Improving Perception Accuracy with Multi-sensory Haptic Cue Delivery

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Abstract. This paper presents a novel, wearable, and multi-sensory haptic feedback system intended to support the transmission of large sets of haptic cues that are accurately perceived by the human user. Previous devices have focused on the optimization of haptic cue transmission using a single modality and have typically employed arrays of haptic tactile actuators to maximize information throughput to a user. However, when large cue sets are to be transmitted, perceptual interference between transmitted cues can decrease the efficacy of single-sensory systems. Therefore, we present MISSIVE (Multi-sensory Interface of Stretch, Squeeze, and Integrated Vibration Elements), a wearable system that conveys multi-sensory haptic cues to the user's upper arm, allowing for increased perceptual accuracy compared to a single-sensory vibrotactile array of a comparable size, conveying the same number of cues. Our multi-sensory haptic cues are comprised of concurrently rendered, yet perceptually distinct elements: radial squeeze, lateral skin stretch, and localized cutaneous vibration. Our experiments demonstrate that our approach can increase perceptual accuracy compared to a single-sensory vibrotactile system of comparable size and that users prefer MISSIVE.

1 Introduction

Wearable haptic feedback devices are appealing for their ability to convey rich and varied tactile information to a human user in a compact form-factor. A range of applications for haptic cueing have been explored, from navigational assistance to sensory substitution feedback for individuals with vision, hearing, or proprioception impairments. Haptic cueing using wearable tactile actuators has been effectively used for encoding speech [8, 10, 15, 17, 18, 26, 28, 29], providing movement guidance [14, 19], and performing audio- [11] and video- to-tactile translation [12]. Tactile feedback can also be an effective form of communication in contexts where individuals are already visually or aurally saturated [23].

A variety of mechanisms have been designed to render haptic feedback, the majority of which utilize cutaneous sensory channels such as skin stretch, pressure, or vibration. These modalities of haptic feedback are favorable for wearable devices because they can be actuated with low voltage servos or motors, and require only a small on-board battery and microcontroller to operate. Skin stretch devices leverage a no-slip contact between an end effector and skin so that when the end effector is displaced, a mild skin shear sensation is produced. They can be rocker-based [3,5,13], linear [1], or rotational [4,27]. These mechanisms have been used primarily for directional guidance to indicate desired forearm rotations and translations, as well as for sensory feedback [5]. Pressure-inducing devices often consist of a motorized or pneumatically-actuated band that tightens around the arm. These devices have been successfully used for emotional indicators in digital communication [20] and to provide directional information [19]. The third category of wearable haptic feedback, vibration, is the most widely reported in the literature. Vibration feedback is most commonly implemented with vibrotactors due to their small form factor and ability to be driven at varying frequencies and amplitudes. By arranging multiple vibrotactors in a specific spatial configuration, an extensive number of actuation patterns can be rendered. Vibration has been used to convey a wide variety of meaningful metrics, including: grasping force [19], deviation from a postural set point [6,9], object slip [25], real-time quality of task performance [16], or navigational cues [21].

It is clear that there are not only many ways to implement haptic feedback, but also many pertinent applications for which it would be beneficial. What is not clear, however, is what methods should be used in which contexts in order to maximize the efficacy of the feedback. Ideal haptic feedback delivers the desired information quickly through tactile cues that users can perceive and distinguish accurately. When the information is simple and can be encoded within a few haptic cues (forward, back, right, left navigation cues, for example), the methods described previously are suitable. To communicate more complex information, a higher information transfer rate is required. Although information transfer rates can be increased simply by presenting low-information cues at a faster rate, studies have shown that it is more effective to present information-rich cues at a slower rate [2,22]. In other words, the key to increasing information transfer through the haptic channel is not to increase the presentation *rate* of cues, but rather to increase the information *content* of each cue [22].

In order to increase the information content of a haptic cue, more actuators are needed. However, integrating a substantial number of actuators into a wearable device is difficult because the inter-actuator spacing must be large enough to maintain high localization accuracy and minimize perceptual interference. As a result, these devices are sizable and can quickly become impractical for many wearable applications.

A number of the haptic devices reported in the literature encounter these challenges because they are uni-modal, that is, they only utilize a single actuator type. Given the diversity of mechanoreceptors in the skin, it is probable that wearable haptic devices that stimulate a range of mechanoreceptors may be able to overcome the limitations of single-modality wearable haptic feedback devices that have been prevalent in the literature. We hypothesize that a multi-sensory device, which can render a more diverse range of stimulations, will allow for the creation of a large set of perceptually-distinct cues while still maintaining a small, wearable form-factor. Multi-sensory devices are advantageous because they integrate actuators that operate at different frequencies, thereby allowing multiple stimuli to be rendered at once. Studies have indeed shown that more reliable perception of a physical attribute is possible when multiple tactile stimuli are combined [7]. The integration of multiple haptic modalities into a single system can also help reduce the inter-actuator spacing and perceptual interference between cues.

