Multi-Sensory Stimuli Improve Distinguishability of Cutaneous Haptic Cues

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***Abstract*—Wearable haptic systems offer portable, private tactile communication to a human user. To date, advances in wearable haptic devices have typically focused on the optimization of haptic cue transmission using a single modality, or have combined two types of cutaneous feedbacks, each mapped to a particular parameter of the task. Alternatively, researchers have employed arrays of haptic tactile actuators to maximize information throughput to a user. However, when large cue sets are to be transmitted, such as those required to communicate language, perceptual interference between transmitted cues can decrease the efficacy of single-sensory systems, or require large footprints to ensure salient spatiotemporal cues are rendered to the user. In this paper, we present a wearable, multi-sensory haptic feedback system, MISSIVE (Multi-sensory Interface of Stretch, Squeeze, and Integrated Vibration Elements), that conveys multi-sensory haptic cues to the user's upper arm. We present experimental results that demonstrate that rendering haptic cues with multi-sensory components—specifically, lateral skin stretch, radial squeeze, and vibrotactile stimuli—improved perceptual distinguishability in comparison to similar cues with all-vibrotactile components. These results support the incorporation of diverse stimuli, both vibrotactile and nonvibrotactile, for applications requiring large haptic cue sets.**

***Index Terms*—wearable haptics, cutaneous haptic feedback, vibrotactile stimuli, skin stretch, psychophysical evaluation.**

I. Introduction

We typically process language inputs through one of two sensory modalities: vision (for written language) or audition (for spoken language). However, there are many situations in which our visual and auditory channels are unavailable, either due to physiological impairment or because they are occupied by other inputs. In these contexts, the ability to communicate language through haptic channels would be advantageous.

The notion of tactile communication is certainly not novel. One of the earliest systems for haptic language transmission was developed by Geldard in 1957 [1], which he called *vibratese*. With an array of five vibrotactors, he created a set of 45 tactile cues using combinations of pulse location, amplitude, and duration to encode the letters of the English alphabet, numeric digits, as well as a few common words. Although vibratese proved to be learnable, as one subject was eventually able to interpret 38 words per minute, the learning process was quite slow: participants required approximately 12 hours to achieve "satisfactorily high" performance in identifying individual letters before moving on to words and short messages.

Now, more than 60 years later, advances in both haptics research and wearable technology have stimulated a renewed interest in tactile language transmission. The commercial availability of vibrotactors, along with their low cost, small form factor, and programmable versatility, has encouraged many groups to explore haptic communication using vibrotactile cues to encode letters or phonemes.

Designing the set of cues to use in these applications, however, is neither trivial nor straightforward. Because language transmission occupies a discrete and high-dimensional information space, the cue set must comprise a relatively large number of cues (on the order of 26-40, depending on whether letters or phonemes are used), which need to be distinguishable from each other. In this paper, we address the challenges posed by these design criteria and show that utilizing multiple *types* of tactile stimuli, instead of vibration alone, improves perceptual distinguishability among discrete haptic cues.

A. Challenges With Vibrotactile Perception

While it is typically not difficult to design a large set of vibrotactile stimuli that are *physically* distinct, it is far less straightforward to design a large set of *perceptually* distinct cues. The challenge stems from the fact that human perception of vibration stimuli is affected by a multitude of factors, making it extremely difficult to establish universal heuristics for creating distinguishable vibrotactile cues (see [2] for a review). The most significant challenge is arguably that the underlying parameters characterizing a vibration stimulus — namely, frequency, amplitude, and waveform — are often not perceived individually [3]. Instead, humans tend to perceive an overall intensity of the vibration, which is a complex fusion of the individual parameters but most strongly influenced by amplitude and frequency. A consequence of this multivariate relationship is that certain combinations of amplitude and frequency can produce "equal-sensation" stimuli even if the actual parameter values are different [2], [4].

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Moreover, the relative salience among vibrotactile parameters is difficult to model. Focusing on the methodology for designing *sets* of tactile cues, MacLean and Enriquez [5] attempted to map out the perceptual space of haptic icons as a function of frequency, force amplitude, and wave shape. A characterization of this nature would facilitate the design of haptic cue sets by allowing interaction designers to choose stimuli with the maximal amount of "spread" in perceptual space. Within a set of vibrotactile stimuli combining different frequencies (0.5, 5, 20, and 100 Hz), force amplitudes (12.3, 19.6, and 29.4 mNm), and wave shapes (sine, square, and sawtooth), the authors found that the frequency component was substantially more salient than amplitude or wave shape. Their results also indicated a non-linear effect of range on the relative salience, such that at the lowest and highest values (0.5 and 100 Hz), the frequency component was so dominant that it masked nearly all variation in the other parameters. Participants' ability to perceive differences in wave shape and amplitude was improved by limiting the range to a narrower frequency band; however, this approach also decreases the number of distinguishable values, or levels, that the parameter can take on. The authors saw some evidence of this in a subsequent study that utilized the same haptic device and frequency values of 7, 10, and 18 Hz [6].

Therefore, many designers choose to modulate spatiotemporal parameters of vibrotactile cues instead of (or in addition to) stimulus intensity, as we seem to be much better at identifying the location and timing of cutaneous stimuli than the amplitude and frequency [2]. For this reason, many devices designed for applications that require large cue sets utilize vibrotactor arrays, which allow for a larger number of perceptually-distinct stimuli to be created by varying the number, location, and temporal pattern of actuated tactors [7]–[9]. The main drawback to this approach is that these devices often need to cover a large area of skin in order to provide sufficient spacing between vibrotactors. If the inter-actuator spacing is too small, spatial interference can decrease localization accuracy [10]–[12], and actuating multiple tactors can elicit sensory illusions such as increased stimulus intensity [12], [13], sensory saltation [14], or funneling [15], [16]. Unfortunately, the areas of the body that could accommodate smaller inter-actuator spacing due to higher sensory sensitivity, such as the fingertips, tongue, and face, tend to be unsuitable and intrusive locations for wearable devices. Consequently, it becomes difficult to create small, wearable, vibrotactile devices that can render large cue sets while avoiding the higher-resolution areas required for everyday activities. The other disadvantage of temporal cues is that rendering the component stimuli sequentially increases the duration of the cue, which tends to diminish the overall information transfer (IT) rate. Since we are already accustomed to high IT rates in language communication (speech and reading are on the order of 40 to 60 bits/sec [17]), information throughput speed is an important consideration for any realistic implementation of a haptic language.

B. Non-Vibrotactile Sensations

To maximize IT rate, the best strategy appears to be balancing a high static IT (information content in each cue) with a slightly slower presentation rate, while keeping the duration of the cues themselves short [18]. Specifically, Tan *et al.* recommend modulating "as many stimulus attributes as possible with as little perceptual interaction among them as possible" [19]. This key principle led us to hypothesize that the individual component stimuli of a haptic cue could be easier to distinguish if they were different *types* of cutaneous stimulation: e.g., if cues were rendered as combinations of *both* vibrotactile and non-vibrotactile sensations.

