Evaluating factors affecting the perception of multi-sensory vibration and skin-squeeze cues during voluntary movement.

Zachary Logan, Quinn Deitrick and Katie Fitzsimons

***Abstract*—Haptic wearables are capable of increasing realism in VR/AR, enabling an additional stream of information in robotic teleoperation, and augmenting feedback for motor learning. However, it is not clear how the perceptual capacity of end-users may be affected by real-world scenarios. Specifically, we hypothesized that perception of multi-sensory cues would be less accurate when the cues were presented during voluntary movement as opposed to cues presented at rest. We also believed that differences in haptic perception might be overcome with data-driven models of user perception. In this study, participants respond to a multi-sensory haptic cue indicating the direction and speed with vibration and skin squeeze, respectively. The accuracy of this response was evaluated at rest and during voluntary motion. The experimental results demonstrate that voluntary motion does not have a significant impact on the perception accuracy of haptic cues. Perception models were fit to the participant responses and compared using absolute decoding error. The results of the model analysis shows that data-driven models could be used to provide improved haptic feedback across users.**

I. Introduction

Vibrotactile feedback is one of the most common forms of haptic feedback and is becoming increasingly common in consumer electronics, where it can significantly enhance user experiences with a handful of haptic symbols communicating basic information [1]. Vibrotactile feedback can be used for more complex information such as the force and direction of a collision [2], navigation data for obstacle avoidance on a powered wheelchair [3], and the target direction of a 3D goal point [4]. The complexity in these haptic signals is limited by the user's ability to perceive and correctly interpret subtle differences in spatial and temporal patterns of vibration [5]; therefore limiting the effectiveness of haptic displays in facilitating feedback between humans and autonomous agents in virtual reality, teleportation, or collaborative tasks. One way to increase the information transfer of tactile displays is by adding other sensory modalities, such as skin-squeeze and skin-stretch—increasing the number of distinct cues. Several groups have developed multi-sensory devices that, through the addition of actuators rendering various tactile stimuli, are capable of presenting a higher number of symbols at a higher rate than haptic displays based on vibrotactile stimuli alone [6]–[8]. Haptic devices that combine vibration with skin-squeeze or skin-stretch have been used to support the teleoperation of multiple flying devices [8], and gamified physical therapy regimens [9]—where the user must perceive intrinsic tactile stimuli related to dynamics of the activity while under increased cognitive load.

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However, presentation of different tactile modalities simultaneously can interfere with our ability to perceive the haptic stimuli [10]–[13]. This interference, also known as tactile masking, has been observed in prior studies using multi-sensory devices [6], [14], [15], resulting in degraded perceptual performance. Tactile masking is a phenomenon that is caused when one or more stimuli mask or overpower the sensations created by other stimuli. Intrinsic stimuli can have a similar effect. Several studies have found that a reduced ability to correctly perceive vibrotactile feedback during motion is caused by interference from other stimuli inherent to the task being performed. This phenomenon, known as tactile suppression, has been observed when presenting vibrotactile-only stimuli during simple finger motions [16], [17], juggling [18], and back-bending motions [19].

The effects of tactile suppression are less prominent at limb locations expecting tactile feedback during a specific task [20] such as the finger directly involved in a grasping task [21]. Tactile suppression is frequently observed in short, discrete activities such as bi-manual reaching, where participants' ability to perceive vibration has its most significant reduction zero to fifty milliseconds before the participant's motion [22]. However, low to moderate levels of physical activity and sitting versus standing do not have any significant impact on participants' ability to recognize spatiotemporal vibration patterns [23].

Tactile suppression could be mitigated by modeling the reduced perceptual sensitivity during motion. Vibrotactile devices will often utilize a perceptual model to control and predict where the user will feel a phantom sensation [24]–[26]—a vibrotactile illusion created when two actuators are activated simultaneously and the virtual stimulus is perceived at some point between the two tactors [24], [26], [27]. Personalized models significantly increased the perception and correct interpretation of vibrotactile cues using phantom sensation when participants were at rest [28].

In this paper, we evaluated whether tactile suppression had a significant impact on perception of multi-sensory cues during voluntary motion and found that our main hypothesis was not supported. That is, tactile suppression phenomena is not the main factor affecting tactile perception. This implies that design of wearable haptic feedback systems should first account for variation in sensitivity across feedback locations rather than the an individual's current state of motion. This paper further evaluated whether sensitivity-adjusted perception models could be a basis for an effective multi-sensory controller that reduces the effect of stimulus location on perception and found that sensitivity-adjusted models reduced the error for both vibrotactile and squeeze based cues.

II. METHODS

In this study, we investigate the effect of voluntary motion on the perception of multi-sensory haptic cues used for motion guidance by comparing how participants perceive, interpret, and respond to multi-sensory haptic cues presented when they are at rest versus when they are already in motion. The experimental setup used a haptic feedback platform to provide motion guidance cues indicating a desired movement direction and speed, a robotic data collection platform, and a visual display. We hypothesized that participants presented with multi-sensory haptic cues while already in motion would have difficulty interpreting the cue, resulting in greater deviation from the direction and speed indicated by the motion guidance cue. As with previous studies, the location of the tactors may also affect perception.

