Effects of Interfering Cue Separation Distance and Amplitude on the Haptic Detection of Skin Stretch

Andrew K. Low, Zane A. Zook, Joshua J. Fleck, and Marcia K. O'Malley

***Abstract*—Multi-sensory haptic cues, which contain several types of tactile stimuli that are presented concurrently to the user, have been shown to be useful for conveying information-rich cues. One limitation of multi-sensory cues is that user perception of individual cue components can be hindered by more salient components of the composite cue. In this article, we investigate how amplitude and distance between cues affect the perception of multi-sensory haptic cues. Specifically, participants' absolute threshold perception of stretch cues was measured in the presence of interfering squeeze cues using a modular testbed. We evaluated ten conditions of varying interference amplitude and distance between cues. We found that interference cue amplitude and distance between cues both have a statistically significant effect on the absolute perception of stretch cues. As interference cue amplitude increases, and as distance between cues decreases, absolute perception of stretch cues worsens. These results inform design considerations for future wearable multi-sensory haptic devices, so that cue salience can be maximized and interference effects minimized.**

***Index Terms*—Multi-sensory haptics, psychophysics, haptic perception, cutaneous haptics.**

I. Introduction

Wearable haptic devices are attached to the body and interact with a user through the sense of touch. Such devices allow users to receive feedback from the device or additional information without diverting their attention away from the primary task. These devices tend to be portable and easily worn without affecting the performance of every day tasks, or limiting range of motion of the limbs on which they are worn. These devices are especially useful in applications such as enhancing virtual reality (VR) experiences [1], interaction and engagement in rehabilitation settings [2], and motion feedback and sensing [3].

Wearable haptic devices commonly convey tactile cues such as skin stretch, squeeze, and vibration. Stretch cues can be produced via on-skin linear [4], [5] and rotational [6], [7] mechanisms, as well as perpendicular rocker systems [8], [9] that press and translate on the skin without slipping. Squeeze cues are typically created using a band that tightens around the arm, exerting a radial force on the arm [6], [10], [11]. Vibration cues are generated in many ways, including through embedded voice coils, linear resonant actuators, and rotary electromagnetic actuators [12]. Haptic devices typically convey only a single form of haptic feedback, often one of these three types of cutaneous cues. However, it is possible to design devices that are able to convey a wider variety of cues to the user by combining two or more types of these cutaneous cues concurrently [1], [13]. Such concurrent cues also improve perception accuracy over single-sensory cues in transmitting the same quantity of information [13].

These simultaneous cues take advantage of the multiple types of mechanoreceptors that are found in the skin. Mechanoreceptors are cells specialized in detecting vibration, stretch, and other haptic stimuli [14]. They allow humans to receive a variety of stimuli and distinguish between cues of varying types. Cues that can elicit the response of different kinds of mechanoreceptors are defined as multi-sensory cues [15]. By leveraging the sensitivity and specificity of these receptors, haptic devices can produce simultaneous, multi-sensory cues that convey a wider range of information to users than can be achieved with single modality devices such as vibrotactor arrays. Because of these advantages, wearable haptic devices increasingly incorporate combinations of cues, such as skin stretch, squeeze, and vibration, to convey complex information to the user [10], [11], [13], [16], [17].

Multi-sensory haptic devices display cues concurrently and often in close proximity to each other. This approach increases the chance of degraded perceptual performance, such as one cue masking another, reducing perceptual thresholds. Prior work observed a high incidence of cue confusion in cases of simultaneous, adjacent cues conveyed with a multi-sensory haptic device, particularly when identifying cues that combined stretch and squeeze actuation modalities [13], [18]. This interference effect was subsequently investigated with a grounded haptic device [19], and results showed a significant interference effect between skin stretch and squeeze cues on the forearm. The perception of skin stretch cues was affected by squeeze cue interference, while the perception of squeeze cues was not affected by stretch cue interference. While this prior work identified the *existence* of perceptual interference between these types of cues, the influence of cue proximity and magnitude on perceptual interference has not been studied.

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The authors are with the Department of Mechanical Engineering, Rice University, Houston, TX 77005 USA (e-mail: andrew.low@stanford.edu; gadzooks@rice.edu; jjf8@rice.edu; omalleym@rice.edu).