Other research groups have explored a multitude of non-vibrotactile stimuli. Two of the most common sensations are radial squeeze [20]–[24] and various forms of skin stretch, which include both linear [25], [26] and rotational [27], [28] displacement of a small contact area, as well as circumferential twist of a band around the arm [20], [21], [23], [24]. Most of this prior work focuses on preliminary investigation of the design and perception of these individual sensations. It is usually motivated by the desire to find more natural or intuitive forms of haptic feedback in specific applications. For example, while vibration is suitable for discrete event notifications, radial squeeze seems to be a more intuitive mechanism for conveying kinesthetic information, such as grasp force [21], [23], because our sensory system is already accustomed to using cutaneous pressure for estimating the magnitude of interaction forces. Similarly, skin stretch seems to be a more intuitive mechanism for conveying proprioceptive information, such as hand aperture [26] or limb movement [27], since it has an inherent directional component and also mimics the natural mechanics of how skin stretches during joint flexion [29].

It is becoming more common to see these haptic mechanisms integrated into *multi-sensory* devices, which we define here as haptic devices that are capable of rendering more than one type of cutaneous sensation. Baumann *et al.* [22] created a wrist device that can squeeze and tap; Casini *et al.* [21] created the CUFF, an armband that can squeeze and twist; and Meli *et al.* [23] developed the hBracelet, which has two CUFF-like armbands connected to each other with a linear actuator, allowing for linear skin stretch to be rendered between the bands in addition to all combinations of squeeze and circumferential twist of each band individually. Some systems incorporate vibration as well, such as the device presented by Aggravi *et al.* [24] which can render squeeze, circumferential stretch, and vibration by integrating four vibrotactors into a CUFF-like armband. Others have taken a different approach altogether, using shape-changing interfaces to explore diverse forms of haptic interaction [30].

However, all of these devices have been used to provide proportional feedback or directional guidance such that each haptic sensation is mapped independently to a physical (or virtual) parameter, and different levels of the sensation correspond to different levels of the parameter. For example, Meli *et al.* mapped the stretch component of the hBracelet to the weight of a virtual object and the squeeze component to the user's grip force [23]. Participants therefore only needed to perceive the approximate magnitude of each sensation, rather than the specific level of actuation. Moreover, while users did need to monitor multiple stimuli simultaneously, each haptic

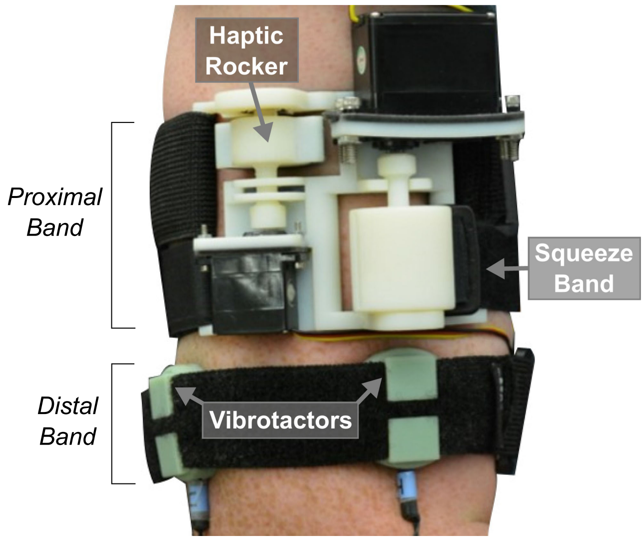

Fig. 1. MISSIVE: a multi-sensory, wearable haptic device used to render multi-sensory tactile cues. The system comprises a Proximal Band (top) and a Distal band (bottom) spaced approximately three inches apart (center-to-center) on the upper arm. The Proximal Band includes the lateral skin stretch and radial squeeze mechanisms, and the Distal Band houses an array of four vibrotactors spaced 90° apart.

sensation was interpreted independently of other stimuli; in other words, the information conveyed by multiple stimuli rendered concurrently was simply the superposition of their individual mappings.

We instead propose a different implementation of multi-sensory stimulation: to create a large set of *discrete* haptic cues, each of which is defined as a specific combination of tactile sensations. This implementation allows for each cue to be encoded individually, making it more suitable for speech transmission and other applications occupying high-dimensional information spaces. To our knowledge, there are no reports in the literature in which various forms of tactile stimuli were combined to create a set of discrete, multi-sensory haptic cues. In contrast to similar research studies that utilize all-vibrotactile cues, we hypothesized that the stimulus diversity within multi-sensory cues would improve perceptual distinguishability, thereby allowing the cues to be rendered on a relatively small area of the skin in a non-intrusive area of the body.

Thus, we sought to evaluate whether a large set of haptic cues would be more easily distinguishable if they were rendered in a multi-sensory format than a single-sensory format. Specifically, we chose to compare a set of 32 cues combining vibration, lateral skin stretch, and radial squeeze sensations to a set of similarly-rendered, vibration-only cues. User study results suggest that rendering haptic cues with multi-sensory stimuli improves distinguishability by reducing perceptual interference between cue components.

II. Methods

A. Hardware Design

Two hardware systems were used to render haptic cues. Multi-sensory cues were rendered with MISSIVE (Multi-sensory Interface of Stretch, Squeeze, and Integrated Vibration Elements, Fig. 1): a compact, wearable device designed for the upper arm [31]. A separate, single-sensory (vibrotactile) system was developed to render single-sensory cues. Both devices consisted of three haptic actuation components split between two bands, a *Proximal Band* and a *Distal Band*, which were spaced roughly three inches apart on the user's arm. The Proximal Band housed two of the actuation mechanisms, and the Distal Band constituted the third. The design details of each system are discussed below and summarized in Table I.

1) Multi-Sensory System: MISSIVE is a multi-sensory haptic device capable of rendering three different cutaneous sensations on the upper arm: lateral skin stretch, radial squeeze, and vibration. The Distal Band consists of four vibrotactors (C2 Tactors, Engineering Acoustics Inc.) positioned on the top, right, bottom, and left sides of the user's arm. These vibrotactors have a ø 7.9 mm contactor housed in a ø 30.2 mm enclosure. For an average-size user with an upper arm circumference of 33.3 cm [32], the inter-actuator spacing would be approximately 8.3 cm. Subjects were allowed to adjust the precise positioning of each tactor so that they perceived the locations of the *stimuli* to be on the top, right, bottom, and left sides of the arm when their arm was extended in front of them, palm facing down. All vibrotactors were actuated at a frequency of 265 Hz to maximize the displacement amplitude of the contactor.

The Proximal Band houses both the radial squeeze and lateral skin stretch mechanisms. The radial squeeze component is actuated by a servomotor (HS-485HB, Hitec RCD USA, Inc.) connected to one end of a non-elastic armband. As the servomotor rotates, it elicits a squeezing sensation by pulling on the armband, causing it to tighten around the user's arm. The lateral skin stretch component uses the design of the Rice Haptic Rocker presented by Battaglia *et al.* [26]. The mechanism includes a servomotor (HS-5070MH, Hitec RCD USA, Inc.) connected to a semicircular rocker, which is pressed against the user's arm. The surface of the rocker is rubber-coated to form a non-slip contact with the user's skin. The stretch sensation is elicited by rotating the rocker, which creates a small displacement of the skin in the mediolateral direction.