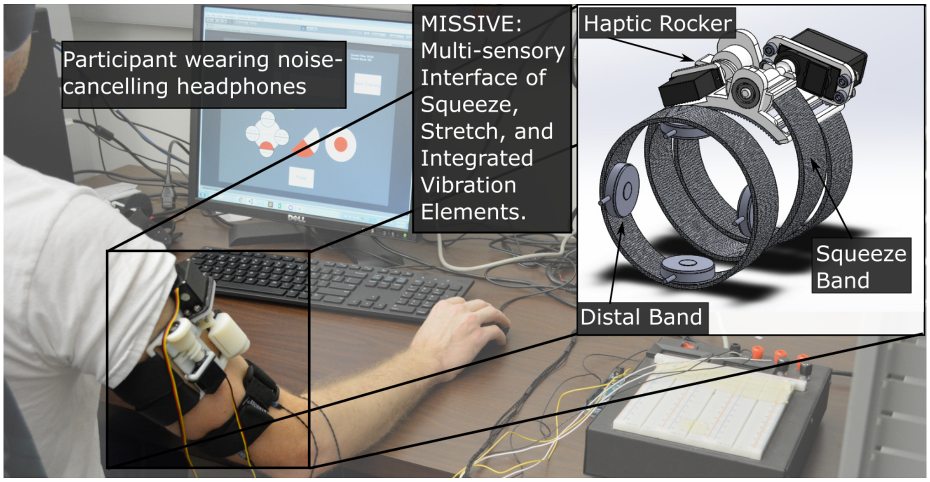

Fig. 1. The participant wears the MISSIVE on their upper arm. The bands are spaced three inches center-to-center. The Proximal Band comprises the lateral skin stretch and radial squeeze devices, and the Distal Band houses an array of four vibrotactors spaced 90° apart around the arm.

In this paper, we introduce MISSIVE (Multi-sensory Interface of Stretch, Squeeze, and Vibration Elements), a novel, multi-sensory, wearable haptic actuator that delivers concurrent tactile cues through combinations of vibration, radial squeeze, and lateral skin stretch. We present the design of this novel haptic device, as well as an assessment of the perceptual accuracy of our multi-sensory system compared with that of an analogous single-sensory device. Our study results show that MISSIVE outperformed the single-sensory system with respect to both presentation identification accuracy as well as user preference.

2 MISSIVE: Multi-sensory Haptic Device

MISSIVE is a compact device capable of delivering a variety of tactile cues to the upper arm of the user. It integrates three types of haptic actuators—a vibrotactor band, radial squeeze band, and haptic rocker—to produce concurrent sensations of vibration, radial squeeze, and lateral skin stretch, as shown in Fig. 1. To make the wearable actuator more compact, the squeeze band and the haptic rocker are mounted on the same frame, worn approximately 3 inches above (on the proximal side of) the vibrotactor band. We will refer to the two bands by their position on the arm (i.e. the Proximal Band and the Distal Band).

2.1 Distal Band

The Distal Band consists of four vibrotactors (C2 Tactors, Engineering Acoustics Inc., USA) positioned on the top, right, bottom, and left sides of the user's upper arm. The tactors are 1.2 inches in diameter and are actuated by a voice coil mechanism. In this

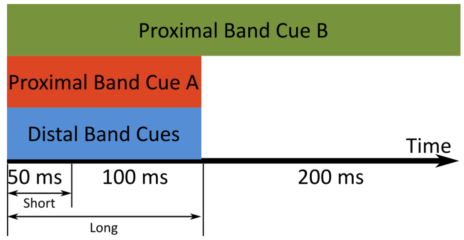

Fig. 2. Relative timing of the three haptic cues within a single presentation. The total duration of the haptic presentation is 350 ms. All three cues begin at the same time but have different durations. The Proximal Band Cue B actuates for 350 ms, the Proximal Band Cue A actuates for 150 ms, and a single Distal Band vibrotactor actuates for either 50 ms (short cue) or 150 ms (long cue).

study, they are driven at a frequency of 265 Hz, corresponding to the maximum vibration amplitude of the vibrotactors. In addition, this frequency value falls within the region of maximum sensitivity for the Pacinian corpuscle, the skin's vibration-sensing mechanoreceptor. This design allows for a large set of haptic cues to be defined using combinations of tactor location(s) and vibration patterns.

2.2 Radial Squeeze Band

The design of the radial squeeze band is based on a similar device developed in the MAHI Lab, the Rice Squeeze Band [24]. It consists of a strap that is connected to a servomotor on one end and wraps around the user's arm. When the servomotor is actuated, it tightens the band and squeezes the user's arm. The servomotor (HS-485HB, Hitec RCD USA, Inc.) has a maximum torque output of 588 mNm.

