Effect of Tactile Masking on Multi-Sensory Haptic Perception

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Abstract—Multi-sensory wearable haptic devices are able to encode a variety of information using multiple haptic cues. However, simultaneous cues can be misperceived due to tactile masking effects. In this paper, we investigate the effect of masking on the perception of skin stretch and squeeze. We performed three experiments measuring the just-noticeable difference (JND) and the absolute threshold of skin stretch and squeeze alone and in the presence of simultaneous haptic cues. Additionally, we investigate the relative perceptual amplitudes of these haptic cues. Results indicate that the JND for a skin stretch cue increases with a masking squeeze cue, while the JND for a squeeze cue does not change with a masking stretch cue. Also, masking has a significant effect on the absolute threshold of both skin stretch and squeeze. These results suggest that the effect of masking diminishes as haptic cues become larger in amplitude. The results from the subjective equality experiment suggest a potential nonlinear relationship between perceptual magnitudes. Further testing should be carried out to investigate this relationship. Future multi-sensory devices can use these perceptual experiment findings to ensure the delivery of salient cues to users.

Index Terms—multi-sensory haptics, cutaneous haptics, psychophysical evaluation, tactile masking, haptic perception

1 Introduction

HAPTIC cues are increasingly being integrated in wearable devices because of their ability to transfer detailed information to the human user. These devices use touch cues to send encoded messages to users or to supplement messages being passed through the other senses. While the visual and auditory channels alone are generally sufficient for conveying feedback to users, there are many times when these senses become overwhelmed or are unavailable, especially in today's information-driven world. It has been well-documented that sensory overload caused by excessive visual and auditory stimulation beyond an individual's tolerance level can lead to various negative psychophysical effects. Prior work by Lipowski reviews various auditory and visual studies exploring the causes of sensory overstimulation and its effect on the psychological and physical well being of subjects [1]. In such situations, the sense of touch could be an alternative channel for feedback, with information transferred through wearable haptic feedback devices. Such devices would allow users to receive feedback or additional information without diverting their visual attention away from the primary task. To maximize the saliency of haptic feedback in wearable devices, we have seen significant research into and development of new types of haptic sensations beyond the ubiquitous vibrotactile feedback, including sensations such as skin stretch and squeeze. These haptic modalities are used to send encoded information in various applications including virtual reality [2], [3], language transmission [4], [5], navigation [6], [7], interaction and engagement in rehabilitation settings [8], and motion feedback [9]. The pursuit of detailed information encoding in wearable haptics has also driven the development of multi-sensory haptic devices that stimulate multiple haptic channels, either in sequence or simultaneously. A better understanding of how the simultaneous display of multi-sensory cues may result in misperception due to tactile masking, defined as the obscuring of the perception of one stimulus by the presence of another stimulus [10], is needed to inform device design. In this paper, we focus on two cutaneous haptic sensations — skin stretch and squeeze — to show the extent to which masking between these haptic cues may affect their perceptual distinguishability.

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1.1 Haptic Cue Types

Wearable haptic devices rely on cutaneous haptic cues to deliver information. Two of the most popular of these cues are skin stretch and squeeze. These cues have been investigated as ways to induce the sensation of an object and other encoded information by mimicking proprioceptive cues without necessitating the use of a kinesthetic device.

Skin stretch has been investigated as a way to replicate the sensation of an object by mimicking the proprioceptive cues an object would normally provide without reaction forces. Skin stretch devices typically leverage a no-slip contact between an end effector and the skin to produce a mild skin shear sensation. Such devices can be rocker-based [6], [11], linear [12], [13], [14], or rotational [15], [16], [17]. The interest in skin stretch can be partially attributed to the modality's ability to deliver continuous or directional information inherent in the stretch itself. In our experiments, we use a rocker-based skin stretch device described in Section 2.3.

Squeeze devices typically tighten a band around a user's limb to deliver a distributed pressure sensation. This is a particularly convenient cue to use in wearable devices because the same grounding strap used to mount the device to the user can be actuated to deliver a squeeze cue. Similarly to skin stretch, squeeze has the potential to deliver continuous information encoded at different amplitudes of squeeze [2], [15], [18]. Squeeze devices use a few different actuation approaches. The main difference is in the actuation style of the squeeze band. Most commonly, the squeeze is coupled with some stretching of the skin due to a single actuator tightening the band from one side. There has also been some work in developing more complex mechanisms using multiple actuators [2] or other clever mechanical solutions [3] to deliver a pure normal force. In our experiments we use a common single actuator squeeze device described in Section 2.3.

1.2 Multi-Sensory Haptics

Multi-sensory haptics combines actuation strategies from single-sensory haptics to provide a more detailed stimulus to a user. In wearable multi-sensory devices, vibration, skin stretch, and squeeze are commonly used. The use of these multi-sensory cues has proved to be an effective strategy for providing a wide range of information to a trained user in a short period of time [19].

Researchers have investigated multi-sensory haptics to overcome limits in our perceptual ability to differentiate single-sensory haptic cues [20]. This limited perceptual ability, also called tactile masking, has been shown in single-sensory vibration cues to result in increased perceptual thresholds [10] or in difficulty with cue differentiation in location and time [21]. Tactile masking makes it more difficult for a user to perceive changes in haptic cues after sustained periods of haptic actuation.

While there are many advantages of multi-sensory devices over single-sensory devices, multi-sensory devices could also result in tactile masking. For example, when multiple mechanoreceptors are stimulated simultaneously, perceptual performance is degraded. Our lab has observed this perceptual degradation in prior work where a vibration, skin stretch, and squeeze device was used to train a participant to understand phonemes, or language building blocks, from simultaneous multi-sensory haptic cues. In this series of studies, Dunkleberger et al. and Sullivan et al. reported that participant errors in mapping haptic cue to phonemes were most prevalent for cues comprised of simultaneous skin stretch and squeeze cues [4], [20]. The confusion that occurred during the simultaneous actuation of skin stretch and squeeze has not been thoroughly studied and motivated this current work investigating perceptual performance with stretch and squeeze type haptic cues.