2) Single-Sensory System: The single-sensory system was designed to be a vibration-only device that was analogous in form factor, actuator location, and principle to the MISSIVE. Thus, it also comprised three actuator mechanisms located on two bands, as shown in Fig. 2. The Distal Band was identical to the Distal Band on the MISSIVE (four vibrotactors located on the top, right, bottom, and left sides of the arm). The Proximal Band was created by replacing each of the lateral stretch and radial squeeze mechanisms with a C2 vibrotactor. The vibrotactor replacing the lateral stretch mechanism was positioned on the top side of the arm so that the vibration stimulus was rendered in approximately the same location as the skin stretch sensation. The vibrotactor replacing the radial squeeze mechanism was positioned on the bottom side of the arm to limit interference with the top vibrotactor on the Proximal Band. Like the vibrotactors on the Distal Band, the Proximal Band vibrotactors were driven at a frequency of 265 Hz to maximize contactor motion.

TABLE I
CORRESPONDING CUES BETWEEN MISSIVE AND THE SINGLE-SENSORY DEVICE

	ACTUATORS		CUES
	MISSIVE	**Single-Sensory System**	**Description**
Distal Band Component	4 Vibrotactors	4 Vibrotactors	Location + Duration
Proximal Band Component A	Haptic Rocker	1 Vibrotactor (top)	On/Off (150 ms)
Proximal Band Component B	Radial Squeeze Band	1 Vibrotactor (bottom)	On/Off (350 ms)

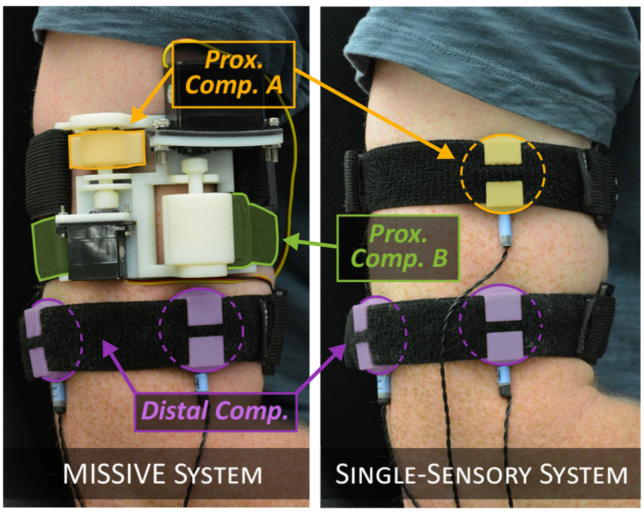

Fig. 2. Comparison of corresponding cue components on the single-sensory (SS) and multi-sensory (MS) systems. Proximal Component A represents the haptic rocker on the MS system and the top vibrotactor of the Proximal Band on the SS system. Proximal Component B represents the squeeze band on the MS system and the bottom vibrotactor of the Proximal Band on the SS system (not visible in figure). The Distal Band Component was the same for each system (left and bottom vibrotactors not visible in figure).

B. Haptic Cue Set

A set of 32 discrete haptic cues was used in the experiment. Each cue was made up of three components: a Distal Band Component and two Proximal Band Components (A and B). When a cue was rendered, the actuation of all three components were initiated simultaneously, as shown in Fig. 3. The Proximal Band cue components were limited to two states, on or off, since pilot testing indicated that it was difficult to distinguish various levels of squeeze and stretch. The Distal Band cue component was defined by two dimensions: location (four states) and duration (two states), for a total of eight distinct Distal Band stimuli. Each cue was referred to by the actuation states of its three components according to the format [*Proximal Component A*]–[*Proximal Component B*]–[*Distal Component*]; for example: On–Off–Left$_{\text{High}}$. Details of the actuation characteristics are discussed below and are summarized in Table I.

1) Multi-Sensory Haptic Cue Set: The components of the multi-sensory cues were developed through pilot testing and assigned as follows:

Proximal Band Component A: *Skin stretch.* In the *on* state, the skin stretch stimulus was rendered by commanding a rotation of the haptic rocker for 75 ms, then commanding the motor to return to the neutral position, for a total cue duration of 150 ms. Because timing of the cue and not displacement of the rocker was controlled, the position of the rocker at its full rotation is approximate, and roughly 30°. In the *off* state, no skin stretch stimulus was rendered.

Proximal Band Component B: *Radial squeeze.* In the *on* state, the squeeze stimulus was rendered by commanding a rotation of the servomotor for 175 ms, which tightened the band, then commanding the motor to return to the neutral position, for a total cue duration of 350 ms. Pilot testing indicated that this was the maximum actuation speed that could provide a sufficiently-salient squeeze force. In the *off* state, no squeeze stimulus was rendered.

Distal Band Component: *Vibration location & duration.* The vibration component of each cue was rendered as a single pulse on one of the four Distal Band vibrotactors. The pulse location was referred to by the position of the actuated vibrotactor (*top*, *right*, *bottom*, or *left*). The duration of the pulse was either 50 or 150 ms, referred to as *low* and *high*, respectively. This terminology was chosen because the longer pulse appeared to have a higher intensity than the shorter pulse, so labeling them accordingly was more intuitive to novice users.

Therefore, the multi-sensory format of the cue On–Off–Left$_{\text{High}}$, for example, would be:
Proximal Component A: Stretch **on**
Proximal Component B: Squeeze **off**
Distal Component: **Left** vibrotactor, **high** pulse

2) Single-Sensory Haptic Cue Set: To make the two cue sets as similar as possible, the single-sensory cue components were rendered in the same fashion — i.e., with the same states and for the same duration — as the multi-sensory cue components. Thus, the components of the single-sensory cues were assigned as follows:

Proximal Band Component A: *Top vibrotactor.* Like the corresponding component in the multi-sensory system, this component was limited to two states, *on* and *off*. However, instead of a 150 ms skin stretch stimulus, this cue component was rendered as a 150 ms vibration stimulus.

Proximal Band Component B: *Bottom vibrotactor.* Like the corresponding component in the multi-sensory system, this component was also limited to two states, *on* and *off*. However, instead of a 350 ms squeeze stimulus, this cue component was rendered as a 350 ms vibration stimulus.

Distal Band Component: *Vibration location & duration.* Since the Distal Band hardware in the two systems was identical, we used the same eight cue components as in the multi-sensory cue set (i.e., *low* and *high* vibration pulses on the *top*, *right*, *bottom*, and *left* sides of the arm).

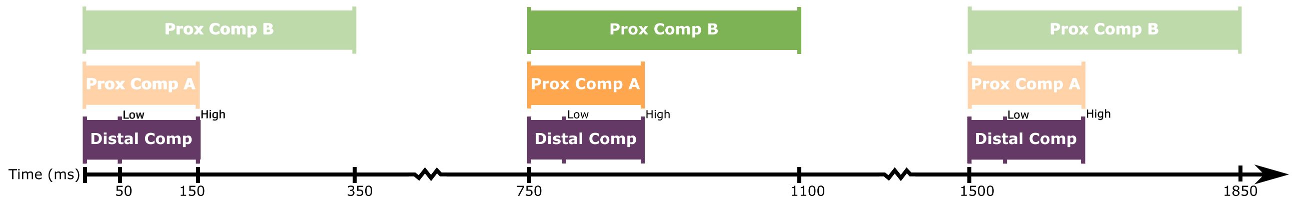

Fig. 3. Haptic cue components and AXB presentation format. Each cue was made up of three components: a Distal Band Component and two Proximal Band Components (A and B). Cues were rendered using an AXB presentation format in each trial, wherein three cues were rendered in succession, 400 ms apart, and users were asked to identify the second (middle) cue.