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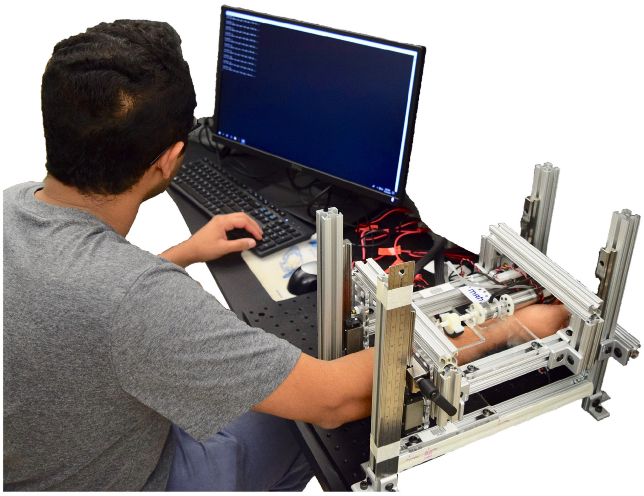

Fig. 1. Experimental setup. In this experiment, participants placed arm in the experimental AIMS testbed, and haptic test cues were applied. The participant answers prompts on the computer monitor regarding detectability of multi-sensory haptic cues delivered to the forearm via the AIMS Testbed. During experimentation, the participant's view of the setup was blocked and the participant wore headphones to isolate them from auditory stimuli.

In this paper, we investigate how the proximity and amplitude of a concurrent interfering cue in a multi-sensory haptic system affects perception of a primary cue conveyed to a user's forearm (see Fig. 1). We choose to focus on the forearm since many wearable haptic devices have been designed for wearability on the distal upper limb, and a deeper understanding of the perception of such cues displayed on the forearm can inform the design of future devices. The detectability of these cues is quantified using a 50% absolute threshold, a measure in psychophysics that determines the level at which a subject can detect a stimulus only 50% of the time [20]. The absolute threshold measure has been used in haptics to measure the detectability of small haptic cues [21] and multi-finger haptic interaction [22]. Multi-sensory cues have been previously analyzed via the same testbed system, where just-noticeable differences [19], which determine the minimum difference in cue magnitude needed to perceive difference, rather than detection thresholds, were studied. This paper presents a comparison between the perception of stretch cues for varying amplitudes of interfering squeeze cues (including a no-interference condition) and for varying separation distances between the primary and interfering cues.

II. Method

A. Participants

Fourteen participants were involved in this study, ranging in age from 19 to 25 (average age 20.9, 2 left handed participants, 6 male), all without any physical or medical conditions that could affect arm haptic perception. The participants gave verbal and written consent to participate in this experiment, and all testing procedures were approved prior to experimentation by the Rice University Institutional Review Board (IRB-FY2019-49).

B. Experimental Setup

All experiments were conducted using the Adjustable Instrumented Multisensory (AIMS) Testbed [23], shown in Fig. 1. This system is designed to provide multi-sensory haptic cues to multiple sites on the arm simultaneously with a high degree of accuracy and repeatability. This consistency in cue presentation is difficult to accomplish using on-body devices due to issues of grounding and reliability in positioning.

The testbed consists of a modular frame into which a subject's forearm is inserted, and through which instrumented haptic modules can be inserted to apply controlled stimuli to the subject's arm. In this experiment, squeeze and stretch modules were used [23]. The squeeze module accomplishes a radial squeeze effect on the upper forearm via an adjustable strap mechanism, while the stretch module deforms the skin laterally across the arm via a rocker. Both modules are driven by Maxon DCX22S motors and position-controlled via a Maxon EPOS4 Controller Module. Each motor module is instrumented with a ATI Nano-25 force-torque sensor in line with the primary actuation mechanism to ensure consistency in cue delivery. Force and torque data were collected from these sensors to compare applied forces and monitor for the occurrence of slip in the stretch condition.

In this experiment, the squeeze module was fixed in position on the bottom tier of the testbed, while the stretch module was placed in one of three different positions on the upper tier of the testbed to provide variation in cue separation distance. Both modules were actuated in the counterclockwise direction, with the stretch module deforming the skin laterally to the right and the squeeze module exerting a force radially onto the forearm.

C. Haptic Cue Conditions

Participants' absolute threshold perception of stretch cues was evaluated under the effect of two factors: interference cue amplitude and cue separation distance. The primary cue that participants were asked to detect was a stretch cue created by the rocker on the stretch module, while the interference cue was a squeeze cue created by a strap mechanism on the squeeze module. The absolute threshold was measured using the method of constant stimuli [20]. In this method, a participant is presented with a set of primary cues varying in amplitude along with a constant interference cue and asked whether or not they can detect the primary cue. From these results, a subject's absolute threshold response can be determined as the primary cue amplitude at which the participant can detect the stimulus 50% of the time. The method of constant stimuli was chosen among other viable methods of measurement in the interest of experimentation time for participants.