1.3 Contributions

In this paper, we quantify the discriminability, saliency, and perceptibility of skin stretch and squeeze cues when they are presented simultaneously to better inform the design of future multi-sensory haptic devices. In a preliminary psychophysical investigation of multi-sensory cues comprised of skin stretch and squeeze, we found that the just-noticeable differences of skin stretch and squeeze varied significantly when confounding masking cues were added as compared to the no-masking case [22]. This work, which we present in detail in Section 3.1, shows that there is an effect of masking on the perception of multi-sensory haptic cues. To further understand the effect of masking, we investigated two additional perceptual quantities: the absolute threshold of skin stretch and squeeze alone and in the presence of a masking cue and the points of subjective equality between skin stretch and squeeze. We report on these experiments in detail in Section 3.2 and in Section 3.3, respectively. We comment on the relationship between masking and the perception of skin stretch and squeeze cues based on the results of these experiments in Section 4.

2 Methods

To measure the effect of masking on perception, we investigated three perceptual quantities using the method of constant stimuli. The just-noticeable difference is the smallest change in stimulus magnitude that a person can sense. The absolute threshold is the smallest stimulus amplitude that a person can sense. The point of subjective equality is the amplitude of stimulus that feels indistinguishable from another type of stimulus. To measure these quantities with the method of constant stimuli, subjects are presented with and asked to compare sets of stimulus pairs consisting of a reference stimulus and a comparison stimulus. For the experiments we performed, two cutaneous haptic cues were used as stimuli: skin stretch and squeeze.

2.1 Participants

A total of 13 participants (6 female, 11 right-handed, 20-29, average age 23) took part in the just-noticeable difference experiment. A total of 13 participants (5 female, 11 right-handed, 19-27, average age 23) took part in the absolute threshold experiment. A total of 13 participants (3 female, 12 right-handed, 20-29, average age 24) took part in the subjective equality experiment. Participants in all experiments did not suffer any cognitive or motor impairment that would affect their ability to follow experimental procedure. All participants gave informed consent and all procedures and methods of the experimental protocol were approved by the Rice University Institutional Review Board (IRB-FY2019-49).

2.2 Experiment Design

We conducted three psychophysical experiments to quantify multi-sensory haptic perception of skin stretch and squeeze. During each experiment, the AIMS testbed, shown in Figure 1, was covered with an opaque cloth and participants wore noise-canceling headphones playing pink noise to isolate them from visual or auditory stimuli. Participants interacted with a text interface on a computer screen that provided them with information about their input and the trial number.

All conditions were presented in a randomly generated order to the participant in each experiment. In each condition, the selected seven comparison stimuli for each

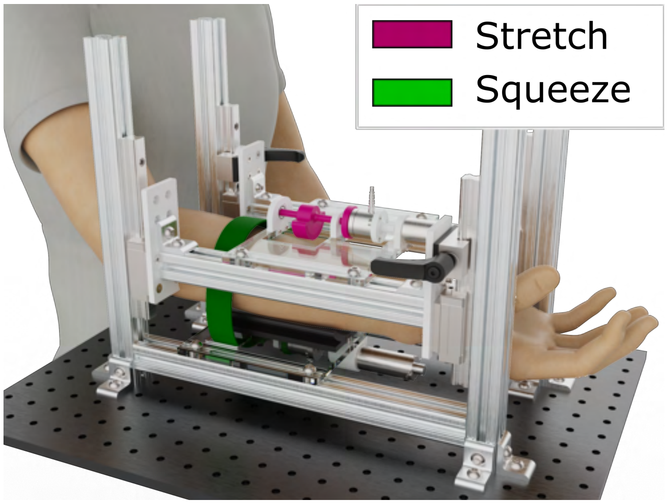


Fig. 1. The AIMS testbed was used to conduct psychophysical experiments. The user inserts their forearm into the device from the side with the squeeze band (in green), with their palm facing up such that the squeeze band tightens down on the proximal forearm. The skin stretch module (in magenta) on the upper platform of the device is adjustable and can be lowered onto the user's forearm. The squeeze module on the bottom of the device holds the armrest that the user rests their forearm upon and grounds the squeeze band which wraps around the user's forearm.

experiment as reported in Sections 2.2.1, 2.2.2, and 2.2.3 were each delivered 50 times to a participant for a total of 350 trials per condition. Extensive pilot testing was conducted to determine the best ranges for the seven comparison stimuli presented in each condition. To derive reasonable values from the psychometric curve, the range for the stimuli was chosen such that the smallest stimulus in the range was perceivable in less than 10% of trials and the largest stimulus was perceivable in more than 90% of the trials [23].

2.2.1 Just-Noticeable Difference

Wearable devices that deliver a variety of haptic cues are limited by human ability to perceive the difference between cues. By knowing the just-noticeable difference, or the minimum difference in cue amplitude to be perceptually distinct, a haptic designer can maximize the number of cues they can provide to a user. We saw the difficulty in making perceptually distinct skin stretch and squeeze cues in our lab's prior multi-sensory investigation as described in Section 1.2 [4]. Therefore we began with JND in our perception experiments.