Therefore, the single-sensory format of the cue On–Off–Left$_{\mathrm{High}}$, for example, would be:
Proximal Component A: Top vibrotactor **on**
Proximal Component B: Bottom vibrotactor **off**
Distal Component: **Left** vibrotactor, **high** pulse

3) Multi-Sensory Validation Testing: To verify that the salience of the individual multi-sensory component stimuli were approximately equal, preliminary validation testing was performed with five participants (three male, average age 24.2). Simpler versions of the multi-sensory cues were created by combining two component stimuli instead of three. The actuation characteristics of each component were the same as described in Section II-B1. The validation testing included three parts: one part for cues combining vibration + skin stretch (16 cues), one for combinations of vibration + squeeze (16 cues), and one for combinations of skin stretch + squeeze (3 cues; Off–Off was omitted). Each part consisted of a brief familiarization period followed by an evaluation. In the evaluation task, each cue was rendered five times, in random order, and subjects were asked to identify the cue using a computer GUI. The cue could not be replayed once it had been rendered, but correct answer feedback was provided after each trial. The order of the three parts was randomized across subjects.

Participants were able to identify the cues with a high degree of accuracy: 81% correct for vibration + skin stretch (82% for the vibration component and 99% for the stretch component), 88% for vibration + squeeze (89% for the vibration component and 99% for the squeeze component), and 97% for skin stretch + squeeze (99% for the stretch component and 99% for the squeeze component). These results indicated that there were no substantial interaction effects hindering the perceivability of the individual stimuli.

C. Experiment Setup & Protocol

The main comparison experiment was conducted in the same manner as the multi-sensory validation testing, in which subjects were asked to identify each component of the haptic cues rendered on their arm. In this experiment, subjects were assessed on both systems in a repeated-measures crossover format, and the full set of 32, three-component cues was used. In the first half of the protocol, subjects performed training and testing on one randomly-selected system, and then repeated the process with the other system in the second half. All subjects wore the MISSIVE on their right arm and used the computer mouse with their right hand. The full protocol took approximately 90 minutes.

1) Subjects: Twelve Rice University graduate and undergraduate students (eight male, four female, average age 23.9) participated in the experiment. Participants had minimal to no prior experience with haptic devices. All users gave informed consent and received a gift card for participating in the experiment.

2) Cue Presentation: In order to simulate a realistic implementation in which users would need to interpret a stream of cues, each trial was presented using an AXB format, as shown in Fig. 3; that is, three haptic cues were rendered successively, 400 ms apart, and subjects were asked to identify the second (middle) cue by indicating the perceived state of each cue component on a computer GUI. Throughout the entirety of the experiment, subjects listened to pink noise to block out the sounds of the actuators.

3) Training: For each hardware system, subjects were given 10 minutes to train before they began testing. During this training phase, they could freely move between a familiarization interface and a self-test interface. The familiarization interface allowed users to click on icons corresponding to each component and then feel the resultant cue rendered on their arm. In the self-test interface, a random cue was rendered and the user was asked to identify the three cue components. After two minutes in the familiarization interface, subjects were encouraged to move on to the self-test interface.

4) Testing: After ten minutes of training on the first device, participants began the testing phase. Testing consisted of 160 trials (five repetitions of each cue) in a randomized order. Subjects were not permitted to replay the cues once they had been rendered, but correct answer feedback was provided after each trial. Participants proceeded through the trials at their own pace, without a time constraint.

D. Data Analysis

Data were analyzed to evaluate whether haptic cues rendered with multi-sensory components were easier to distinguish than analogous cues with single-sensory components. Confusion matrices were calculated for both systems and used to compute the following metrics for each cue:

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*.

TABLE II
AVERAGE METRIC VALUES FOR SINGLE- AND MULTI-SENSORY CUE SETS. POSITIVE DIFFERENCE VALUES INDICATE BETTER PERFORMANCE WITH THE MULTI-SENSORY SYSTEM. *P*-VALUES CORRESPOND TO PAIRED T-TESTS. $^*p < .05$

	Single	Multi	Diff.	*p*-value
True Positive Rate	30.7%	38.6%	+7.9%	.002*
Positive Predictive Value	29.1%	39.3%	+10.2%	< .001*
Identification Accuracy				
Proximal Component A	74.8%	71.2%	-3.6%	.216
Proximal Component B	82.6%	85.7%	+3.1%	.048*
Distal Component	41.9%	56.2%	+14.3%	< .001*

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*.

Cue Component Identification Accuracies (IA): Of the number of trials in which the *cue* was rendered, the percentage in which a specific cue *component* was correctly identified.

Although all three metrics evaluate perceptual accuracy, they measure slightly different facets. For example, if the cue On–Off–Left$_{\text{High}}$ were rendered 10 times, the number of times the *entire* cue (all three components) was correctly identified would be reflected by the TPR, and the number of times each specific cue *component* was correctly identified would be reflected by the corresponding IA. PPV, on the other hand, is calculated relative to the number of user responses: if users *perceived* the cue On–Off–Left$_{\text{High}}$ 20 times, but they were correct in only 10 of those trials, the PPV for that cue would be 50%. Thus, PPV provides a measure of perceptual reliability from the perspective of the user.

For each metric, a paired t-test was used to compare the effects of rendering cues in a multi-sensory format versus a single-sensory format.

III. RESULTS

Average TPR, PPV, and IA across all cues in each system are shown in Table II, where *p*-values correspond to paired t-tests comparing single-sensory cues to analogous multi-sensory cues. Overall, participants were able to identify multi-sensory cues more accurately than corresponding single-sensory cues (mean difference of 7.9% and 10.2% for TPR and PPV, respectively). Average identification accuracies for the Proximal Band cue components were generally high (> 70%) and similar in magnitude between the two systems. The largest difference between single- and multi-sensory cues occurred in the identification accuracy of the Distal Band cue component, which was 14.3% higher for the multi-sensory cue set than the single-sensory set.

Figs. 4-6 show TPR, PPV, and IA plotted for each cue. In these figures, the 32-cue set is separated into four sub-groups based on the states of the two proximal components: group 1 (Off–Off) includes cues with both components off; group 2 (Off–On) includes cues with Component A off and Component B on; group 3 (On–Off) includes cues with A on and B off; and group 4 (On–On) includes cues with both components on. The eight cues in each sub-group therefore differ only by the Distal Band component. Each plot corresponds to a sub-group of cues, and each radial axis within the plot corresponds to a specific Distal Cue Component. The radial axes are oriented topographically to coincide with the physical location of the Distal Band vibrotactor.

Figs. 4 and 5 show that for all but a few cues, multi-sensory stimuli had higher true positive rates and higher positive predictive values than single-sensory stimuli. In both systems, TPR and PPV tended to decrease as the number of active actuators increased.

Table III shows the average TPR differences between single-sensory and multi-sensory rendering for a variety of cue parameters. These values suggest that rendering cues with multi-sensory components was especially beneficial for cues with Distal Band components involving the top vibrotactor (+11%), left vibrotactor (+10%), or a low pulse type (+9.4%). There was an especially large boost in TPR when Proximal Component A (skin stretch/top vibrotactor) was *on* and Proximal Component B (squeeze/bottom vibrotactor) was *off*.

