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Enhancing Multi-Sensory Cue Salience and Perceptual Identification in a Wearable Haptic Device

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Abstract— **Wearable haptic devices increasingly incorporate a variety of cutaneous haptic cues, enabling the creation of multi-sensory stimuli that can encode complex information. In prior work, a multi-sensory wearable device comprised of squeeze, skin stretch, and vibrotactile cues called MISSIVE was shown to be effective at encoding large cue sets; however, skin stretch was often misinterpreted when presented with a simultaneous squeeze cue. In this paper, we present the design of a multi-sensory haptic wearable named MISSIVE-2 that foregoes skin stretch in favor of a larger set of vibrotactile cues that can be presented with or without a simultaneous squeeze cue. We evaluated cue identification accuracy in a human-subject study and demonstrate very good performance in both true positive rate (84.0%) and positive predictive value (86.2%), objective measures of perceptual performance, with MISSIVE-2, especially compared to that observed with the original MISSIVE device. Analysis of the confusion matrix of all forty haptic cues revealed that user errors were most likely to occur for vibration cues presented at the top of the wrist, under a module housing control electronics, and in the presence of a simultaneous squeeze cue, though performance was still much improved compared to that with MISSIVE. These findings suggest that users can reliably perceive multi-sensory cues presented with MISSIVE-2. Future work will explore applications of MISSIVE-2 for haptic communication.**

I. INTRODUCTION

Wearable haptic feedback devices can provide users with various types information, serving either as the primary source of information, or as an alternative channel when individuals are already visually or aurally saturated [1]. These wearable devices have been applied effectively to fields such as speech encoding [2][3], guidance [4][5], robotic teleoperation [6][7], rehabilitation [8][9], and gaming [10][11]. Many of these scenarios require haptic feedback that can communicate complex information beyond just a few simple cues.

When providing complex information to a user via a wearable haptic device, high levels of information transfer are required. One method of increasing information transfer rates is to simply increase the rate at which low-information cues are presented; however, increasing information content of cues has shown to be more effective at increasing information transfer rate [12] [13].

Multi-sensory haptic devices, which convey combinations of tactile cues and therefore have the ability to stimulate multiple types of mechanoreceptors simultaneously, have been proposed as a means to increase the information content in haptic cues. Indeed, Sullivan et al. demonstrated that multi-sensory devices are better suited for increasing information content than single-sensory devices [14]. A number of multi-sensory wearable haptic devices have been described in recent years, including the hBracelet [15] and CUFF [16], which offer both squeeze and skin stretch cues. Other devices also integrate vibration feedback, including MISSIVE (skin stretch, squeeze, and vibration) [13][14] and Tasbi (squeeze and vibration) [17].

Fig. 1. MISSIVE-2 is a multi-sensory haptic wristband capable of delivering large sets of discrete haptic cues comprised of squeeze and vibration feedback. The vibrotactile band is positioned at the wrist, with the squeeze mechanism proximal to the vibrotactile band.

In their work, Sullivan et al. showed that a multi-sensory device, MISSIVE (Multi-sensory Interface of Stretch, Squeeze, and Vibration Elements), resulted in higher cue identification accuracy than a comparable wearable haptic device comprised of only vibrotactile elements [14]. Despite these promising results, participants often failed to identify the presence of some multi-sensory cue components, most commonly skin stretch when presented jointly with squeeze [14]. The phenomenon of multi-sensory cue masking has also been studied by Zook et al., and findings indicate that squeeze cues are more salient than stretch cues [18].

To address the limitations of cue identification performance in MISSIVE, this paper presents the design of MISSIVE-2 (see Fig. 1), a wearable haptic device designed to increase cue identification accuracy by improving the saliency of the haptic sensations. Details on the design of MISSIVE-2 and its haptic cues are presented in Section II. Section III describes our experimental evaluation of cue identification accuracy using MISSIVE-2. Results are

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presented in Section IV and discussed in Section V, including a comparison of our findings relative to cue identification accuracy performance using the prior version of MISSIVE.