2.3 Haptic Rocker

The lateral skin stretch actuator is the Rice Haptic Rocker, which was designed by Clark and described in [3]. The device comprises a servomotor connected to a rubber-coated, semi-circular end-effector that is pressed against the user's arm. When the servomotor is actuated, it induces a mild skin-shear sensation by rotating the end-effector and stretching the skin. The servomotor (HS-5070MH, Hitec RCD USA, Inc.) has a maximum torque of 375 mNm.

3 Methods

3.1 Participants

Eight able-bodied participants (four male, six right-handed, 18-24 years old) took part in the experiment. The participants did not suffer from any physical or cognitive impairment that could interfere with their ability to follow the instructions of the study, nor any pathology that could affect tactile sensation or muscular activity of the forearm. They had little to no prior experience with haptic devices. The methods and procedures

Table 1. Corresponding cues between MISSIVE and single-sensory devices (see Fig. 1)

	ACTUATORS		CUES
	MISSIVE	**Single-sensory System**	**Description**
Distal Band	4 vibrotactors	4 vibrotactors	Short/long pulse
Proximal Band Cue A	Haptic Rocker	1 vibrotactor (top)	On/off (150 ms)
Proximal Band Cue B	Radial Squeeze Band	1 vibrotactor (bottom)	On/off (350 ms)

described in this paper were carried out in accordance with the recommendations of the Institutional Review Board of Rice University with written informed consent obtained from all participants.

3.2 Haptic Presentation Set

We developed a set of 32 haptic presentations to use in this identification experiment. Each presentation contained three components: a vibration cue, a lateral skin stretch cue, and a radial squeeze cue, which were all actuated concurrently. The vibration cues were rendered by activating a single tactor (top, right, bottom, or left) for a short (50 ms) or long (150 ms) pulse, resulting in eight unique cues. The radial squeeze and lateral skin stretch cues were rendered as binary, on/off cues. The radial squeeze cue was rendered by tightening the radial squeeze band for 175 ms and then releasing for 175 ms, resulting in a total cue duration of 350 ms. The lateral skin stretch cue was rendered by rotating the haptic rocker 30° and then returning it back to its center position, resulting in a total cue duration of 150 ms. Pilot testing was used to determine these cue actuation patterns to be easily perceptible and of similar intensity. A visualization of the relative timing of the three cues is shown in Fig. 2.

3.3 Single-sensory Format

To compare the distinguishability of multi-sensory versus single-sensory presentations, we designed an analogous vibration-only device by replacing each of the Proximal Band actuators with vibrotactors. The haptic rocker was replaced by a vibrotactor in the Proximal Band positioned on the top side of the user's arm, and the radial squeeze band was replaced by a vibrotactor in the Proximal Band positioned on the bottom side of the user's arm. The Proximal Band cues on the single-sensory system were rendered in the same way (i.e. on/off) and for the same amount of time as the corresponding cues on the multi-sensory system. For simplicity, we will use "Cue A" to refer to the haptic rocker or top vibrotactor cue and "Cue B" to refer to the radial squeeze band or bottom vibrotactor cue. Thus, on both devices, Proximal Band Cue A is a 150 ms on/off cue, and Proximal Band Cue B is a 350 ms on/off cue. A summary of the cues and actuators in each system is presented in Table 1.

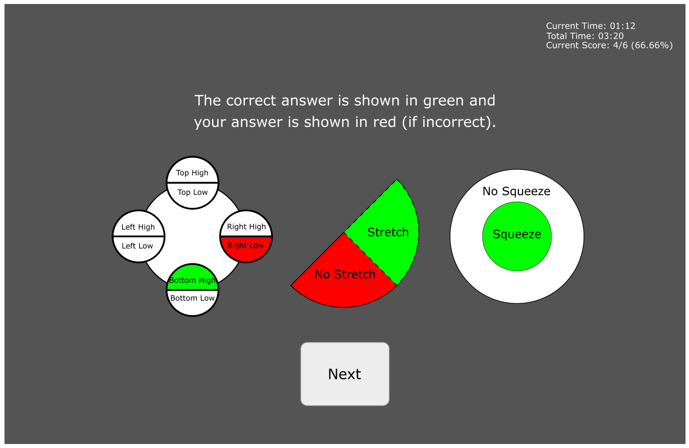

Fig. 3. Testing Graphical User Interface - After the user clicks "next", three haptic presentations are played one after the other with an inter-cue interval of 400 ms. The user responds by clicking on the images corresponding with the cue that they felt on their arm (in the single-sensory condition, participants are taught to interpret the lateral skin stretch and radial squeeze buttons as Cue A and Cue B respectively). After they submit their response, the correct answer is displayed in green, and the haptic cue is played again on their arm.