Fig. 6 shows how well the individual components were perceived within each cue. For Proximal Components A and B, the shapes of the IA plots (top and middle rows) are relatively round and symmetrical, indicating that participants' ability to perceive those components was largely unaffected by the Distal Band stimulus. In contrast, the shape of the Distal Component IA (bottom row) plots are markedly less circular. While the contours for the multi-sensory cue set are fairly amorphous, the contours for the single-sensory cue set exhibit a star-like shape, indicating that identification accuracy tended to be better when the Distal Band Component was a high (150 ms) pulse than a low (50 ms) pulse.

Fig. 7 shows the most common response for each cue when rendered on the single-sensory system and on the MISSIVE. When cues were rendered with multi-sensory components, the most common responses were the correct answers for all but four cues. When mistakes were made, subjects tended to miss the stretch component when both stretch and squeeze were on. When cues were rendered with all vibrotactile components, the errors typically occurred in identifying the distal component rather than either of the proximal components. The responses also tended to converge on certain cues and were overall less systematic than on the multi-sensory system.

IV. DISCUSSION

In this study, we sought to determine whether a large set of haptic cues could be perceived more accurately if the cues were rendered in a multi-sensory format than a single-sensory format. Both single-sensory and multi-sensory cues were defined by three, concurrently-rendered components: two Proximal Band components and one Distal Band component. In the multi-sensory cues, Proximal Components A and B were lateral skin stretch and radial squeeze; in the single-sensory cue set, components A and B were single vibration pulses on the top and bottom sides of the arm. In both cue sets, the states of the two Proximal Band components were limited to on or off. The Distal Band, comprising four vibrotactors on the top, right,

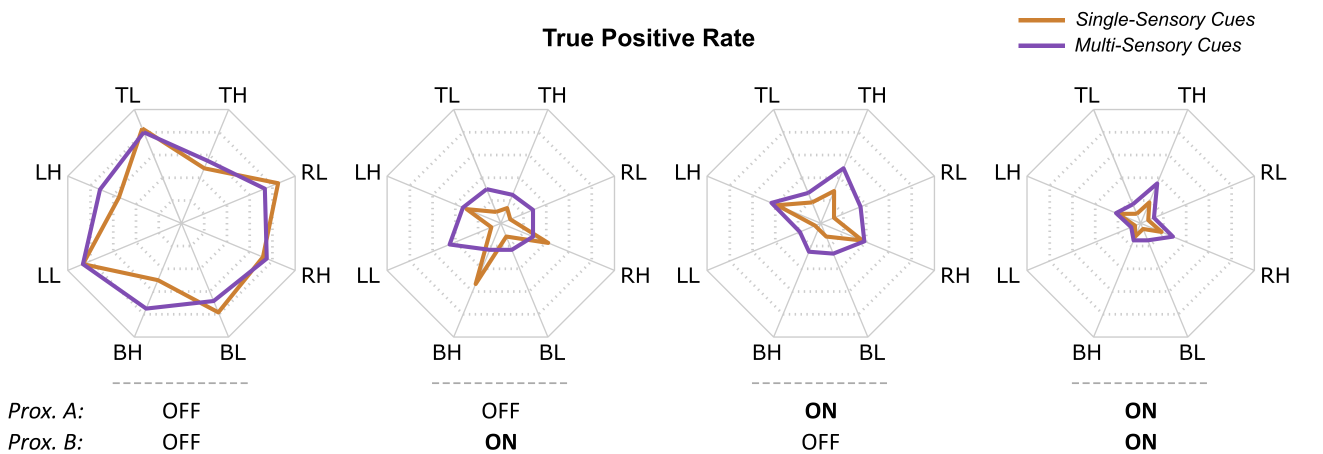

Fig. 4. True positive rate for each cue when rendered with single-sensory components versus multi-sensory components. The cues are separated into four groups categorized by the states of the Proximal Band Components, which are listed below each plot. Within each graph, the 8 cues are arranged topographically based on the state of the Distal Band Component (T/R/B/L for top/right/bottom/left vibrotactor and L/H for low/high pulse). All radial axes range from 0% (center point) to 100% (outermost boundary), marked in increments of 20%.

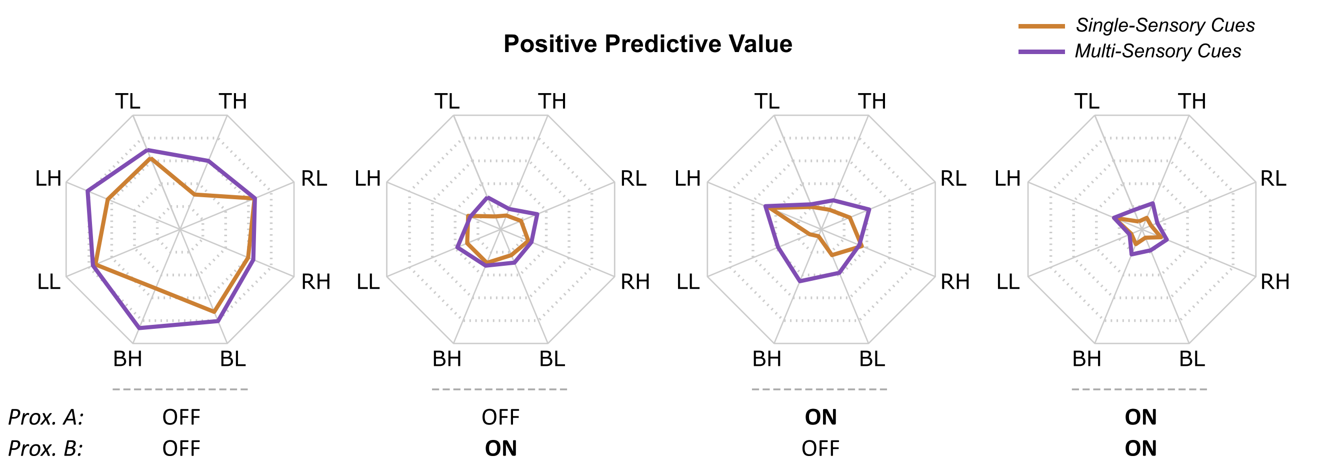

Fig. 5. Positive predictive value for each cue when rendered with single-sensory components versus multi-sensory components. The cues are separated into four groups categorized by the states of the Proximal Band Components, which are listed below each plot. Within each graph, the 8 cues are arranged topographically based on the state of the Distal Band Component (T/R/B/L for top/right/bottom/left vibrotactor and L/H for low/high pulse). All radial axes range from 0% (center point) to 100% (outermost boundary), marked in increments of 20%.

bottom, and left sides of the arm, was identical in both the multi- and single-sensory systems. Distal Band cue components were rendered as a low or high pulse at one of the four vibrotactor locations, resulting in a full set of 32 cues.

A. *Multi-Sensory Cues Are Easier to Distinguish than Single-Sensory Cues*

Experiment results suggest that haptic cues are indeed easier to identify when they are rendered with multi-sensory components than single-sensory components. The true positive rate of each multi-sensory cue was approximately 8% higher, on average, than the corresponding single-sensory cue. Although TPR differences for individual cues ranged from +37% to -30%, only five of the 32 cues had higher TPR scores on the single-sensory system than on the multi-sensory system. The difference in PPV was even more substantial than for TPR, with multi-sensory cues scoring 10% higher, on average, than single-sensory cues. PPV differences for individual cues ranged from +40% to -2%, and only two cues had higher positive predictive values in the single-sensory system than in the multi-sensory system. These results lead us to suspect that information transfer was also higher for the multi-sensory system than the single-sensory system, although not enough data were collected to compute an accurate estimate of IT [33], [34].