II. DEVICE DESIGN

MISSIVE-2 is a multi-sensory haptic device designed to be worn on the wrist and forearm. Its compact form factor and adjustable sizing limit the extent of movement restrictions or discomfort, resulting in a device that is comparable to what one might be experience wearing a smart watch. Experiments have demonstrated that subjects have a much better response to haptic cues when the haptic display is placed around the wrist [19]. Localization of haptic cues near to an anatomical point of reference, such as the wrist or the elbow, is more precise than when cues are midway along a limb section, and the wrist offers a balance of proximity to the finger, sensitivity, surface area, and social acceptability [20]. For these reasons, MISSIVE-2 is designed to be worn on the wrist and forearm, unlike the MISSIVE, which was placed on the upper limb.

MISSIVE-2 is assembled from off-the-shelf and 3D printed components, keeping overall device cost low. Open source hardware and software tools are used to drive the low-cost vibrotactile actuators, while a commercially available servo is used to create the squeeze effect.

A. Vibrotactile Band

Vibrotactile feedback has been used to send information to a user in a non-disruptive way using the tactile sense, when the visual or auditory channels are occupied and engaged in a primary task [19]. Wrist worn wearables have been used previously for conveying vibrotactile feedback [17].

MISSIVE-2 features a vibrotactile band with eight tactor modules, evenly distributed around an elastic band. The accordion design of the elastic bands and their fabrication with compliant material allows the device to expand to fit wrists with a circumference between 140 mm and 220 mm. An unactuated ratcheting mechanism is integrated into the top module of the vibrotactile band to improve the fit of the band after it is placed on the wrist, ensuring close contact between the vibrotactors and the skin of the user, thereby improving the sensation of the tactile cues. Details of the mechanism are provided in Fig. 2. In addition to housing the ratcheting mechanism and one of the eight vibrotactile actuators, the top module also houses the control electronics PCB, where the eight linear resonant actuators (LRA) are connected. The band interfaces with a control computer through a micro HDMI port.

LRAs (Mplus, LRA1040) provide salient vibrotactile cues at eight locations around the band. These actuators have a resonant frequency of 175 Hz, well within the range of vibrations that stimulate a response from Pacinian Corpuscles (PC) in the skin (30 to 1,000 Hz) and close to the frequency resulting in peak stimulation of these mechanoreceptors (200 to 300 Hz) [19]. The LRAs are driven through Syntacts, an open-source suite of vibrotactile software and hardware based on control of vibration actuators via digital audio interfaces [21]. Vibrational cues designed in Syntacts are displayed through a StarTech 7.1 USB audio interface, and then amplified by a Syntacts Amplifier v3.1 board to provide sufficient power to drive the LRAs in the vibrotactile band.

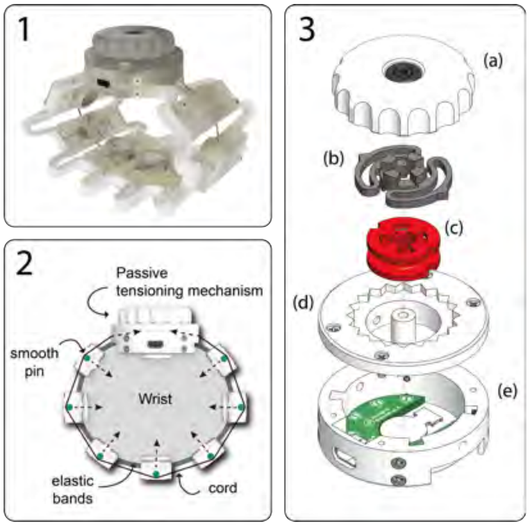


Fig. 2. MISSIVE-2 vibrotactile band (**1**). When tightened, tactor modules are held in place around the circumference of the wrist (**2**). An exploded view of the case shows the ratcheting mechanism used to produce a good fit regardless of wrist circumference (**3**). The ratcheting mechanism consists of a knob (a) to tighten or release the tension of the band. A planar spring (b) and a spool (c) are housed inside a circular lid (d) with a toothed groove to latch the position of the planar spring.