The just-noticeable difference experiment tested four conditions: stretch stimuli alone, stretch stimuli with squeeze masking, squeeze stimuli alone, and squeeze stimuli with stretch masking. The reference stimulus for the squeeze condition was a squeeze stimulus in the middle of the squeeze comparison stimuli range, while the reference stimulus for the stretch conditions was a stretch stimulus in the middle of the stretch comparison stimuli range. These ranges for each condition are as follows:

- Stretch Stimuli alone: $13°$, $26°$, $39°$, $52°$, $65°$, $78°$, and $91°$ (degrees of stretch motor actuation)
  Corresponding to 3.87, 7.69, 11.41, 15.00, 18.36, 21.51, and 24.38 (mm of linear displacement)
- Stretch Stimuli with Squeeze Masking: $13°$, $26°$, $39°$, $52°$, $65°$, $78°$, and $91°$ (degrees of stretch motor actuation) masked by $52°$ (degrees of squeeze motor actuation)
  Corresponding to 3.87, 7.69, 11.41, 15.00, 18.36, 21.51, and 24.38 (mm of linear displacement) masked by 13.8 (mm of band displacement)
- Squeeze Stimuli alone: $13°$, $26°$, $39°$, $52°$, $65°$, $78°$, and $91°$ (degrees of squeeze motor actuation)
  Corresponding to 3.45, 6.90, 10.35, 13.80, 17.25, 20.70, and 24.15 (mm of band displacement)
- Squeeze Stimuli with Stretch Masking: $13°$, $26°$, $39°$, $52°$, $65°$, $78°$, and $91°$ (degrees of squeeze motor actuation) masked by $52°$ (degrees of stretch motor actuation)
  Corresponding to 3.45, 6.90, 10.35, 13.80, 17.25, 20.70, and 24.15 (mm of band displacement) masked by 15 (mm of linear displacement)

The just-noticeable difference experiment was performed over the course of two sessions separated by at least six hours and no more than 48 hours. In each trial the participant received a comparison cue and a reference cue in randomized order and then indicated if the first cue or the second cue seemed larger. The interstimulus interval in each trial was 1 second. Participants were forced to respond with either a 1 or a 2 to this question indicating the first cue or the second cue, before moving to the next trial. This subject response paradigm is called a two-alternative forced choice, or 2AFC, task and is fundamental to the the method of constant stimuli as described in Section 2. Each trial took 1 to 3 seconds and no subject took longer than 12 minutes to complete any condition. All participants completed each session, including experiment explanation time, post-experiment survey time, and a 5 minute break, in under one hour. Each participant completed 4 conditions of 350 trials each for a total of 1400 trials over two sessions.

2.2.2 Absolute Threshold

From our JND experiment we noticed that the detectability of cues seems to change with the addition of haptic masking, motivating our investigation into the absolute thresholds of skin stretch and squeeze. Here we investigated the 50% absolute threshold of these multi-sensory cues, which is a psychophysical measure of the detectability of a cue [23].

The absolute threshold experiment tested four conditions: stretch stimuli alone, stretch stimuli with squeeze masking, squeeze stimuli alone, and squeeze stimuli with stretch masking. Results from pilot testing indicated that masking had a large effect on absolute detection. As such, it was necessary to identify an appropriate range of stimulus intensities for each experimental condition. The minimum intensity was set to 0 degrees of actuation for each experimental condition, ensuring that these stimuli were perceivable in less than 10% of trials. The maximum value of stimulus intensity for each condition was selected based on pilot testing to ensure that it was perceivable in more than 90% of trials. The intermediate stimulus intensities chosen for each condition were equally spaced between 0 degrees of motor actuation and the maximum value of stimulus intensity. The stimulus intensity values presented for each experimental condition were as follows:

- Stretch Stimuli alone: $0°$, $0.1°$, $0.2°$, $0.3°$, $0.4°$, $0.5°$, and $0.6°$ (degrees of stretch motor actuation)
  Corresponding to 0, 0.03, 0.06, 0.09, 0.12, 0.15, and 0.18 (mm of linear displacement)
- Stretch Stimuli with Squeeze Masking: $0°$, $7°$, $14°$, $21°$, $28°$, $35°$, and $42°$ (degrees of stretch motor actuation) masked by $52°$ (degrees of squeeze motor actuation)
  Corresponding to 0, 2.09, 4.17, 6.23, 8.27, 10.28, and 12.25 (mm of linear displacement) masked by 13.8 (mm of band displacement)
- Squeeze Stimuli alone: $0°$, $0.5°$, $1°$, $1.5°$, $2°$, $2.5°$, and $3°$ (degrees of squeeze motor actuation)
  Corresponding to 0, 0.13, 0.27, 0.40, 0.53, 0.66, and 0.80 (mm of band displacement)
- Squeeze Stimuli with Stretch Masking: $0°$, $7°$, $14°$, $21°$, $28°$, $35°$, and $42°$ (degrees of squeeze motor actuation) masked by $52°$ (degrees of stretch motor actuation)
  Corresponding to 0, 1.86, 3.72, 5.57, 7.43, 9.29, and 11.15 (mm of band displacement) masked by 15 (mm of linear displacement)

In each trial, the participant received a single stimulus cue and then indicated if they could feel the cue. Participants were required to respond with either a yes or no to this question before moving to the next trial. This yes/no task took 1 to 3 seconds per trial and no subject took longer than 12 minutes to complete any condition. After completing two conditions, the participant was given a 5 minute break during which their arm was removed from the AIMS testbed. After the break, participants completed the last two conditions. Each participant completed four conditions of 350 trials each for a total of 1400 trials. All participants completed the entire experiment including experiment explanation time, post-experiment survey time, and a 5 minute break, in under one hour total.

2.2.3 Subjective Equality

Because skin stretch and squeeze are fundamentally different types of haptic cues, it would be useful to understand how the perceived intensities of each type of cue compare. Such analysis could be inform results from our masking experiments. To address this, we considered the point of subjective equality between skin stretch and squeeze cues as a possible method to compare the different amplitudes. The point of subjective equality has been investigated in prior single-sensory studies in haptics for vibration feedback. The researchers in these studies used psychophysical measures to determine lines of equal subjective magnitude as frequency and amplitude of vibration stimuli were manipulated [24], [25], [26]. These studies show the efficacy of measuring subjective equality to differentiate types of mechanical stimuli. Therefore, we similarly attempt to investigate the subjective equality between mechanical stimuli, specifically skin stretch and squeeze cues, to better interpret our results from our prior studies.