The difference between PPV and TPR values provides additional insight into how each cue is perceived. When TPR is much *larger* than PPV (e.g. single-sensory Off–On–Bottom$_{\mathrm{High}}$), it signifies that users are perceiving those cues more often than they are actually rendered. Although this tends to increase the number of correct responses (i.e., TPR), it also leads to a higher number of false positives, which decreases PPV. On the other hand, when TPR is much *smaller* than PPV (e.g. multi-sensory On–Off–Bottom$_{\mathrm{High}}$), it signifies that users tend to "miss" those cues when they are rendered; however, when they *do* perceive those stimuli, their perception is usually correct.

Cues in sub-group 4 (On–On) tended to have the lowest TPR and PPV scores overall, as these cues were the most

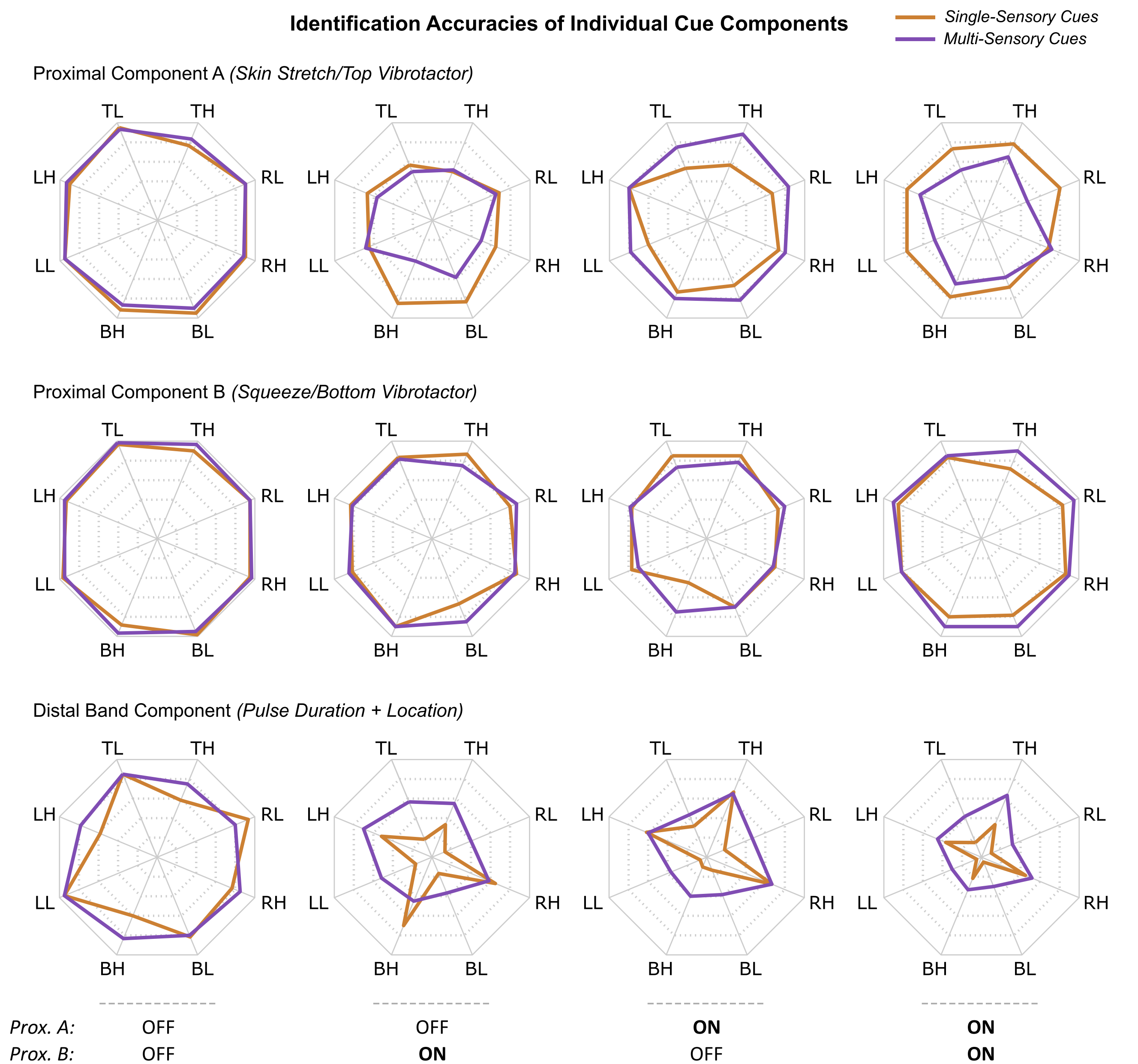

Fig. 6. Identification accuracies of Proximal Cue Component A (top row), Proximal Cue Component B (middle row), and the Distal Cue Component (bottom row) when rendered within single-sensory and multi-sensory cues. The 32-cue set is separated into four groups categorized by the states of the Proximal Band cue components, which are listed at the bottom of the figure. Within each plot, the 8 cues are arranged topographically based on the state of the Distal Band component (T/R/B/L for top/right/bottom/left vibrotactor and L/H for low/high pulse). All radial axes range from 0% (center point) to 100% (outermost boundary), marked in increments of 20%.

complex and required subjects to focus on four different stimulus parameters occurring simultaneously. Although this trend is not surprising, it does suggest that there might be a limit to how many concurrent stimuli we can perceive naturally, i.e., without training. Nevertheless, rendering these cues with multi-sensory components increased TPR and PPV scores by approximately 7% on average (7.3% for TPR and 6.9% for PPV). This finding is especially relevant for applications like language transmission, where utilizing complex cues might be necessary to render a large cue set on a small area of the body [35]. Interestingly, in *both* the single- and multi-sensory systems, the cues in this sub-group were most often identified as On–On–Top_{High}. While it is unclear why that particular cue was the most commonly-perceived, the ratio of incorrect to correct responses was substantially lower for the multi-sensory system—1.8:1 versus 6.1:1—suggesting that the multi-sensory format helped to reduce the perceptual confusion.

B. *Diversifying Cue Component Stimuli Reduces Perceptual Interference*

Trends within the data suggest that the single-sensory cues were susceptible to perceptual masking and localization issues between the Distal and Proximal Bands. Within the multi-sensory cues, on the other hand, those spatial interference problems appear to have been mitigated by the stimulus diversity of the cue components. This inference is corroborated by the

TABLE III
COMPARISON OF TRUE POSITIVE RATES AVERAGED ACROSS VARIOUS PARAMETERS FOR SINGLE- VERSUS MULTI-SENSORY CUES. POSITIVE DIFFERENCE VALUES INDICATE BETTER PERFORMANCE WITH THE MULTI-SENSORY SYSTEM

	Single	Multi	Difference
Distal Components			
Duration			
Low Pulse	27.7%	37.1%	+9.4%
High Pulse	33.8%	40.1%	+6.4%
Location			
Top	28.5%	39.6%	+11.0%
Right	35.0%	39.8%	+4.8%
Bottom	28.3%	34.0%	+5.6%
Left	31.0%	41.0%	+10.0%
Proximal Components			
Comp. A – Comp. B			
Off–Off	69.8%	73.1%	+3.3%
Off–On	22.1%	29.6%	+7.5%
On–Off	19.4%	32.7%	+13.3%
On–On	11.7%	19.0%	+7.3%

fact that multi-sensory rendering was especially beneficial for improving the perceivability of the Distal Band component. As shown in Table II, the difference in average IA for the Distal Band component between the two cue sets was 14.3%, the largest of any metric. Furthermore, comparison of the Distal Band IA values for individual cues (Fig. 6, bottom row) shows that the multi-sensory system outperformed the single-sensory system for all but six cues. In other words, subjects' ability to correctly identify the Distal Band component—a vibration stimulus—was significantly better when the Proximal Band stimuli were not also vibrotactile.