B. Squeeze Band

Radial squeeze feedback has been shown to require less attention than vibration feedback [22]. This difference in attention demand allows squeeze feedback to pair well with vibration feedback, and has been incorporated in a number of wearable multi-sensory haptic devices that also feature vibration feedback [17] [13] [14].

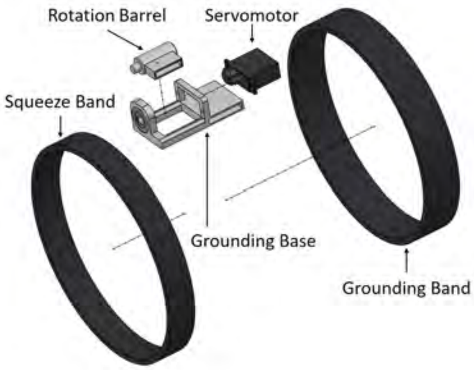


Fig. 3. Exploded view of MISSIVE-2's squeeze mechanism. The squeeze mechanism consists of a $64 \times 32 \times 6$ mm grounding base, and 25 mm wide grounding strap, which hold the Hitec HS-5070MH servomotor, and 12 mm diameter rotation barrel. The 19 mm wide squeeze strap is run through the rotation barrel, and around the user's arm. The servomotor is connected to the rotation barrel, causing the barrel to rotate and tighten the band around the arm when a signal is received.

MISSIVE-2 uses a squeeze actuation mechanism similar to that featured in both its predecessor, MISSIVE [13] [14], as well as the Rice Squeeze band [23]. An exploded view of the squeeze mechanism is provided in Fig. 3. The radial squeeze band is worn on the lower portion of the forearm, proximal to the vibrotactile band on the wrist. The band has five components: a grounding base, a rotation barrel, a squeeze strap, a grounding strap, and a servomotor. The grounding base and strap serve as the foundation for the mechanism, allowing the squeeze band, rotation barrel, and servomotor to move without causing the device to shift on the user's arm. The grounding base measures $64 \times 32 \times 6$ mm and the grounding strap width measures 25 mm, giving the squeeze mechanism a compact form factor, similar to that of a wristwatch. The bottom of the grounding base is padded with a felt-like material to prevent unpleasant skin contact. When the servomotor is actuated, it rotates the barrel causing the squeeze band to tighten around the user's arm. While the servomotor (HS-5070MH, Hitec RCD USA, Inc.) has a maximum torque of 375 mNm, allowing it to be perceivable by the user but not mask the vibration cues.

III. METHOD

To determine the cue identification accuracy with MISSIVE-2, an absolute identification experiment was conducted following methods used in prior work with MISSIVE so that findings could be directly compared [13] [14].

A. Participants

A total of 12 participants took part in the study (10 male, 10 right-handed, aged 19-28, average age 23.8). All participants were healthy adults and did not report any cognitive or sensory impairments that would inhibit their ability to complete the experiment. All participants gave informed consent, and the protocol was approved by the Rice University Institutional Review Board (IRB-FY2020-43).

B. Experimental Hardware

Each participant wore MISSIVE-2 on their right wrist and forearm, and their view of MISSIVE-2 and its actuation mechanisms was obstructed by a box placed over the arm. Participants wore noise-cancelling headphones playing pink noise to mask any auditory cues from the device. A GUI was created using Unity to support training and to guide the user through the experiment (see Fig. 4).

C. Multi-Sensory Cues

A total of 40 multi-sensory haptic cues were developed and presented to participants using MISSIVE-2. Each cue is defined by 3 components: the vibration cue type (Smooth, Double, Burst, Tremor, Pulse), the vibrotactor location used to convey the vibration cue (top, left, bottom, or right), and the state of the squeeze cue (squeeze or no squeeze). Note that for this experiment, only four LRAs within MISSIVE-2 were activated, corresponding to locations on the top, bottom, left, and right side of the wrist. The squeeze cue, when present, was delayed from the onset of the vibration cue by 150 ms, in a manner similar to that used to vary the timing of MISSIVE's multi-sensory cues [24].