A total of ten conditions involving interfering squeeze amplitude and cue separation distance were tested (see Fig. 2); these conditions included three different levels each for interference amplitude (low: 6.9 mm, medium: 13.8 mm, and high: 20.7 mm) and cue separation distance (close: 63.5 mm, middle: 80.0 mm, and far: 96.5 mm), and a no-interference, stretch-only condition to have a baseline performance for

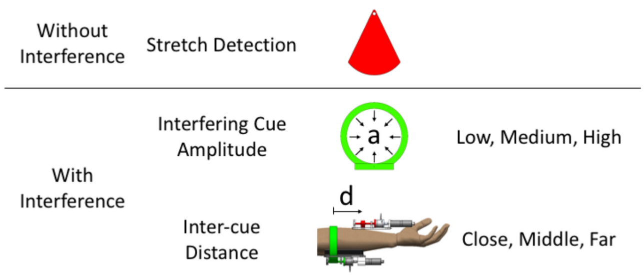

Fig. 2. Matrix of ten conditions (one no interference condition and nine interference conditions) tested for the experiment. The interference amplitude had three settings: low (a = 6.9 mm), medium (a = 13.8 mm), and high (a = 20.7 mm). Similarly, the inter-cue distance also had three settings: close (d = 63.5 mm), middle (d = 80.0 mm), and far (d = 96.5 mm). Combined, these levels combined produced the nine interference conditions tested.

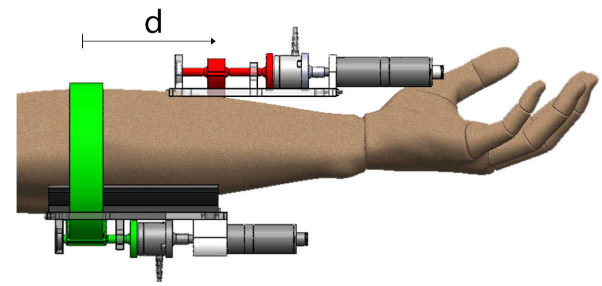

Fig. 3. 3D CAD Model of the stretch and squeeze modules used in this work. Absolute thresholds for the squeeze cue were investigated in the presence of interfering squeeze cues that varied in amplitude and distance from the stretch cue. The distance *d* represents the distance between the two cues applied.

comparison. In the no-interference condition, the squeeze module was still in place with the skin but was not used, and both modules were positioned at the close distance setting.

Stretch and squeeze cues were generated by controlling the angular position of each motor. The amount of stretch is reported as the linear displacement of the skin (in millimeters) based on the angle of rotation and radius of the rocker. The amount of squeeze is reported as the change in circumference of the squeeze band that encircles the forearm. The middle level of interference cue amplitude was chosen based on previous work by Zook *et al.* in multi-sensory cue perception testing [19]. The other interference cue amplitudes were determined by evenly spacing between high interference and no-interference, for three levels of interference and one no-interference condition. The minimum and maximum values of separation distance were constrained by the configuration of the stretch and squeeze modules within the AIMS testbed. The maximum cue separation distance was determined by the largest distance possible on the forearm that could still deliver cues. The minimum cue separation distance was established by the minimum distance of separation of the stretch module from the squeeze module on the AIMS Testbed, and the middle distance was the average of the maximum and minimum distance.

Seven stretch cues were presented to participants for each test condition, ranging from no stretch cue (displacement of 0 mm) to a stretch cue that could be detected every time. In order to have a meaningful analysis, the range of stretch cues tested had to be well-bounded to generate an accurate measure of the absolute threshold perception. To do this, the upper bound for the stretch cue range in each interference condition (including the no-interference condition) was determined through extensive pilot testing to fit a psychometric curve. As stretch cues were being compared to stretch cues only, it was acceptable to have different stretch cue ranges for each interference condition. The maximum stretch cue for each conditions was: 0.2 mm for the stretch only condition, 8.8 mm for all low interfering squeeze conditions, 12.2 mm for all medium interfering squeeze conditions, and 15.5 mm for all high interfering squeeze conditions. The test stimuli were equally spaced between the lower and upper bound cue values, inclusive.