3.4 Procedure

A repeated-measures, cross-over design was used in which half of the participants performed training and testing with MISSIVE first followed by the single-sensory system. The other half started with the single-sensory system, followed by MISSIVE.

Training Participants interacted with the haptic devices through the graphical user interface (GUI) shown in Fig. 3. Participants were given ten minutes of self-guided training immediately before testing for each system. The self-guided training consisted of two interfaces which could be navigated between freely. The first interface allowed participants to explore the haptic cues by selecting an activation pattern for each component and clicking the mouse to feel it rendered on their arm. The second interface allowed users to simulate the testing protocol by clicking the mouse to feel three presentations. After responding which presentation was the second one, they were shown the correct answer and the presentation was replayed.

Testing During the testing phase, the haptic presentations were rendered with either MISSIVE or with the single-sensory device, and participants were asked to identify them through the computer interface. Each of the 32 presentations was presented five times, in random order, for a total of 160 trials. Participants advanced through the 160 trials at their own pace, and no time constraint was imposed. However, in order to mimic a more realistic application of haptic cue identification, cues were masked during testing using an AXB presentation format. On each trial, participants were presented with three haptic presentations, 400 ms apart, and were asked to identify the second (target) cue.

Table 2. MISSIVE and single-sensory system average accuracy scores and *p*-values for statistical comparisons

	Overall Score	Distal Band Cue	Proximal Band Cue A	Proximal Band Cue B
Multi-sensory	41.4%	62.5%	69.4%	87.3%
Single-sensory	30.5%	42.8%	73.6%	81.3%
p	<.01	<.01	.07	.26

A masked paradigm allows for variable response rates because it separates the time taken for the mental identification process from the physical act of clicking on the chosen response. After the testing, users were asked if they had any preference for either haptic device on a three point scale (i.e. preference for the single-sensory device, no preference, or preference for MISSIVE).

3.5 Data Analysis

An overall presentation accuracy score for each participant on each system was calculated as the percent of *presentations* correctly identified during testing. Accuracy scores for each cue component were also calculated. Paired, within-subjects t-tests were run on the accuracy scores to evaluate whether single- or multi-sensory cues were more easily identifiable. Confusion matrices were generated to visualize overall perceptual performance by aggregating the presentation and response data across all participants for each system.

4 Results

4.1 Perception Accuracy

In the multi-sensory condition, there was an overall mean presentation accuracy of 41.4%, which was greater than the overall mean presentation accuracy of 30.5% in the single-sensory condition ($t(7) = 3.6, p < .01$). For the Distal Band, accuracy in the multi-sensory condition was 62.5%, higher than the 42.8% in the single-sensory condition ($t(7) = 5, p < .01$). The accuracy of Proximal Band Cue A in the multi-sensory condition (69.4%) was not significantly lower than in the single-sensory condition (73.6%) ($t(7) = 2.2, p = .07$). Finally, the accuracy of Proximal Band Cue B in the multi-sensory condition (87.7%) was not significantly higher than the accuracy in the single-sensory condition (81.3%) ($t(7) = 1.2, p = .26$). Five of the users preferred MISSIVE to the single-sensory system, two had no marked preference, and one preferred the single-sensory system. These results are summarized in Table 2 and in Fig. 4.

4.2 Confusion Matrices

Confusion matrices for both systems are presented in Figs. 5 and 6, where rows are the perceived cues and columns are the actual presented cues. The 32-by-32 matrix is

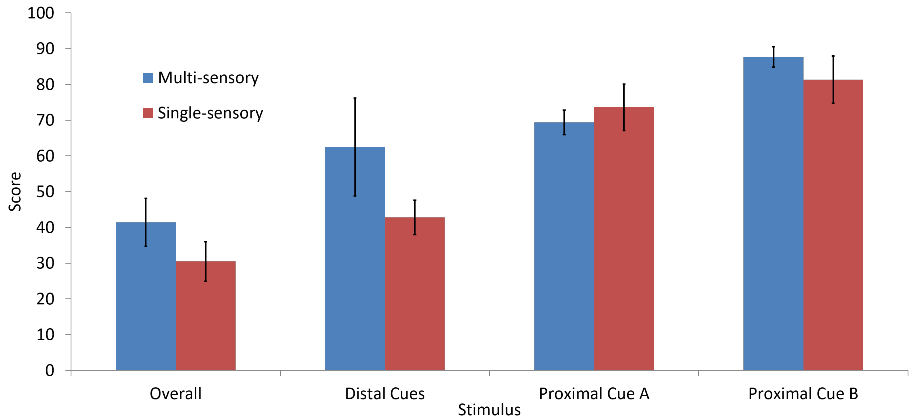

Fig. 4. The mean percent correct for both systems is compared ($N = 8$). The overall scores are significantly different ($p < .01$), and the Distal Band vibrotactor accuracies are significantly different ($p < .01$). Error bars denote the 95% confidence interval.

divided into a 4-by-4 matrix of sub-matrices with heavy lines corresponding to different levels of activation of Proximal Band Cue A, and B (on/off). Cells are filled in with a percentage according to the proportion of times the participants responded a certain way when presented with a given cue. The main diagonal of the confusion matrix illustrates the correct answers (i.e. the perceived presentation matches the actual presentation).