Fig. 4. MISSIVE-2 Graphical User Interface. Visual representation of all 40 haptic presentations MISSIVE-2 can produce. This GUI was used to train and test subjects for the absolute identification experiment.

Using Syntacts, we carefully designed and refined 5 salient, unique vibration cue signals. These signals are named **Smooth**, **Double**, **Burst**, **Tremor**, and **Pulse**, based off the sensations they create on the user's skin. Each of these signals is based closely around the LRAs resonant frequency of 175 Hz. The waveforms of the vibrotactile cues are represented in Fig. 5. Signal amplitudes in Syntacts vary from 0 to 1, and are converted to voltages by the digital to analog converter.

Smooth provides a soft vibration on the user's skin, similar to what one would feel from a cell phone vibration. This signal is comprised of a 175 Hz Sine wave at an amplitude of 0.75 and lasts 300 ms.

Double is comprised of a sine wave with a frequency of 180 Hz at max amplitude, which is amplitude modulated by a sine wave with a frequency of 3 Hz at an amplitude of 1. The signal lasts 340 ms, creating a sensation of two smooth vibrations on the skin, with a short pause between them.

Burst consists of a square wave at 175 Hz at max amplitude amplitude modulated by a sine wave at $50Hz$ at an amplitude of 1. The signal plays for 100 ms, and the resulting sensation is a short, intense vibration.

Tremor is comprised of a square wave at 175 Hz at max amplitude amplitude modulated by a sine wave at $7Hz$ at an amplitude of 0.75. The signal plays for 400 ms, and the resulting sensation is a quick, gentle shake on the skin.

Pulse is the most complex of the vibrotactile cues. It is made up of two parts, the downbeat and the upbeat. The downbeat is a sine wave at 175 Hz at max amplitude, with a 100 Hz/s chirp, and an exponential decay parameter of 19. The exponential decay function is displayed as

$$y = A * sin(t) * e^{-\lambda * t}$$

where A is amplitude, t is time, and λ is the exponential decay parameter. The upbeat is a sine wave at 200 Hz, with a -100 Hz/s chirp and an exponential decay parameter of 19. The downbeat is played first, followed by the upbeat.

This downbeat-upbeat sequence occurs twice, with a 50 ms pause in between. The signal has an overall duration of 500 ms, and creates the sensation of a heartbeat.

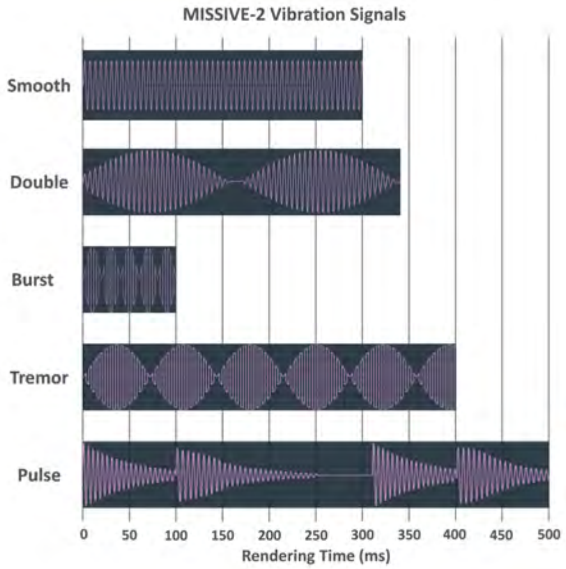


Fig. 5. Visualization of MISSIVE-2 vibration cues designed with Syntacts.

D. Experimental Procedure

Prior to the start of the experiment, participants were introduced to MISSIVE-2 and the GUI and were allowed to train with the device for a total of 10 minutes. The first 3 minutes of the training phase allowed participants to experience any of the 40 haptic presentations with MISSIVE-2 worn on their arm, familiarizing them with the sensations produced from the different haptic presentations. The next 7 minutes of the training phase served as a practice test, in which three haptic cues were played in an AXB format (three cues played in short succession, 400 ms apart). Participants were asked to identify the second signal. The AXB format was used to mimic the application of haptic speech transmission, where haptic cues representing letters or phonemes are rendered in short succession to convey words [24]. The order in which the haptic cues were presented during training was pseudo-randomized to ensure that the cues were presented in a random order, but participants would gain experience with each of the 40 cues. During the training phase, correct-answer feedback was provided via the GUI.