The subjective equality experiment tested two conditions: stretch stimuli to a squeeze reference and squeeze stimuli to a stretch reference. The intermediate steps chosen in each stimuli range in each condition were equally spaced from one another between the minimum and maximum stimuli chosen in each range. The squeeze reference was the middle of the squeeze stimuli range and the stretch reference was the middle of the stretch stimuli range. These ranges for each condition are as follows:

- Stretch Stimuli to Squeeze Reference: $1°$, $11°$, $21°$, $31°$, $41°$, $51°$, and $61°$ (degrees of stretch motor actuation)
  Corresponding to 0.30, 3.28, 6.23, 9.13, 11.97, 14.71, and 17.35 (mm of linear displacement)
- Squeeze Stimuli to Stretch Reference: $1°$, $11°$, $21°$, $31°$, $41°$, $51°$, and $61°$ (degrees of squeeze motor actuation)
  Corresponding to 0.27, 2.92, 5.57, 8.23, 10.88, 13.54, and 16.2 (mm of band displacement)

In each trial, the participant received a comparison cue and a reference cue in randomized order and then indicated if the first cue or the second cue seemed larger. The inter-stimulus interval in each trial was 500 ms. Participants were forced to respond with either a 1 or a 2 to this question indicating the first cue or the second cue, before moving to the next trial. This 2AFC task took 1 to 3 seconds per trial and subjects took no more than 12 minutes per condition. Each participant completed two conditions of 350 trials for a total of 700 trials. All participants completed the entire experiment, including experiment explanation time, post-experiment survey time, and a 5 minute break in under one hour, total.

2.3 Experimental Testbed

All experiments were performed on the AIMS testbed [27]. The AIMS testbed is a grounded, modular, and highly instrumented testing platform developed to robustly investigate the interactions between multi-sensory haptic cues. The AIMS testbed is capable of many configurations and is customized to a specific experiment. It is also grounded and equipped with force sensors to focus on the direct effect of multi-sensory haptic cues on perception. For perceptual experiments in this paper, the AIMS testbed was equipped with a skin stretch and a squeeze module (see Figure 1).

The skin stretch module is made up of a 3D-printed stretch rocker, an ATI Nano25 6-axis force and torque sensor, and a custom Maxon DCX22S DC motor (with a GPX22HP 83:1 planetary gearhead, maximum continuous torque of 1.21Nm and nominal voltage of 12V). The stretch rocker is a half cylinder with radius 15.4mm that has rubber attached to the outer radius of the material to create a full radius of 17.1mm. This rocker is attached in line with the force sensor and the motor to a platform on the upper tier of the AIMS testbed. This upper tier of the testbed is lowered onto the participant's forearm to between 0.4N and 0.5N of normal force on the skin. Once this normal force has been reached the upper tier of the testbed is locked manually. This maintains contact between the tactor of the stretch rocker and the participant's skin on the upper forearm to ensure that the tactile cues being delivered are solely of skin stretch and have no slip component. The motor is controlled by a Maxon Epos 4 controller at 2.5kHz which receives commands from a central computer at a rate of 1000Hz. A Quanser Q8 DAQ was used to measure motor position values at a rate of 1000Hz directly from the motor encoders in parallel with the Epos controller control loop.

The squeeze module is made up of a 3D-printed squeeze band barrel, a squeeze band, an ATI Nano25 force and torque sensor, and a custom Maxon DCX22S DC motor (with a GPX22HP 83:1 planetary gearhead, maximum continuous torque of 1.21Nm and nominal voltage of 12V). The squeeze barrel is a half cylinder of width 25mm and radius 15.2mm with a slit on the end to attach to the squeeze band. This squeeze band attaches to the squeeze barrel, wraps around the participant's forearm, and is anchored to a fixed acrylic piece on the other end. When the servomotor connected to the squeeze barrel is actuated, the band wraps around the barrel, in turn tightening the band around the participant's arm. The resulting action delivers normal and tangential forces to the skin in a manner similar to many squeezing devices currently reported in the literature [2], [15], [18]. The participant's forearm rests on a 3D-printed armrest to provide a comfortable place for their arm during experiments. The entire module is attached to the lower tier of the AIMS testbed and spaced relative to the stretch module such that the modules' points of contact with the skin are approximately 38mm from one another. Just like for the stretch module, the motor on the squeeze module is controlled by a Maxon Epos 4 controller. Motor positions were similarly measured by a Quanser Q8 DAQ directly from the motor encoders. The force and torque data for both modules are read directly by the central computer using a National Instruments PCIe DAQ Card at a rate of 1000Hz.

To achieve the various desired levels of skin stretch and squeeze, the motors in both modules are position-controlled to degrees of motor actuation. To allow for easier reproduction of results, experimental conditions are reported in terms of the linear displacement of the skin in the skin stretch module's case and in terms of the change in length of the squeeze band in the squeeze module's case.

3 Results

Perceptual thresholds for the haptic cues of skin stretch and squeeze were determined using the method of constant stimuli as described in Section 2. For each experiment, in each condition, we plot each subjects' response proportions against the condition stimuli to visualize the goodness of fit of the psychometric curves used to calculate the respective perceptual threshold. Although the squeeze and skin stretch modules were position-controlled in terms of degrees of motor actuation, to improve reproducibility, results are reported in terms of millimeters of expected skin displacement. The calculated perceptual thresholds for each experiment are plotted as bar graphs against the experiment's conditions. We report three types of perceptual thresholds: Just-noticeable difference (JND), absolute threshold, and point of subjective equality (PSE).