5 Discussion

The objective of this study was to compare users' ability to discern haptic cues when they were presented with MISSIVE and with a comparable single-sensory device. Data were analyzed both in terms of overall presentation accuracy and cue accuracy. Distal Band cue perceptual accuracy for MISSIVE exceeded that of the single-sensory case—even though they are identical in design—highlighting an advantage of the multi-sensory approach. The Distal Band vibration cues were masked by Proximal Band vibration cues in the single-sensory system, while in MISSIVE the vibration cues were masked by lower frequency radial squeeze and lateral skin stretch cues in the Proximal Band. This distinction is likely the explanation for the superior performance of vibration cue identification in the multi-sensory condition.

Proximal Band Cue A and B perceptual accuracies were not significantly different between the single- and multi-sensory systems. The accuracy observed in these cues was higher than the accuracy recorded for the distal band, likely because the Proximal Band cues were longer and were therefore more easily identified. However, because these cues were so prominent, they tended to mask the distal band cues.

The confusion matrices show more specifically where errors occurred. Off-diagonal elements in the same sub-matrices as the main diagonal denote Distal Band errors. Elements in off-diagonal sub-matrices denote incorrect Proximal Band responses (i.e. not correctly identifying radial squeeze or lateral skin stretch). Within those off-diagonal

Actual Presentation

Perceived Presentation			Stretch Off																Stretch On															
			Squeeze Off								Squeeze on								Squeeze Off								Squeeze on							
			TS	TL	RS	RL	BS	BL	LS	LL	TS	TL	RS	RL	BS	BL	LS	LL	TS	TL	RS	RL	BS	BL	LS	LL	TS	TL	RS	RL	BS	BL	LS	LL
Stretch Off	Squeeze Off	TS	78	2.2	2.2	0	0	0	0	0	0	0	0	0	0	0	2.2	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4	0
		TL	0	56	0	0	0	0	0	0	0	4.4	0	0	0	0	0	0	0	6.7	0	2.2	0	2.2	2.2	2.2	0	2.2	0	0	0	0	0	0
		RS	8.9	0	78	4.4	6.7	2.2	0	0	0	0	2.2	0	0	0	0	0	2.2	0	4.4	0	0	0	0	0	0	0	2.2	0	0	0	0	0
		RL	0	16	2.2	71	0	0	0	0	0	4.4	0	0	0	0	0	0	2.2	2.2	2.2	11	0	6.7	0	2.2	0	0	0	0	0	0	0	0
		BS	0	0	6.7	0	73	2.2	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0
		BL	0	0	0	2.2	2.2	80	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	6.7	0	0	0	0	0	0	0	0	0	0
		LS	4.4	2.2	0	0	2.2	0	91	6.7	0	0	0	0	2.2	0	0	0	2.2	0	0	0	0	0	4.4	0	0	0	0	0	0	0	0	0
		LL	0	0	0	0	0	0	0	78	0	0	0	2.2	0	0	0	4.4	0	0	0	0	0	0	0	6.7	0	0	0	0	0	0	0	0
	Squeeze on	TS	0	0	0	0	0	0	0	0	29	6.7	6.7	2.2	6.7	0	2.2	2.2	2.2	0	0	0	2.2	0	0	0	22	4.4	6.7	0	0	0	2.2	2.2
		TL	0	2.2	0	0	0	0	0	0	8.9	27	6.7	6.7	4.4	2.2	0	13	8.9	2.2	0	0	2.2	2.2	2.2	2.2	13	18	2.2	2.2	2.2	2.2	6.7	2.2
		RS	0	0	0	0	0	0	0	0	2.2	0	29	2.2	8.9	0	2.2	0	0	0	6.7	0	0	0	2.2	0	6.7	0	24	0	11	2.2	4.4	0
		RL	0	0	2.2	0	0	0	0	0	0	0	6.7	31	4.4	4.4	0	0	0	2.2	2.2	13	2.2	0	0	2.2	4.4	4.4	8.9	22	2.2	2.2	2.2	0