During the testing phase, each of the 40 cues was rendered in AXB format (with the test cue represented by X) 5 times, for a total of 200 trials. No time restrictions were placed on the subjects, and they were not given the ability to replay the cues once they had been rendered. As in the training phase, correct answer feedback was provided.

E. Data Analysis

Cue identification accuracy was visualized with a confusion matrix. Then, data from the experiment were analyzed to determine cue identification accuracy with MISSIVE-2. The following outcome measures were computed:

True positive rate (TPR): The number of trials in which the cue was correctly *identified* as a percentage of the trials in which the cue was *rendered*.

Positive predictive value (PPV): The number of trials in which the cue was *rendered* as a percentage of the trials in which the cue was *identified*.

These two metrics examine different aspects of perceptual accuracy. For example, if the cue Top-Burst-NoSqueeze was rendered 50 times, TPR would reflect the number of times that this cue was *correctly* identified. If the user was to perceive Top-Burst-NoSqueeze 100 times, but they were only correct 50 times, the PPV would be 50%, as PPV measures the perceptual reliability from the perspective of the user.

The sets of TPR and PPV data were tested for normality using a Shapiro-Wilk test. After confirming that the data did not differ significantly from a normal distribution, a two-sample t-test was used to compare the perception accuracies of MISSIVE-2 with findings from a prior experiment with MISSIVE [13] [14].