3.1 Just Noticeable Difference

We computed JNDs from psychometric curve fits on each subject's experimental data for each condition. Figure 3 shows the JNDs across all subjects for all conditions. The stretch conditions and the squeeze conditions were tested using a paired t-test to determine if masking had a statistically significant effect on the JND of skin stretch or of squeeze. The JND for the stretch stimuli alone condition ($\mathrm{M} = 4.20$ mm, $\mathrm{SD} = 1.90$ mm) showed a statistically significant difference compared to the stretch stimuli with squeeze masking condition ($\mathrm{M} = 6.29$ mm, $\mathrm{SD} = 2.63$ mm) as determined by a paired t-test; $t(12) = -4.79, p \leq 0.05$. The JND for the squeeze stimuli alone condition ($\mathrm{M} = 2.78$ mm, $\mathrm{SD} = 0.96$ mm) failed to show a statistically significant difference compared to that of the squeeze stimuli with stretch masking condition ($\mathrm{M} = 3.08$ mm, $\mathrm{SD} = 0.98$ mm); $t(12) = -1.65, p = 0.12$. The differences in variability between the positive and negative "Difference to Reference Cue" ranges indicate that the interference effect only occurs when the stretch comparison cue is smaller than the reference cue (negative "Difference to Reference Cue" region). In other words, squeeze interference has an asymmetric

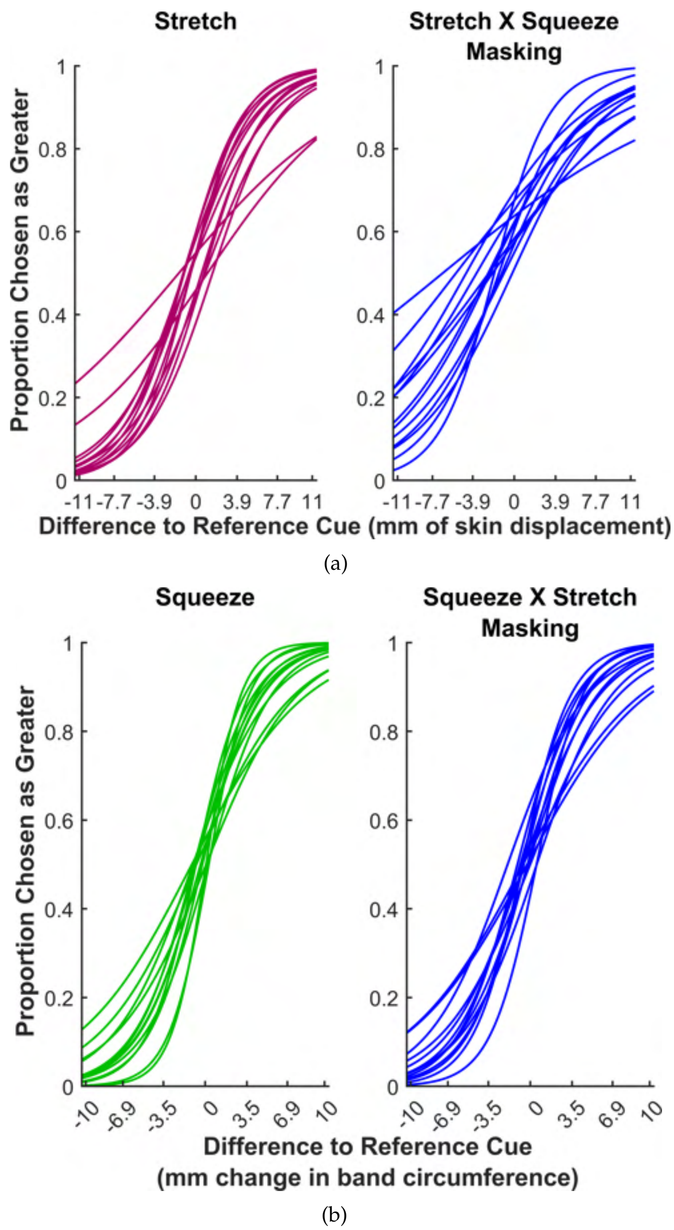


Fig. 2. The response proportion curves for each subject at each stimulus level in each condition for the just-noticeable difference experiment. (a) The response proportions for the stretch stimuli alone and the stretch stimuli with squeeze masking conditions. (b) Revised figure. The response proportions for the squeeze stimuli alone and the squeeze stimuli with stretch masking conditions.

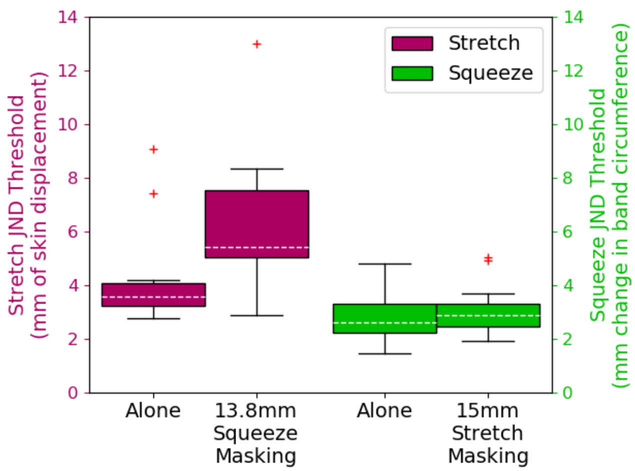


Fig. 3. Just-noticeable difference thresholds for the stretch conditions and squeeze conditions. (left) The stretch stimuli alone condition showed a statistically significant difference to the stretch stimuli with squeeze masking condition. (right) The squeeze stimuli alone condition did not show a statistically significant difference to the squeeze stimuli with stretch masking condition

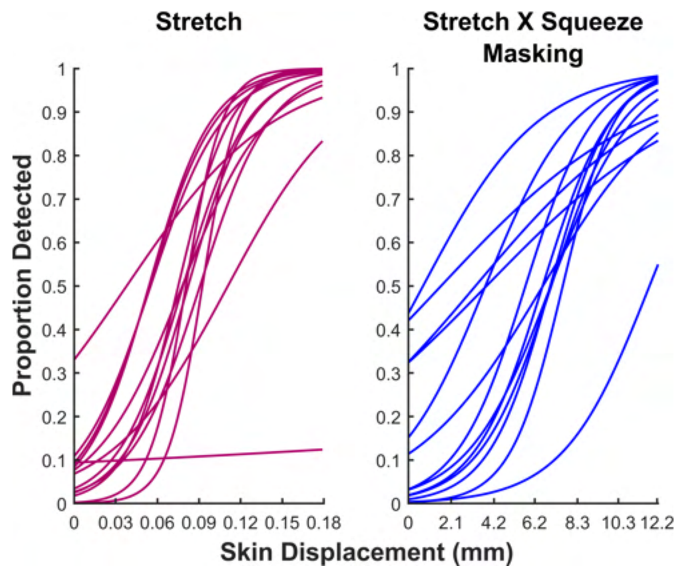
effect on stretch perception. A comprehensive quantitative analysis of the differences in variability is presented in Zook et al. [22].