		BS	0	0	0	0	4.4	2.2	0	0	2.2	0	8.9	0	22	4.4	2.2	0	0	0	2.2	0	4.4	6.7	0	0	0	0	2.2	0	18	4.4	4.4	2.2
		BL	0	0	0	0	0	0	0	0	0	2.2	0	6.7	11	18	0	2.2	0	0	0	0	2.2	2.2	2.2	0	0	2.2	0	4.4	0	18	0	2.2
		LS	0	0	0	0	0	0	4.4	2.2	4.4	0	2.2	0	2.2	2.2	47	2.2	0	0	0	0	2.2	0	6.7	2.2	0	0	4.4	2.2	11	2.2	27	11
		LL	0	0	0	2.2	0	0	0	2.2	2.2	4.4	0	0	0	2.2	11	31	0	0	0	0	0	2.2	0	11	4.4	0	0	0	6.7	2.2	4.4	18
Stretch On	Squeeze Off	TS	6.7	0	0	0	0	0	0	0	11	0	0	0	0	0	4.4	0	27	4.4	13	0	6.7	2.2	13	0	4.4	0	0	0	0	0	2.2	0
		TL	0	22	0	0	0	0	0	0	2.2	16	2.2	4.4	0	0	0	2.2	11	49	4.4	6.7	4.4	4.4	2.2	0	4.4	4.4	0	0	0	2.2	2.2	0
		RS	0	0	6.7	0	0	0	0	0	0	0	4.4	0	0	0	0	0	6.7	0	42	4.4	18	2.2	13	4.4	0	0	0	0	0	0	0	0
		RL	0	0	0	13	0	0	0	0	0	0	2.2	2.2	0	0	2.2	0	2.2	20	6.7	42	2.2	6.7	2.2	6.7	0	0	2.2	2.2	0	2.2	0	0
		BS	0	0	0	0	11	2.2	0	0	0	0	2.2	0	0	2.2	0	0	0	0	4.4	0	31	13	2.2	4.4	0	0	2.2	0	2.2	2.2	0	0
		BL	0	0	0	0	0	8.9	0	0	0	0	0	2.2	2.2	6.7	0	2.2	2.2	0	0	0	0	27	0	2.2	0	0	0	0	0	2.2	0	0
		LS	0	0	0	0	0	0	4.4	0	0	0	0	0	0	0	0	2.2	2.2	0	2.2	0	4.4	0	24	6.7	0	0	0	0	4.4	0	2.2	0
		LL	0	0	0	2.2	0	0	0	8.9	0	2.2	0	0	0	0	2.2	6.7	0	0	0	0	2.2	2.2	2.2	33	0	0	0	2.2	0	0	0	4.4
	Squeeze on	TS	0	0	0	0	0	0	0	0	18	6.7	2.2	2.2	0	0	4.4	2.2	6.7	0	0	0	0	0	4.4	0	18	6.7	13	6.7	2.2	4.4	6.7	0
		TL	0	0	0	4.4	0	2.2	0	0	2.2	11	2.2	2.2	4.4	6.7	0	2.2	0	4.4	2.2	0	0	0	0	2.2	6.7	44	2.2	8.9	2.2	11	6.7	22
		RS	0	0	0	0	0	0	0	0	4.4	2.2	11	2.2	4.4	4.4	0	0	4.4	2.2	4.4	0	4.4	0	0	0	6.7	4.4	13	4.4	6.7	4.4	6.7	0
		RL	0	0	0	0	0	0	0	0	2.2	4.4	0	27	2.2	4.4	2.2	0	2.2	4.4	2.2	18	2.2	2.2	0	2.2	2.2	2.2	2.2	33	4.4	11	2.2	4.4
		BS	0	0	0	0	0	0	0	0	4.4	4.4	8.9	0	16	2.2	6.7	0	2.2	0	0	2.2	4.4	2.2	0	0	2.2	0	0	2.2	18	4.4	4.4	4.4
		BL	0	0	0	0	0	0	0	0	0	0	0	6.7	0	27	0	0	2.2	0	0	0	2.2	8.9	0	0	0	2.2	2.2	8.9	0	18	0	4.4
		LS	2.2	0	2.2	0	0	0	0	0	4.4	2.2	2.2	0	6.7	6.7	4.4	6.7	2.2	0	0	0	0	0	16	0	4.4	0	6.7	0	6.7	2.2	8.9	0
		LL	0	0	0	0	0	0	0	0	2.2	2.2	0	0	0	6.7	6.7	20	0	2.2	0	0	0	0	0	8.9	0	4.4	4.4	0	2.2	2.2	2.2	22

Fig. 5. Confusion matrix for the multi-sensory system ($N = 8$): The 32-by-32 matrix is divided into a 4-by-4 matrix of sub-matrices with heavy lines corresponding to different levels of activation of Proximal Band Cue A, and B (on/off). Vibrotactors are labeled by their location: T/L/B/R and pulse duration: S/L. Cells are filled in with a percentage according to the proportion of times the participants responded a certain way when presented with a given cue. The main diagonal of the confusion matrix illustrates the correct answers (i.e. the perceived presentation matches the actual presentation). With the multi-sensory system, more confusion consistently occurs mistaking which actuators (i.e. lateral skin stretch, radial squeeze, or both) are active. The vibrotactor accuracy is strong (errors are inconsistently distributed) even in off-diagonal sub-matrices, indicating that even when the participants mistook one actuator for another, they could still accurately identify the vibrotactor.