IV. RESULTS

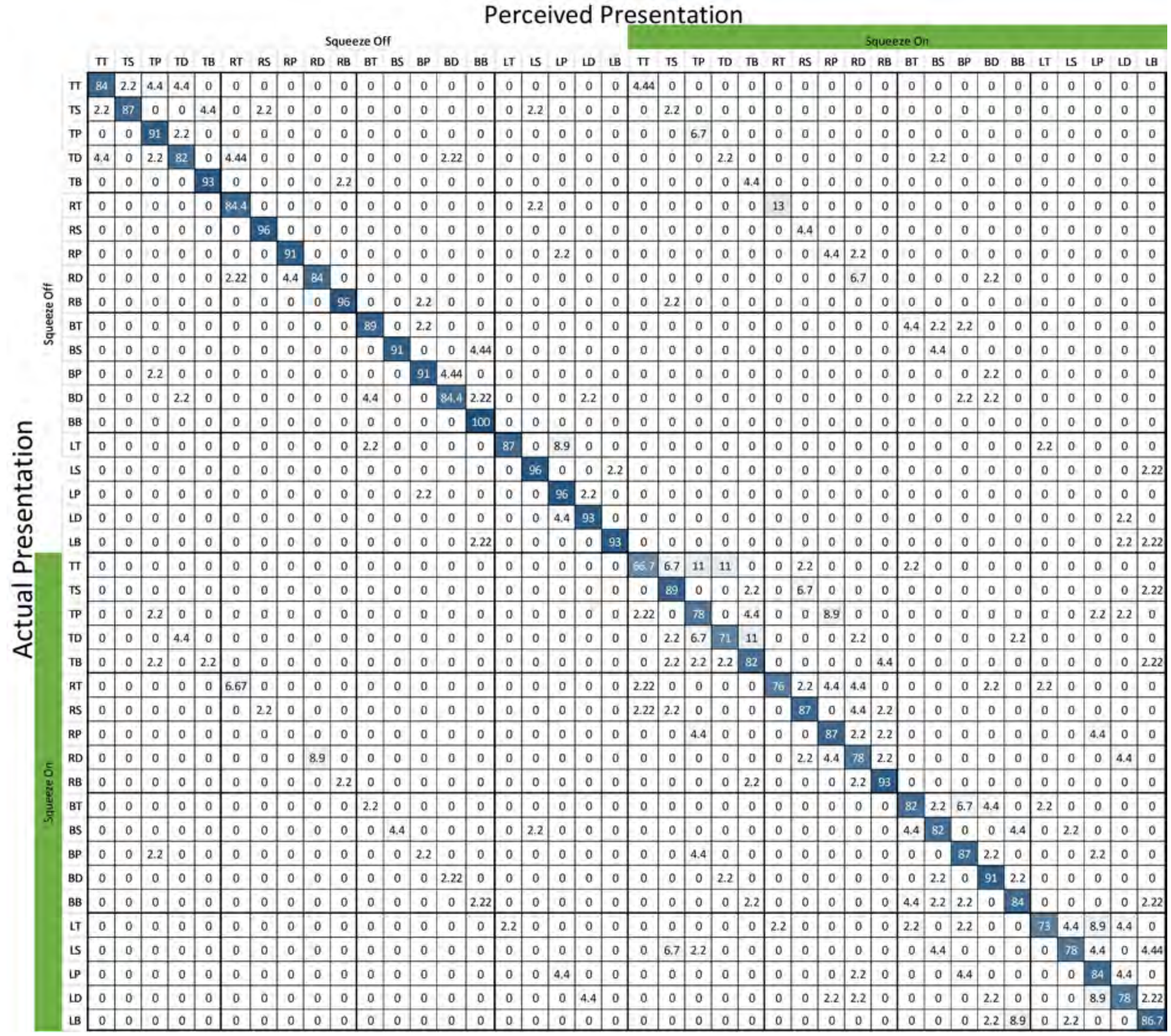
A confusion matrix was created to visualize cue identification accuracy (see Fig. 6). The 40-by-40 matrix is organized such that each 5-by-5 sub-matrix corresponds to a given vibrotactor location. Each large quadrant corresponds to squeeze on versus squeeze off. The vibrotactors are labeled by their location: **T**op, **L**eft, **B**ottom, **R**ight; and their signal: **T**remor, **S**mooth, **P**ulse, **D**ouble, **B**urst. Cells contain percentages calculated from the proportion of times a user gave a specific response after having received a specific cue. The higher the percentage in a cell, the darker the cell. The main diagonal of the confusion matrix represents the correct response given the cue presented. For cues comprised only of vibration, identification accuracies ranged from 77.0% to 98.3%. For cues comprised of vibration and squeeze, identification accuracies ranged from 61.7% to 95.0%

The mean TPR and PPV values for cue identification with MISSIVE-2 are presented in Table I, along with the same results from a prior experiment with MISSIVE [14]. *P*-values were calculated using a two-sample t-test comparing the average TPR and PPV for each device. Overall, participants using MISSIVE-2 were able to identify a higher percentage of cues than those that used the MISSIVE. The TPR for MISSIVE-2 compared to MISSIVE improved by 45.4%, for an overall TPR of 84.0%. The PPV for MISSIVE-2 compared to MISSIVE improved by 45.6%, for an overall PPV of 86.2%.

TABLE I

AVERAGE TRUE POSITIVE RATE (TPR) AND POSITIVE PREDICTIVE VALUE (PPV) FOR MISSIVE AND MISSIVE-2. POSITIVE DIFFERENCE VALUES INDICATE BETTER PERFORMANCE WITH MISSIVE-2. *P*-VALUES CORRESPOND TO TWO-SAMPLE T-TESTS. $*p < 0.05$.

	MISSIVE	**MISSIVE-2**	**Diff.**	***p*-value**
TPR	38.6%	84.0%	+45.4%	< 0.001*
PPV	40.6%	86.2%	+45.6%	< 0.001*