Fig. 6 (bottom row) shows the individual Distal Band IA values, which quantify how often the Distal Band Cue Component was correctly identified for each cue. Particularly for the single-sensory cues, these plots reveal errors that point to problems with both localization and salience. When both proximal components were *off*, IA was better for *low* pulses (TL, RL, BL, LL) than *high* pulses; this is likely because the high pulses were more similar to the Proximal Band cues, causing confusion. However, once one or both of the Proximal Components were *on*, IA was better among cues with *high* pulses (TH, RH, BH, LH), indicated by the star-like shapes in the plots. This was most likely a salience issue: when the Distal Band pulse was low (50 ms), it was overshadowed by the Proximal Band components, since they were substantially longer pulses. The exception to this trend occurred when the location of the Distal Band cue was on the *opposite side* of the arm from the Proximal Band cue (e.g. On–Off–Bottom$_{High}$). Although users could perceive that there were two stimuli, they had trouble distinguishing which was the Distal Band stimulus and which was the Proximal Band stimulus. In contrast, while pulse duration and location did have an influence on Distal Band IA for the multi-sensory system, the effect was substantially less than for the single-sensory system.

It is particularly interesting to note the difference in Distal Band IA for cues in group 1 (Off–Off, Fig. 6, bottom row),

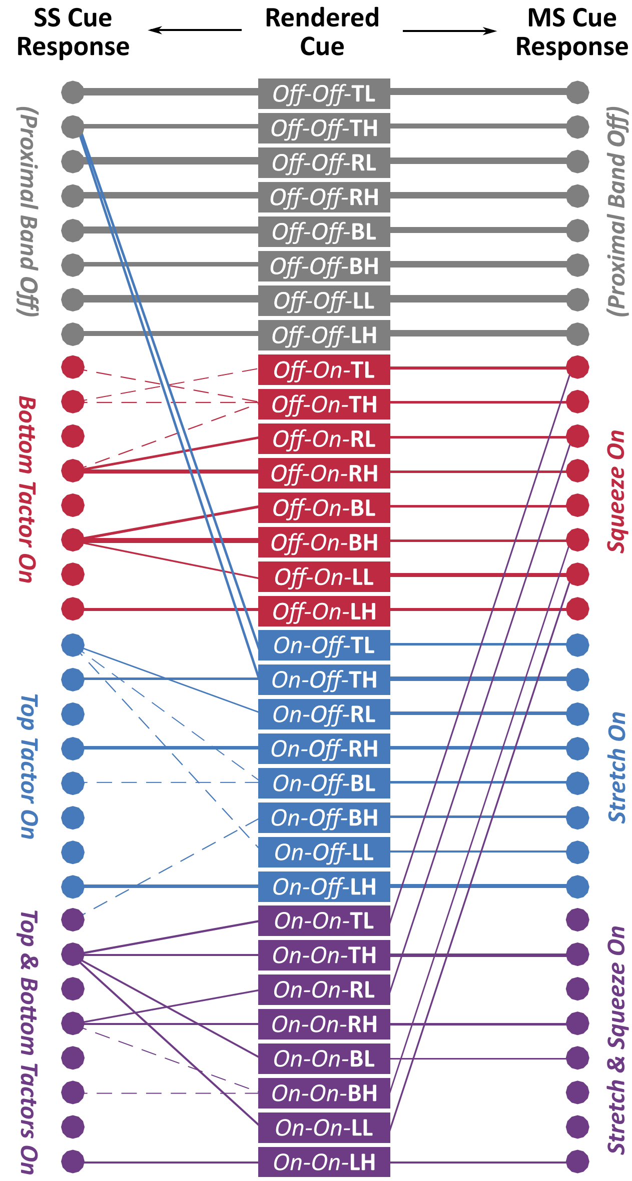

Fig. 7. Visual representation of the most common cue identification responses on both systems. Each row corresponds to the haptic cue listed in the center column, color-coded by sub-group. When each cue was rendered, the most common response on the single-sensory (SS) system and multi-sensory (MS) system are indicated by lines on the left side and right sides, respectively. Horizontal lines indicate that the most common response was the correct answer. The thickness of the lines corresponds to the frequency of the indicated response, where thinner lines signify lower response frequencies. Dashed lines indicate responses that occurred in less than 15% (9/60) of trials.

which consisted of only a single vibration pulse rendered by one of the Distal Band vibrotactors. Because the Distal Band is identical in both systems, the single- and multi-sensory versions of the cues in this sub-group were *exactly* the same. It is therefore surprising to see a difference in Distal Band identification accuracies between the two systems (single-sensory average: 76.0%; multi-sensory average: 82.7%). As discussed previously, subjects struggled with the *high* vibrotactor pulses in particular on the single-sensory system; further inspection of the confusion matrix revealed that they often perceived those cues in the correct location, but as a *low* pulse. This discrepancy