Psychometric curve fits are presented in Figure 2 for each condition. In each condition, each participant's individual data was fit to a psychometric curve using the logit link function. From each fit psychometric curve, the just-noticeable difference threshold was calculated by finding the stimulus level that would correspond to a proportion chosen as greater of 0.5. These thresholds are shown in Figure 3. Outliers were defined as individuals whose JND was greater than 3 standard deviations beyond the condition mean. There were no outliers in this experiment.

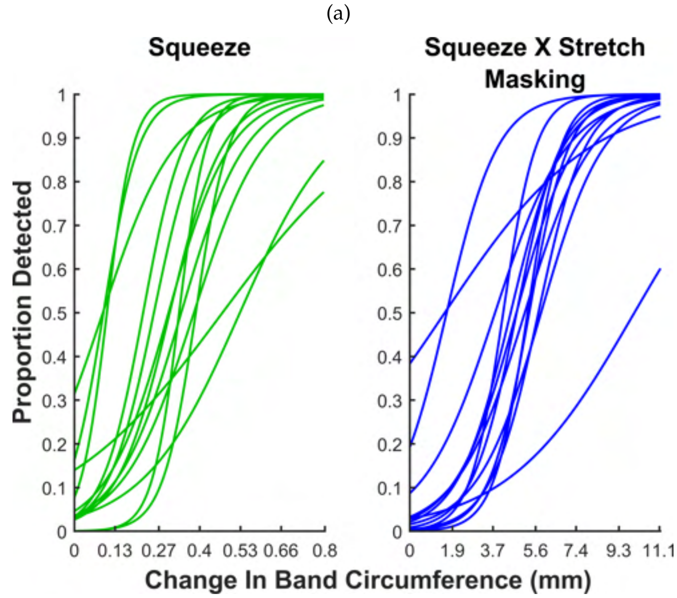
3.2 Absolute Threshold Analysis

A paired t-test was used to determine if masking had a statistically significant effect on the absolute threshold of the skin stretch or squeeze stimuli. The absolute threshold for the stretch stimuli alone condition (M $= 0.07$ mm, SD $= 0.2$ mm) showed a statistically significant difference compared to the absolute threshold for the stretch stimuli with squeeze masking condition (M $= 5.58$ mm, SD $= 2.80$ mm) as determined by a paired t-test; $t(12) = -8.03, p \leq 0.001$. The absolute threshold for the squeeze stimuli alone condition (M $= 0.29$ mm, SD $= 0.13$ mm) also showed a statistically significant difference compared to the absolute threshold for the squeeze stimuli with stretch masking condition (M $= 4.80$ mm, SD $= 1.99$ mm); $t(12) = -10.60, p \leq 0.001$.

Psychometric curve fits are presented in Figure 4 for each condition. In each condition, each participant's individual data was fit to a psychometric curve using the logit link function. From each fit psychometric curve, a single absolute threshold was calculated by finding the stimulus level that would correspond to a response proportion of 0.5. These thresholds are shown in Figure 5. Outliers were defined as individuals whose absolute threshold was greater than 3 standard deviations beyond the condition mean. There



(a)



(b)

Fig. 4. The response proportion curves for each subject at each stimulus level in each condition for the absolute threshold experiment. (a) The response proportions for the stretch stimuli alone and the stretch stimuli with squeeze masking conditions. (b) The response proportions for the squeeze stimuli alone and the squeeze stimuli with stretch masking conditions.

was only one absolute threshold outlier in the experiment in the stretch stimuli alone condition. This outlier is represented in Figure 5 as the red star above the stretch stimuli alone box. For the reported statistical analysis, the outlying absolute threshold was replaced with the stretch condition mean absolute threshold across the other subjects only. The reported mean, standard deviation, and t-test results were performed using this replacement. While there exists a statistically significant difference between the stretch and stretch with squeeze masking conditions regardless of whether this outlier is excluded, we chose to exclude the outlier so the reported stretch absolute threshold mean and standard deviation more accurately reflect that of the population.

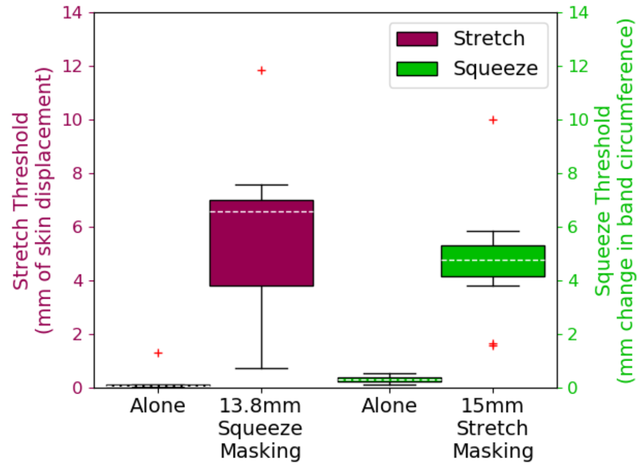


Fig. 5. Absolute thresholds for the stretch conditions and squeeze conditions. (left) The stretch stimuli alone condition showed a statistically significant difference to the stretch stimuli with squeeze masking condition. (right) The squeeze stimuli alone condition showed a statistically significant difference to the squeeze stimuli with stretch masking condition