Perceived Presentation

Actual Presentation		Squeeze Off																				Squeeze On																			
		TT	TS	TP	TD	TB	RT	RS	RP	RD	RB	BT	BS	BP	BD	BB	LT	LS	LP	LD	LB	TT	TS	TP	TD	TB	RT	RS	RP	RD	RB	BT	BS	BP	BD	BB	LT	LS	LP	LD	LB
Squeeze Off	TT	84	2.2	4.4	4.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	TS	2.2	87	0	0	4.4	0	2.2	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	TP	0	0	91	2.2	0	0	0	0	0	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	0	0	0	0	0	0	0
	TD	4.4	0	2.2	82	0	4.44	0	0	0	0	0	0	0	2.22	0	0	0	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
	TB	0	0	0	0	93	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	RT	0	0	0	0	0	84.4	0	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	RS	0	0	0	0	0	0	96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4	0	0	0	0	0	0	0	0	0	0	0	0	0
	RP	0	0	0	0	0	0	0	91	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	4.4	2.2	0	0	0	0	0	0	0	0	0	0	0
	RD	0	0	0	0	0	2.22	0	4.4	84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.7	0	0	0	0	2.2	0	0	0	0	0	0
	RB	0	0	0	0	0	0	0	0	0	96	0	0	2.2	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	BT	0	0	0	0	0	0	0	0	0	0	89	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4	2.2	2.2	0	0	0	0	0	0	0
	BS	0	0	0	0	0	0	0	0	0	0	0	91	0	0	4.44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4	0	0	0	0	0	0	0	0
	BP	0	0	2.2	0	0	0	0	0	0	0	0	0	91	4.44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0
	BD	0	0	0	2.2	0	0	0	0	0	0	4.4	0	0	84.4	2.22	0	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	2.2	0	0	0	0	0	0
	BB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	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
	LT	0	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	87	0	8.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0
	LS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	96	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.22
	LP	0	0	0	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	96	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	LD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4	93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	0
	LB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.22	0	0	0	0	93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	2.22
Squeeze On	TT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	66.7	6.7	11	11	0	0	2.2	0	0	0	2.2	0	0	0	0	0	0	0	0	0
	TS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	89	0	0	2.2	0	6.7	0	0	0	0	0	0	0	0	0	0	0	0	2.22
	TP	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.22	0	78	0	4.4	0	0	8.9	0	0	0	0	0	0	0	0	0	2.2	2.2	0
	TD	0	0	0	4.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	6.7	71	11	0	0	0	2.2	0	0	0	0	0	2.2	0	0	0	0	0
	TB	0	0	2.2	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	2.2	2.2	82	0	0	0	0	4.4	0	0	0	0	0	0	0	0	0	2.22
	RT	0	0	0	0	0	6.67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.22	0	0	0	0	76	2.2	4.4	4.4	0	0	0	0	2.2	0	2.2	0	0	0	0
	RS	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	2.22	2.2	0	0	0	0	87	0	4.4	2.2	0	0	0	0	0	0	0	0	0	0
	RP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4	0	0	0	0	87	2.2	2.2	0	0	0	0	0	0	0	4.4	0	0
	RD	0	0	0	0	0	0	0	0	8.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	4.4	78	2.2	0	0	0	0	0	0	0	0	4.4	0
	RB	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	0	0	0	2.2	93	0	0	0	0	0	0	0	0	0	0
	BT	0	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	82	2.2	6.7	4.4	0	2.2	0	0	0	0
	BS	0	0	0	0	0	0	0	0	0	0	0	4.4	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4	82	0	0	4.4	0	2.2	0	0	0
	BP	0	0	2.2	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	4.4	0	0	0	0	0	0	0	0	0	87	2.2	0	0	0	2.2	0	0
	BD	0	0	0	0	0	0	0	0	0	0	0	0	0	2.22	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	2.2	0	91	2.2	0	0	0	0	0
	BB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.22	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	4.4	2.2	2.2	0	84	0	0	0	0	2.22
	LT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	2.2	0	2.2	0	0	73	4.4	8.9	4.4	0
	LS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.7	2.2	0	0	0	0	0	0	0	0	4.4	0	0	0	0	78	4.4	0	4.44
	LP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4	0	0	0	0	0	0	0	0	0	0	2.2	0	0	0	4.4	0	0	0	0	84	4.4	0
	LD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4	0	0	0	0	0	0	0	0	2.2	2.2	0	0	0	0	2.2	0	0	0	8.9	78	2.22
	LB	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	0	0	0	0	0	0	0	0	2.2	8.9	0	2.2	0	0	86.7