D. Procedure

Each condition consisted of 50 presentations of each of the seven stretch cues, for a total of 350 trials per block, with cues presented to the participant in a randomized order. All condition blocks were also presented in a random order, counterbalanced to reduce learning effects. Given the length of the experiment, the blocks were grouped into three different sessions to minimize fatigue and boredom and to keep sessions to approximately 60 minutes each. The distribution of conditions was assigned randomly across the three testing sessions, with the first and second sessions consisting of three conditions each, and the third session consisting of four conditions. Each testing session was separated by a minimum of 12 hours and a maximum of 36 hours.

At the beginning of testing for each condition, participants placed their right forearm into the AIMS Testbed (see Fig. 1). A Velcro strap was wrapped around the arm, and the stretch module on the upper tier of the testbed was depressed $5\ mm$ into the arm in order for subjects to feel the squeeze and stretch cues, respectively. This action also secured the subject's arm in the testbed and ensured good contact with the two haptic modules (see Fig. 3 for positioning of modules on the forearm). A cover was placed taut over the testbed and participants wore noise-cancelling headphones playing pink noise in order to isolate them from visual and auditory distractions. Participants used a keyboard to interact with a text interface on a computer screen that informed them of which condition they were in just before they started each condition. Participants were instructed to focus on the stretch cue for every condition tested, and to press '1' on the keyboard only if they felt a distinct stretch cue or '2' if they did not. A mandatory training period was conducted prior to starting the experiment. In this period participants were presented with multiple (no more than 10) high squeeze interference amplitude and maximum stretch cues value for that condition (15.5 mm displacement), to give participants an understanding of what they should be detecting during each condition. Training cues were provided until participants acknowledged what was to be detected during each condition; no participant received more than 10 training cues. When the session started, the participant received one haptic cue from the testbed, consisting of one stretch and interfering squeeze cue produced at the same time (or only

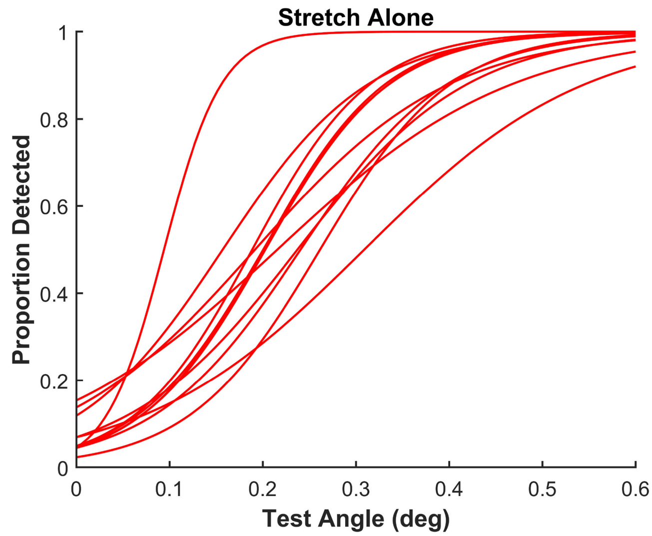

Fig. 4. Example of psychometric summary curve for all participants based on response proportions. The bold line shows the curve created based on the average of all participant response proportions, the shaded area represents the range of values from this average within one standard deviation, and the points show all participants' actual response proportions at each of the seven stretch cues tested for the stretch-only condition.

one stretch cue for the stretch only condition). The initiation of actuation of both stimuli occurred at the same time; however, the stimulus durations were different as cues were position controlled. Participants indicated whether the stretch cue was detected by entering his or her choice on the keyboard ('1' or '2'), after which the testbed would produce the next haptic cue. This continued for 350 cues, at which point the participant completed the condition and was given a mandatory five minute break.

E. Data Analysis

The data collected included participant responses to each cue presentation and the motor position and torque produced by both the squeeze and stretch motors. For each condition, participants' responses were used to calculate the response proportion for each stretch cue amplitude. These response proportions, calculated as the proportion of times the participant said he or she could detect the stretch cue for each stretch cue amplitude, are then plotted and fit to a psychometric (or sigmoid) curve. The psychometric curves were fitted for every condition and each participant, and curves were generated for each condition averaging across all participants. An example of this is shown in Fig 4, which shows the psychometric curve generated for the stretch-only condition for all participants. A scatter plot of the response proportion for each participant for this condition is superimposed onto the curve. Response proportions were used to determine the absolute threshold for each condition via the method of constant stimuli. The stretch cues for each condition were presented in varying amplitude both above and below the threshold, and in a random order. Using the response proportions from each participant, the absolute threshold can be determined as the cue amplitude at which the stretch cue can be detected 50% of the time.