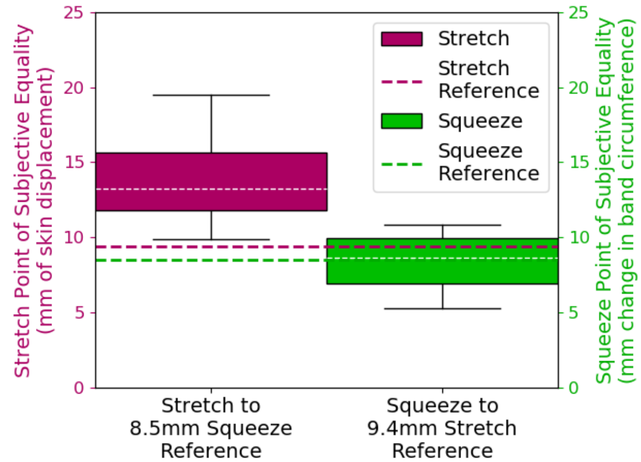


Fig. 7. Points of subjective equality for the stretch stimuli to squeeze reference condition and squeeze stimuli to stretch reference condition. The dotted lines represent the magnitude of the reference cue given for each respective condition. Note that although the scale of each axis is the same in magnitude, the PSE of stretch and the PSE of squeeze are in different units and are not directly comparable.

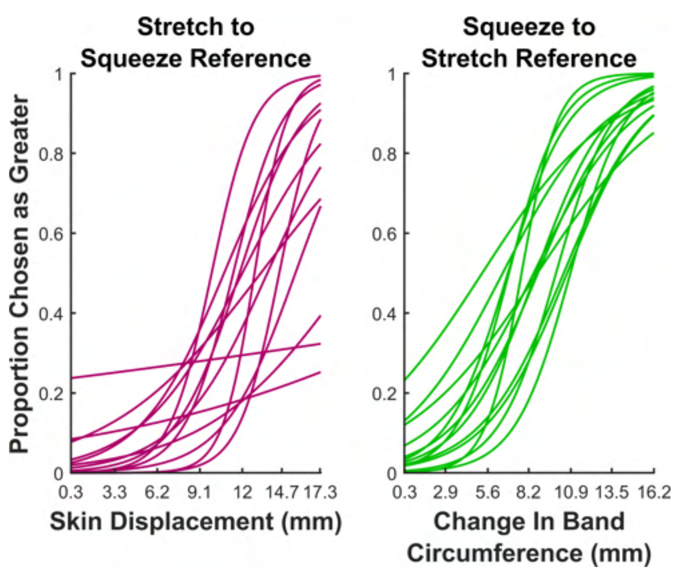


Fig. 6. The response proportion curves for each subject at each stimulus level in each condition for the subjective equality experiment. (left) The response proportions for the stretch stimuli to squeeze reference condition. (right) The response proportions for the squeeze stimuli to stretch reference condition.

3.3 Point of Subjective Equality

The derived points of subjective equality to compare the relative perceived intensities of skin stretch and squeeze for each condition are shown in Figure 7. The point of subjective equality for the stretch stimuli to squeeze reference condition had a mean of 17.20 mm and a standard deviation of 10.10 mm. The point of subjective equality for the squeeze stimuli to stretch reference condition had a mean of 8.46 mm, and a standard deviation of 1.67 mm.

Psychometric curve fits are presented in Figure 6 for each condition. In each condition, each participant's individual data was fit to a psychometric curve using the logit link function. Each participant's psychometric curve was then used to calculate a single point of subjective equality for that participant. As seen in the stretch to squeeze reference condition in Figure 6, the upper end of the psychometric curve has a large amount of subject variability. The upper end of this range would normally be increased in response to these results, as discussed in Section 2.2. However, the upper end of this range was limited by the maximum amount of skin stretch actuation we could deliver before the tactor began to slip.

4 Discussion

4.1 Just-Noticeable Difference

The JNDs for stretch stimuli alone, stretch stimuli with squeeze masking, squeeze stimuli alone, and squeeze stimuli with stretch masking indicate that there is a significant effect of squeeze masking on skin stretch JND. The significant effect of squeeze masking on skin stretch JND can be visualized in Figure 3 by the increase in skin stretch JND from the stretch stimuli to the stretch stimuli with squeeze masking conditions. Looking closely at the psychometric curves reveals that the effect of squeeze masking affects only the perception of small skin stretches. As shown in Figure 2a, the stretch stimuli with squeeze masking condition psychometric curve is consistent with a standard psychometric curve in the positive "Difference to Reference Cue" range but has much more variability in the negative "Difference to Reference Cue" range. In contrast, the stretch stimuli alone condition has a standard psychometric curve shape across the full "Difference to Reference Cue" range. The difference in the psychometric curves between these two conditions indicates that squeeze masking did have an effect on skin stretch JND. Further, because the effect of masking only changed the shape of the psychometric curve in the negative "Difference to Reference Cue" range, which corresponds to small comparison stretch cues in the experiment, the effect of masking predominately affects stretch for small skin stretch cues. For completeness, examining Figure 2b visually confirms that there is no change in the psychometric curve between conditions and therefore there is no change in the squeeze JND between the squeeze stimuli alone and the squeeze stimuli with stretch masking conditions. This difference in the effect of stretch masking and the effect of squeeze masking could be attributed to the difference in skin surface area covered by each haptic module. The squeeze band naturally covers a wider surface area on the skin than the rocker which may have influenced the perceived strengths of these respective masking cues [22].