Fig. 6. Confusion matrix for MISSIVE-2 (*N* = 12). The 40-by-40 matrix is divided into a 8-by-8 matrix of sub-matrices with heavy lines corresponding to the different vibrotactor locations. The vibrotactors are labeled by their location: **T**op, **L**eft, **B**ottom, **R**ight; and their signal: **T**remor, **S**mooth, **P**ulse, **D**ouble, **B**urst. Cells contain percentages calculated from the proportion of times a user gave a specific response after having received a specific cue. The higher the percentage in a cell, the darker the cell. The main diagonal of the confusion matrix represents the correct response given the cue presented.

V. DISCUSSION

The primary goal of MISSIVE-2's design was to improve the cue saliency and perception accuracy compared to its predecessor, MISSIVE. The 45.4% increase in TPR and 45.6% increase in PPV prove that this goal was achieved due to multiple design improvements. First, squeeze-stretch perceptual interactions [18] were eliminated by removing the stretch component from the device. Next, the use of Syntacts to create vibrotactor cues allowed for the creation of more diverse and distinct vibration signals. With MISSIVE, only 3 cues were used: short vibration, long vibration, and double vibration. Syntacts enabled the design of 5 easily distinguishable cues. The decrease in maximum squeeze torque prevented the vibrotactor cues from being masked, another common occurrence with the MISSIVE. Finally, MISSIVE-2 was designed to be worn closer to the wrist for compactness of form factor, where perception of cues may be more reliable than at the mid-point of the upper arm [25].

While the confusion matrix highlights MISSIVE-2's ability to provide salient cues, evidenced by high percentages of accuracy cue identification, it also provides insight into possible areas for improvement. There is a noticeable drop in perception accuracy of both vibrotactor location and signal type when squeeze is actuated. On average, vibrations without squeeze had a 89.4% perception accuracy, whereas vibrations with squeeze had a 78.8% perception accuracy. This 11.4% difference is likely the result of squeeze pulling the user's focus away from the vibration cue, causing them to misinterpret the signal presented. Despite implementing lower squeeze torques in MISSIVE-2 compared to MISSIVE, squeeze masking of vibration cues seems to have still occurred to a certain extent. Possible fixes include longer training times or replacing the squeeze mechanism with a lower intensity cue such as a stretch mechanism. Another common error involved perception of cues from the top vibrotactor. When the top vibrotactor rendered a vibration signal without squeeze, it was sometimes confused with other vibration signals. When rendered with squeeze, the top vibrotactor was incorrectly identified more than any other vibrotactor, with vibration location being confused for one adjacent to it (left or right), and vibration signals being perceived incorrectly. This may be attributable to the increased amount of hardware in the top vibrotactor's housing that might affect the transmission of vibration cues (see Fig. 2). A decrease in vibration intensity could explain the large drop in accuracy when a different sensory cue, in this case squeeze, is being rendered. A possible solution to this issue is to separate the vibrotactor housing from the ratcheting mechanism and control electronics PCB.

VI. CONCLUSIONS

This paper presents the design of a wearable, multi-sensory haptic device, MISSIVE-2, that incorporates vibrotactile and squeeze feedback about the wrist and forearm. The design of MISSIVE-2 was informed by prior experience with multi-sensory wearables that demonstrated the misperception of skin stretch when presented with a simultaneous squeeze cue. We hypothesized that removal of the stretch mechanism and use of a larger set of distinct vibration cues would still accommodate the design of large cue sets, while also enabling higher cue saliency and perception accuracy compared to that of MISSIVE. Consequently, we designed a study to evaluate whether cues created for MISSIVE-2 would be perceived with higher accuracy than cues associated with MISSIVE. Results signify that MISSIVE-2 haptic cues are more salient than the MISSIVE cues. The use of Syntacts, an open source tool for vibrotactile cue design, facilitated the design of unique vibration cues. Future work will explore the utility of MISSIVE-2 for haptic communication applications.

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