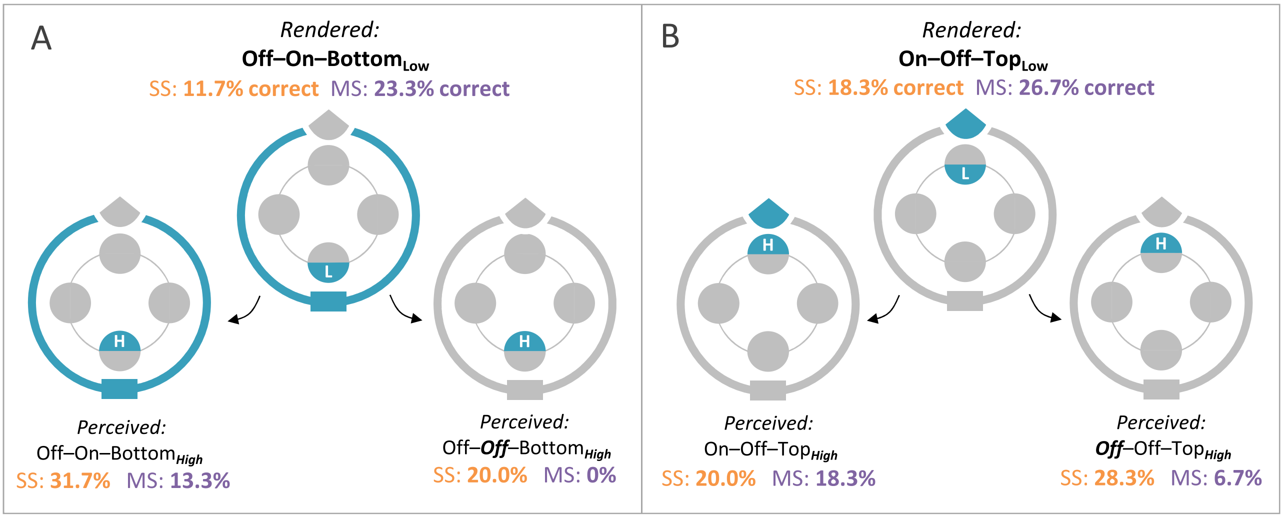

Fig. 8. Examples of cue identification errors resulting from spatial interference. Both hardware systems are depicted by two concentric rings: the outer ring represents the Proximal Band, where Proximal Component A (skin stretch mechanism/top vibrotactor) is represented by the wedge shape on top, and Proximal Component B (squeeze band/bottom vibrotactor) is represented by the thickened ring and the bottom rectangle. The four circles around the inner ring represent the four Distal Band vibrotactors in the corresponding locations. Haptic cues are depicted by the turquoise shading indicating which components are active. The top and bottom halves of each vibrotactor circle correspond to high and low vibration pulses (labeled "H" and "L"), respectively. In each box, the cue on top represents the cue that was rendered, and the corresponding percentages show how often that cue was correctly identified both the single-sensory system (SS, orange) and the multi-sensory system (MS, purple). The two cues on the bottom represent common identification errors in response to the rendered cue, and the corresponding percentage values indicate how often the mistake was made.

is likely attributable to increased confusion among cues in the single-sensory set. Although it is perhaps unintuitive to assume that a user's ability to perceive a certain stimulus would be affected by what other cues are included in the set, this finding underscores the importance of assessing the perceptual characteristics of a cue set as a whole, not just the perceivability of the individual cues.

The advantages of the multi-sensory system were particularly evident in cues involving low Distal Band pulses that were in close proximity to an active proximal component. For example: Off–On–Bottom$_{\text{Low}}$, depicted in Fig. 8 A, where both the bottom vibrotactor on the Distal Band and Proximal Component B (squeeze band or bottom vibrotactor) were active. In the single-sensory system, this cue was correctly identified in only 11.7% of trials; instead, it was most often perceived as Off–On–Bottom$_{High}$ (31.7% of trials), followed by Off–*Off*–Bottom$_{High}$ (20% of trials). These responses suggest that subjects felt a large amount of vibration on the back of the arm, but they were not able to determine the precise location nor distinguish a 50 ms low pulse in the presence of a much longer (350 ms) pulse. In the multi-sensory system, however, this cue was correctly identified twice as often as in the single-sensory system (23.3% of trials), and the number of times it was mistaken for Off–On–Bottom$_{High}$ was substantially lower at 13.3%. Unlike the single-sensory cues, it was never mistaken for Off–*Off*–Bottom$_{High}$ (i.e., squeeze off); in fact, subjects correctly identified the squeeze sensation in 85.0% of trials for this cue, versus 66.7% for single-sensory Proximal Component B. Thus, utilizing a squeeze mechanism instead of an additional vibrotactor appears not only to produce a more recognizable sensation, but also to improve the distinguishability of nearby vibration stimuli.

Similar error trends are evident for On–Off–Top$_{\text{Low}}$, shown in Fig. 8 B, where both the top vibrotactor on the Distal Band and Proximal Component A (skin stretch mechanism or top vibrotactor) were active. This cue was correctly identified (TPR) in 18.3% of trials on the single-sensory system versus 26.7% of trials on the multi-sensory system. While this was the most common response for the multi-sensory system, the most common response for the single-sensory system was *Off*–Off–Top$_{High}$ (28.3%): that is, a single long pulse instead of one short and one long pulse. This mistake was only made in 6.7% of trials in the multi-sensory system, further corroborating the benefits of designing haptic cues with diverse stimuli.

C. *Interactions Between Lateral Stretch and Radial Squeeze Components*

Of course, these findings are heavily influenced not only by the choice of haptic stimuli in the multi-sensory system, but also by the design and integration of the cue components. For this reason, preliminary testing was done on the relative salience of the cue components, rendered in pairs, to ensure that they were all sufficiently perceivable. The results of this validation testing showed that both the stretch and squeeze stimuli were accurately identified ($>98\%$) when rendered in conjunction with vibration as well as with each other.

With respect to the squeeze sensation, results from the full experiment corroborate these findings from the validation testing, and, additionally, that squeeze appeared to be less susceptible to perceptual interference than a vibration pulse of equal duration (average multi-sensory IA: 85.7%; average single-sensory IA: 82.6%).

The lateral skin stretch component, on the other hand, was the only cue component that did not have a significantly higher identification accuracy than its single-sensory analogue. Surprisingly, results suggest that there was some degree of interference between squeeze and stretch. This trend is evident in Fig. 7, as well as in the IA plots for Proximal Component A (Fig. 6, top row), which show that the identification accuracy of the *skin stretch* component decreased when the *squeeze* component was active (average stretch IA when squeeze was off vs. on: 85.4% vs. 57.0%). Moreover, this was the case even when the skin stretch component itself was not active; in other words, when squeeze was on, subjects often perceived a stretch stimulus even when it had not been rendered. The stretch stimulus tended to be incorrectly "added" more often when the Distal Band cue was a high pulse than a low pulse, but there were no obvious trends based on vibrotactor location. One plausible explanation for this illusion is that when squeeze and stretch were both active, the sensory masking (and correct answer feedback) conditioned subjects to doubt their perception of the stretch component; this, in turn, caused them to second-guess themselves when stretch actually *was* off, leading them to respond incorrectly.

Furthermore, it is peculiar that this interference surfaced in the full experiment but not in the validation testing. This discrepancy leads us to hypothesize that there is an effect of cognitive load on sensory acuity, as the AXB presentation format and the increase from two to three components per cue made the full experiment much more challenging than the validation testing. While both of these factors likely contributed to the difference in results, increasing the number of concurrently-rendered stimuli has been shown to have a significant effect on perceptual accuracy. Even with 500 ms cues and large inter-actuator spacing, Wang *et al.* [36] found a 30% drop in tactor localization accuracy for each additional vibration stimulus actuated on users' arms. Regardless of the specific cause, the masking issue could likely be improved by revising the design of the skin stretch component to increase its salience. Future work could include exploring the effects of distributing the skin stretch sensation around the arm, like the CUFF device [21], or slowing down the rotation speed of rocker.

V. Conclusion

Motivated by the ultimate application of haptic language transmission, we hypothesized that combining multiple forms of tactile stimulation would allow us to create a large set of haptic cues that could be rendered in a small, unobtrusive area of the body without sacrificing perceptual distinguishability. To this end, we designed a study to evaluate whether haptic cues are easier to distinguish if their component stimuli are *multi-sensory* than if they are *single-sensory*. Results indicated that rendering haptic cues with multi-sensory components—specifically, lateral skin stretch, radial squeeze, and vibrotactile stimuli—improved perceptual distinguishability in comparison to similar cues with all-vibrotactile components. Although more studies are needed to determine generalizable heuristics for designing multi-sensory cues, these findings encourage the incorporation of diverse stimuli, both vibrotactile and non-vibrotactile, for applications requiring large haptic cue sets.

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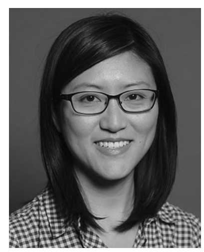

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