4.2 Absolute Threshold

This experiment confirmed our hypothesis that having a masking cue increases a participant's absolute threshold. In both the stretch conditions and in the squeeze conditions, masking very clearly caused the participants' absolute thresholds to increase dramatically. It is interesting to note that in both masking conditions (stretch with squeeze masking and squeeze with stretch masking conditions), the standard deviation for the absolute threshold was much larger than the standard deviation in the stimuli alone cases. The increase in the standard deviation in the masking condition as compared to the stimuli alone cases indicates that there is variability in the way that masking affects participants' absolute thresholds.

In Section 3.1, we reported the just-noticeable difference of skin stretch and squeeze alone and in the presence of a masking cue [22]. In this just-noticeable difference experiment, we investigated how much a cue has to change in amplitude before a participant can perceive the difference. We discovered that squeeze masking had a statistically significant effect on the just-noticeable difference of skin stretch but that skin stretch masking did not have a statistically significant effect on the just-noticeable difference of squeeze. In our absolute threshold experiment, we found that masking caused a drastic increase in the absolute threshold for both skin stretch and squeeze.

4.3 Point of Subjective Equality

The point of subjective equality experiment was performed to better compare the relative perceived intensities of skin stretch and squeeze stimuli. When skin stretch stimuli were compared to a squeeze reference, we found that participants exhibited a large amount of variability in identifying which stretch cue felt similar in amplitude to the squeeze reference cue. In addition, participants perceived the largest stimuli (nearly 17 mm of linear stretch displacement) in the stretch range to feel similar to the squeeze reference (8.5 mm of squeeze band displacement). When squeeze stimuli were compared to a stretch reference, we found that participants were much more consistent in saying that the squeeze stimuli in the center of the stimuli range (approximately 8.2 mm of squeeze band displacement) felt similar to the stretch reference (9.4 mm of linear stretch displacement).

We expected a linear relationship between the perceived amplitudes of skin stretch and squeeze cues, such that the ratio between stretch cue amplitude and squeeze cue amplitude would be approximately the same regardless of condition. However, in the stretch stimuli to squeeze reference condition, the ratio was approximately 2:1 stretch cue amplitude to squeeze cue amplitude. In contrast, in the squeeze stimuli to stretch reference condition, the ratio was approximately 1.15:1 stretch cue amplitude to squeeze cue amplitude. The results of the point of subjective equality experiment suggest a one-way relationship in the perception of skin stretch and squeeze cues, such that participants have different perceived magnitudes of skin stretch and squeeze depending on which cue is the reference to which the other cue is being compared. These results make it difficult to compare perceptual magnitudes between conditions in our JND and absolute threshold experiments. Further investigation is necessary to better understand how the perceived intensities of squeeze and stretch cues compare.

4.4 Effects of Stretch and Squeeze Masking

There is a discrepancy between the effect of masking on just-noticeable difference and the effect of masking on absolute threshold. When small amounts of squeeze were applied to the participant's arm (in the absolute detection experiments), skin stretch masked detection of the squeeze cue, while skin stretch did not seem to detract from the participant's ability to discriminate between two squeeze cues. Conversely, squeeze cues clearly have a masking effect on both the detection of small amounts of skin stretch and on the ability of the participant to discriminate between two stretch cues of different magnitudes. Our subjective equality experiments failed to produce a clear understanding of the relative perceived intensity of these two types of haptic stimuli. As such, our results don't provide specific insight into why this discrepancy exists. One possibility is that the larger contact area between the squeeze band and the skin compared to the rocker and the skin plays a role. Alternatively, the single actuator band-tightening mechanism used to generate squeeze can result in small amounts of skin stretch, which may explain our results. Additional experiments are warranted to explore the interplay between these haptic stimuli.

4.5 Implications for Device Design

The results reported in the just noticeable difference and absolute threshold experiments have important implications for the design of multi-sensory devices. If a device is being designed to deliver information when a participant detects the presence of a cue (e.g. a squeeze cue is delivered to notify the user of a received text message), then multi-sensory masking drastically changes perception and designers must correspondingly design their haptic cues to account for this change in perceivability. On the other hand, if a device is designed to deliver information when a participant detects a difference between a series of cues (e.g. a squeeze cue is delivered once and then once more at a higher amplitude to notify the user of a received text message), then the effects of multi-sensory masking are less significant.

These conclusions are relevant to wearable haptic devices using rocker- or wheel-based stretch actuation, and for devices that employ single actuator squeeze, two commonly used tactile cues in wearables. Devices that generate skin stretch through twisting or through linear actuation to achieve stretch would not necessarily be susceptible to masking by squeeze cues like we observed in these studies with rocker-based stretch cues. Further investigation is needed to determine the specific effect of masking on the perceptual thresholds presented in this study for other variations and multi-sensory combinations of skin stretch and squeeze.

5 Conclusion

The purpose of this paper was to report on the effect of masking on the perception of skin stretch and squeeze cues. Three experiments were conducted to measure the just-noticeable difference, absolute threshold, and point of subjective equality of skin stretch and squeeze cues. The AIMS haptic testbed, capable of transmitting skin stretch and squeeze cues simultaneously, was developed and used to robustly administer each of these experiments. Results from the just-noticeable difference experiment indicated that squeeze masking significantly affects the perception of skin stretch cues when the skin stretch cues are small. These results also indicated that there is a significant effect of masking on the absolute threshold of both skin stretch and squeeze. Comparing our absolute threshold results to the JND findings suggests that there exists a reference cue magnitude at which masking no longer significantly affects the perceptual threshold. To enable more direct comparison of these results between experiments and between conditions, we performed a point of subjective equality experiment. While the points of subjective equality relating skin stretch and squeeze do not seem to be linearly related, the results from the point of subjective equality experiment were ultimately inconclusive and further investigation is required to determine the exact perceptual relationship between the stretch and squeeze cues. These results clearly show there exist significant differences in the way different haptic cue types interact with our perception when displayed alone and when they are delivered simultaneously. Due to these differences, we suggest that designers consider the importance of detectability and distinguishability in their desired multi-sensory devices to minimize the negative effects of masking that will inevitably occur.

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