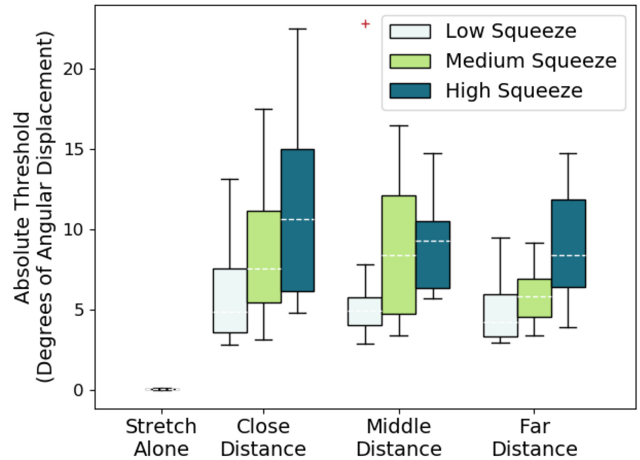

Fig. 5. Average detection threshold angle of rocker actuation for all interference and distance conditions, except the stretch only condition. Error bars represent the standard error of the mean. The stretch only (no-interference) condition is also shown on the graph for comparison, in the Close Distance section .

Data for two of the fourteen subjects were omitted as outliers from the analysis, as the values from these subjects were the only ones that showed to be more than three standard deviations away from the mean. These subjects were found to have not followed experimental instructions accordingly. All presented results are for the remaining 12 subjects.

III. Results

A. Absolute Threshold Analysis

From the collected data, we calculated the mean absolute threshold skin stretch rocker angle for each condition. Psychometric curves with the test angle on the x-axis and detection proportion on the y-axis were drawn for all ten conditions to determine the absolute threshold proportion of 0.5. The curves for one of these conditions are shown in Figure 4. Figure 5 shows mean absolute thresholds compiled across all nine interference conditions, with error bars indicating the standard error of the mean.

The absolute threshold perception for the no-interference condition was 0.026 mm of linear displacement, and the standard error was 0.0024. In contrast, absolute stretch detection thresholds in the presence of an interfering squeeze cue were noticeably larger (linear displacements of 1.8 mm, 2.7 mm, and 3.5 mm for low, medium, and high squeeze amplitude at close distance, respectively). Results of the repeated measures ANOVA indicated that the presence of an interference cue had a statistically significant effect on the absolute threshold of detection of the stretch cue ($F(1.3, 14.5) = 13.3, p < 0.005$ with the Huynh-Feldt correction). Similarly, distance between cues had a statistically significant effect on the absolute threshold of stretch cue detection ($F(2, 22) = 5.3, p < 0.05$). The interaction between distance and amplitude of the interference cue was not statistically significant ($F(3.3, 36.4) = 1.6$, $p = 0.21$ with the Huynh-Feldt correction).

When conditions of the same distance level are compared, it is observed that the absolute threshold increases as the interference levels increase (from low to medium and from medium to high). Similarly, when conditions of the same interference amplitude level are compared, the absolute threshold decreases as distance levels increase (from close to middle and from middle to far). The mean absolute threshold increases significantly from the no interference condition to any of the interference conditions, but the increase in the threshold between the low, medium, and high amplitude interference conditions at a constant distance level is not constant. Similarly, the decrease in threshold between the close, middle, and far distances at the same interference amplitude level is varied.

Data on the force and torque exerted by the motors providing the squeeze and stretch cues were examined to ensure there was no slipping in any of the conditions. These data showed that as the desired position increased, force and torque applied increased. The maximum z-axis torque applied by the squeeze cue motor ranged from 0.2 to 0.3 Nm across conditions, and the maximum z-axis torque applied by the stretch cue motor ranged from 0.02 to 0.04 Nm across conditions.

