 0.3$ for all condition pairs).

This study demonstrates that a body-mounted device can be used to send information as effectively as a fingertip-mounted device. As expected, the forearm-only condition performed worse than the other two conditions because the amplitude of the vibration was closer to the forearm vibration threshold [4]. During piloting we observed that signal amplitude variations also have an effect on the accuracy of the signal perceived, showing that signal amplitude may affect how the simultaneous information is combined. We plan to investigate the effects of acceleration amplitude on the accuracy of the vibrotactile rhythms for simultaneous cues.

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