Perceived Presentation			Actual Presentation																															
			Proximal Band Cue A OFF																Proximal Band Cue A ON															
			Proximal Band Cue B OFF								Proximal Band Cue B ON								Proximal Band Cue B OFF								Proximal Band Cue B ON							
			TS	TL	RS	RL	BS	BL	LS	LL	TS	TL	RS	RL	BS	BL	LS	LL	TS	TL	RS	RL	BS	BL	LS	LL	TS	TL	RS	RL	BS	BL	LS	LL
Proximal Band Cue A OFF	Proximal Band Cue B OFF	TS	71	8.9	0	0	2.2	0	2.2	0	0	0	0	0	0	0	0	0	2.2	0	0	0	2.2	2.2	2.2	0	0	0	2.2	0	0	0	0	0
		TL	6.7	47	0	0	0	2.2	0	0	2.2	6.7	0	0	0	0	0	4.4	27	27	4.4	2.2	8.9	0	13	2.2	2.2	0	0	0	0	2.2	0	0
		RS	2.2	0	71	6.7	8.9	2.2	0	0	0	0	0	0	0	0	0	0	0	0	2.2	0	4.4	0	0	0	0	0	0	0	2.2	0	0	0
		RL	0	4.4	2.2	71	0	2.2	0	0	2.2	0	2.2	4.4	0	0	0	0	2.2	6.7	11	11	0	4.4	0	0	0	0	0	0	0	0	0	0
		BS	0	0	0	0	67	18	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		BL	0	0	0	0	0	42	0	0	2.2	0	4.4	0	18	8.9	6.7	2.2	0	0	0	0	0	0	0	0	0	0	0	0	2.2	0	0	0
		LS	0	0	0	0	2.2	0	73	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		LL	0	0	0	0	0	2.2	0	58	0	0	0	0	0	0	0	4.4	0	2.2	0	0	0	2.2	13	16	0	0	0	0	0	0	0	0
	Proximal Band Cue B ON	TS	2.2	0	2.2	0	0	0	0	0	8.9	6.7	0	2.2	0	0	4.4	0	0	0	2.2	0	4.4	0	2.2	0	6.7	4.4	0	0	0	4.4	2.2	0
		TL	0	2.2	0	0	0	0	0	0	8.9	11	0	4.4	2.2	0	2.2	2.2	4.4	0	4.4	0	4.4	2.2	2.2	0	11	4.4	4.4	2.2	6.7	2.2	2.2	0
		RS	0	0	0	0	0	0	0	0	4.4	0	6.7	4.4	4.4	4.4	0	0	0	0	0	0	0	0	0	0	0	0	2.2	4.4	0	0	0	0
		RL	0	2.2	0	0	0	0	0	0	8.9	11	24	36	2.2	0	4.4	0	2.2	0	4.4	16	0	0	0	0	6.7	6.7	8.9	18	6.7	2.2	2.2	4.4
		BS	0	0	0	0	2.2	2.2	0	0	2.2	2.2	2.2	4.4	8.9	6.7	2.2	4.4	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	0	0
		BL	0	0	0	2.2	0	6.7	0	0	8.9	0	20	2.2	38	51	18	11	2.2	0	0	0	0	4.4	2.2	0	0	2.2	2.2	2.2	2.2	2.2	2.2	2.2
		LS	0	0	0	0	0	0	4.4	0	0	0	0	0	0	0	4.4	0	0	0	0	0	2.2	2.2	0	0	0	0	0	0	0	0	0	0
		LL	0	0	2.2	0	0	0	0	2.2	0	4.4	0	0	0	2.2	11	27	0	0	0	0	0	2.2	2.2	2.2	0	2.2	2.2	2.2	2.2	2.2	8.9	16
Proximal Band Cue A ON	Proximal Band Cue B OFF	TS	0	4.4	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	16	13	13	0	11	4.4	13	2.2	0	2.2	0	0	2.2	2.2	0	0
		TL	0	8.9	0	0	2.2	0	0	0	2.2	4.4	0	0	0	0	0	0	22	24	16	13	13	11	11	8.9	6.7	6.7	2.2	2.2	6.7	2.2	4.4	0
		RS	0	0	8.9	4.4	2.2	2.2	0	0	0	0	0	0	2.2	0	0	0	0	0	8.9	0	0	0	2.2	0	0	2.2	0	0	0	0	2.2	0
		RL	2.2	2.2	0	2.2	0	2.2	0	0	2.2	0	8.9	11	0	0	0	0	0	0	6.7	27	2.2	6.7	0	0	0	2.2	4.4	6.7	2.2	2.2	0	0
		BS	0	0	0	0	2.2	0	0	0	0	0	2.2	0	2.2	0	0	0	2.2	2.2	0	0	8.9	4.4	0	0	4.4	2.2	4.4	0	0	0	0	0
		BL	2.2	0	0	0	0	4.4	0	0	0	2.2	4.4	0	6.7	2.2	0	0	2.2	4.4	0	6.7	6.7	4.4	0	0	4.4	11	2.2	2.2	6.7	8.9	4.4	2.2
		LS	0	2.2	0	0	0	0	6.7	8.9	0	0	0	0	0	0	0	2.2	0	2.2	2.2	0	2.2	2.2	0	2.2	0	0	0	0	0	2.2	0	4.4
		LL	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	13	8.9	0	0	0	0	4.4	0	8.9	40	0	0	0	0	0	2.2	6.7	2.2
	Proximal Band Cue B ON	TS	0	4.4	0	0	0	0	0	0	6.7	4.4	4.4	0	0	2.2	2.2	0	4.4	2.2	0	2.2	2.2	16	11	8.9	8.9	11	4.4	11	8.9	11	6.7	4.4
		TL	0	2.2	0	0	0	0	0	0	8.9	6.7	0	0	0	2.2	0	0	2.2	4.4	6.7	0	0	2.2	2.2	0	20	16	18	2.2	20	8.9	27	4.4
		RS	2.2	0	2.2	2.2	0	0	0	0	2.2	8.9	4.4	2.2	0	0	2.2	0	0	0	4.4	4.4	2.2	4.4	0	0	0	4.4	4.4	4.4	2.2	4.4	0	2.2
		RL	0	0	0	0	0	0	0	0	2.2	6.7	2.2	8.9	0	0	0	0	0	0	0	4.4	0	0	0	0	2.2	4.4	16	20	0	8.9	0	6.7
		BS	0	0	0	0	0	2.2	0	0	4.4	4.4	0	2.2	2.2	2.2	4.4	0	0	0	0	0	2.2	6.7	0	0	2.2	2.2	2.2	2.2	6.7	8.9	8.9	0
		BL	0	0	0	0	0	0	0	0	4.4	2.2	2.2	6.7	2.2	6.7	2.2	2.2	0	0	0	0	4.4	2.2	0	0	8.9	4.4	2.2	6.7	8.9	6.7	0	8.9
		LS	0	0	0	0	0	0	0	2.2	0	4.4	0	0	0	0	8.9	8.9	0	0	0	2.2	0	0	2.2	4.4	2.2	0	2.2	0	2.2	0	0	8.9
		LL	0	0	0	0	0	0	0	2.2	2.2	2.2	0	0	0	0	2.2	11	0	0	2.2	0	2.2	4.4	0	2.2	2.2	0	4.4	2.2	0	2.2	11	22