IV. Discussion

A. *Effect of Varying Squeeze Amplitude on Stretch Detection*

The magnitude of squeeze interference affects the subject's ability to feel stretch cues, as evidenced by the statistically significant differences in detection thresholds, most notable when the interfering cue is in close proximity to the stretch cue. When the mean absolute threshold for the low, medium, and high interference amplitude conditions are compared, it is observed that these means increase with increasing interference amplitude. For example, in the close distance condition, the absolute threshold means for the low, medium, and high squeeze interference were 1.8 mm, 2.7 mm, and 3.5 mm, respectively. The results show an increase in stretch cue absolute detection thresholds, indicating that participants show more difficulty in detecting stretch cues due to increasing squeeze cue interference. Here we observe a masking effect - the squeeze cue obscures, or "masks," the perception of the stretch cue. This masking effect is likely due in part to cue propagation – when the skin is subject to greater amplitudes of interference stimulus (in this case, a squeeze cue), a wider area of mechanoreceptors on the skin is affected. Further, our stretch actuation mechanism relies on tightening of a band around the arm, and this action applies both a tangential force as well as a normal force to the skin. If the interference stimulus is strong enough, it will affect the area of mechanoreceptors to which the stretch cue is applied, interfering with the tactile sensation of the stretch cue [24]. As such, a greater amplitude stretch cue may be required. These observations could also explain our prior findings where squeeze cue perception was not affected by interfering stretch cues, but stretch cue perception *was* affected by interfering squeeze cues. It could be that the perceived strength of the squeeze cue is greater than that of the stretch cue because of the increased contact area between the strap and skin compared to the rocker and skin, and because of the skin stretch that is induced during squeeze by the band tightening mechanism. Future experiments could explore lower levels of squeeze amplitude interference to determine if there is a level of squeeze that is perceivable but does not interfere with the perception of the primary stretch cue. Other mechanisms for the squeeze actuation could also be explored. For example, Tasbi uses a band tightening mechanism that results in very low tangential forces applied to the skin relative to the normal forces that are generated [1]; however, this is a particularly expensive mechanism to fabricate.

B. *Effect of Varying Separation Distance on Stretch Detection*

Our experimental findings show that as the distance between primary and interfering haptic cues increases, detection of the primary cue improves. In comparing the absolute threshold values between the close and far distance conditions, we observe a 0.34 mm decrease in threshold value for the low squeeze amplitude condition, a 0.85 mm decrease for the medium squeeze amplitude condition, and a 0.80 mm decrease for the high squeeze amplitude condition. The increased separation between the cues likely allows for a greater dissipating effect by the skin, inhibiting cue propagation.

The discrepancy in the effect of these two factors may have been affected by the range of distances tested in this experiment. The difference between the closest and furthest configuration of the stretch and squeeze cues was 33.0 mm, and a greater cue distance may have greater effects on absolute threshold values.

C. *Effect of Cue Type on Perception*

This experiment used skin stretch actuation as the primary cue and squeeze actuation as the interfering cue. Zook *et al.* previously reported that the just-noticeable difference (JND) for a stretch cue increased with an interfering squeeze cue, but that the JND for the squeeze cue did not change for an interfering stretch cue [19]. Though not investigated in this study, it is possible that interfering cue amplitude and separate distance would have a similar effect on the perception of other primary cues for combinations of haptic cues different from what we studied here. Examining human perception using different cue types commonly found in haptic devices would be worthwhile in determining the optimal cue type pairing for the perception of multi-sensory cues. For example, the AIMS testbed [23] could be equipped with other haptic modules such as twist or vibration, allowing for additional experiments aimed at evaluating cue separation distance and amplitude effects on perception with such modules. Studies such as these will help to inform the development of future wearable haptic devices to ensure cue salience and reliable perception of multi-sensory cues.

D. *Effects of Cue Location on Perception*

This experiment was conducted on the ventral side of the forearm, which contains the most sensitive skin on the arm besides the hands and cubital fossa (transition area between forearm and back arm) [25]. Perception of cutaneous cues is known to vary widely based on the stimulus location [26]. Future work should address how interfering cue amplitude and separation distance affect perception of the primary cue for other areas of the body.

V. Conclusion

In this study, we investigated the effects of varying squeeze interference amplitude and distance between squeeze and stretch cues on the absolute detection of stretch cues applied to the arm. Using the AIMS Testbed, participants were each tested on ten different conditions of varying interference cue amplitudes and cue separation distances, including one no interference condition. Results indicate that cue interference amplitude and separation distance each have a statistically significant effect on primary cue perception. As cue interference amplitude increases, the absolute threshold perception of the primary cue increases. When cue separation distance increases, the absolute threshold perception of the primary cue decreases. These results have significance in the design and development of haptic devices. As researchers seek to implement multi-sensory haptic cues into devices, it becomes essential that concurrent cues are perceptible to users. The experiments conducted in this paper will inform how user perception is affected by cue separation and interfering cue amplitude. This work also prompts further investigation into the perception of multi-sensory cues. Future research directions include exploring the effect of cue interference amplitude and cue separation distance with different cue types and cue positions on the upper body.

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