Fig. 6. Confusion matrix for the single-sensory system ($N = 8$): The 32-by-32 matrix is divided into a 4-by-4 matrix of sub-matrices with heavy lines corresponding to different levels of activation of Proximal Band Cue A, and B (on/off). Vibrotactors are labeled by their location: T/L/B/R and pulse duration: S/L. Cells are filled in with a percentage according to the proportion of times the participant responded a certain way when presented with a given cue. The main diagonal of the confusion matrix illustrates the correct answers (i.e. the perceived presentation matches the actual presentation). With the single-sensory system, vibrotactor accuracy deteriorates significantly ($t(7) = 5.0, p = .002$).

sub-matrices, the cells follow the same pattern, where the diagonal corresponds to correct Distal Band responses, and off-diagonal elements denote Distal Band errors.

The results indicate that the identification mistakes made with the MISSIVE were far more consistent than on the single-sensory device. Specifically, when stretch and squeeze were both active, users had trouble perceiving the stretch cue. However, with the unimodal system, confusion consistently occurred in identifying which of the vibrotactors was active in the Distal Band, along with errors in mistaking the Proximal Band cues. This suggests that the vibrotactors in the Proximal Band hindered the participants' ability to accurately perceive the vibrotactors in the Distal Band. The regularity of the type of errors observed with the MISSIVE device point to potential opportunities for design improvements that could increase perceptual accuracy.

6 Conclusion

In this work, we present a novel, multi-sensory approach to increase perceptual accuracy of concurrently rendered cues. We combined multiple modalities of haptic cues (vibration, lateral skin stretch, and radial squeeze) that are perceptually distinct and can be recognized when presented concurrently. Experimental results showed that participants were better able to identify concurrent multi-sensory haptic cues compared to a concurrent single-sensory haptic cues. In addition, qualitative feedback from the participants revealed a preference for MISSIVE over the single-sensory system.

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