A. Haptic Platform

We used a haptic platform comprised of eight eccentric rotating mass (ERM) mini-motors (Adafruit)—10mm in diameter and 2.7mm thickness operating at 183 Hz at 5V—arranged in a circular array around the circumference of the forearm, similar to [27], [29], [30], shown in Figure 1. The squeeze mechanism consisted of one band of nylon webbing around the upper arm whose circumference was controlled by a 270-degree high torque servo motor (TianKongRC TD-8120MG) as seen in Figure 1. The shortening of the band by the servo motor produced a squeezing sensation around the upper arm. The servo and tactors were controlled using four DRV 8883 motor drivers and an Arduino Uno that communicated with a host computer to synchronize the cues with the kinematic data collected.

The tactors and servo were activated simultaneously to indicate the desired motion. The activation pattern of the tactor array indicated direction. Participants were asked to move towards the direction where they felt the highest vibration intensity. A target angle of 0 degrees would activate the tactor on the right side of the forearm, while a target angle of 110 degrees would activate tactors on the upper-left surface of the forearm, as shown in Figure 1. The angles used in the present study were 15, 22.5, 50, 75, 105, 112.5, 140, 165, 195, 202.5, 220, 255, 285, 295.5, 310, 345 degrees, and they did not directly correspond to the location of any of the tactors. Therefore, two adjacent tactors were activated simultaneously to create an illusionary stimulus. This phantom sensation would feel as if the vibration was coming from a point between two tactors, at the desired angles. To render these phantom sensations, we used the linear relationship presented by Alles [24] to determine the appropriate intensity of each tactors. As the motors used in this study were ERM vibration motors, the vibration frequency was directly proportional to the intensity of the vibration.

The intensity of the squeeze indicated the desired movement speed that a participant should achieve over the next two seconds. The squeeze level produced by the servo was broken up into four levels corresponding to the servo angle. We set the maximum servo angle to ensure the squeeze band achieved the desired tension without discomfort to the participant.

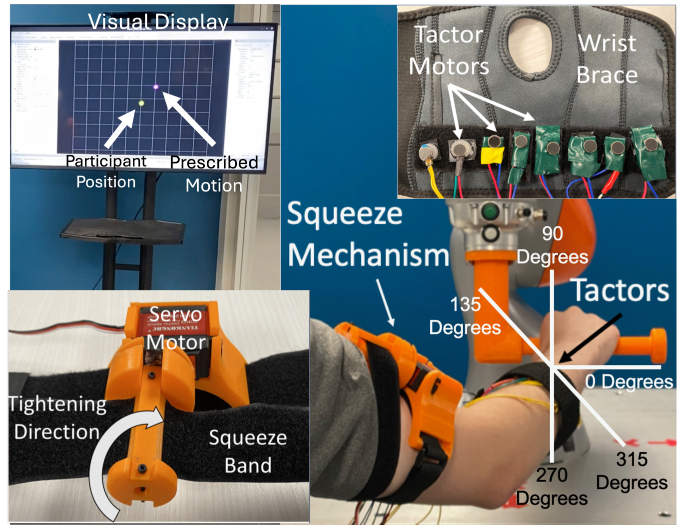

Fig. 1: The haptic platform was comprised of eight vibrating mini-motors arranged in a circular array around the circumference of the forearm and one band of nylon webbing around the upper arm, whose circumference was controlled by a servo motor. The shortening or lengthening of the band produced a squeezing sensation around the bicep. The tactors and servo were actuated simultaneously to indicate the desired motion, with the tactors providing the target angle and the servo providing the target speed.

The maximum speed corresponded to the maximum servo angle (and minimum band length). The other three levels, seventy-five percent, fifty percent, and twenty-five percent of the maximum servo angle, signaled to slower speed values respectively.

B. Robotic Data Collection Platform

The study used a Kuka LBR iiwa as a three-degree-of-freedom joystick to collect user inputs and to constrain the movement of the participants wrist so that the wrist and world coordinate system remained aligned. The iiwa is a seven-degree-of-freedom collaborative robot with a 14 kg payload and has a maximum reach of 820 millimeters. While in use, participants are seated in a chair facing the robot with a visual display and are asked to grasp the robot's end-effector. The robot was operated in cartesian impedance mode where the impedance value in one direction was set to 1,000 N/m, while the impedance values in the other two directions were set to 20 N/m—restricting the motion of the end-effector to the vertical plane with low impedance to in-plane movements. The end-effector's position was computed using forward kinematics and recorded throughout each trial.

C. Visual Display

Along with the haptic platform, participants received feedback from a visual display during each of the trials. The display was used to prompt participants to remain at rest or perform a voluntary movement and signaled when the trial started and stopped. Text indicated stimulus onset and when data collection ended. For static condition trials, text prompted participants to hold still. For voluntary motion conditions, a purple dot was used to trace a desired trajectory, while a yellow dot tracked the participant's actual position as shown in Figure 1. Participants were instructed to follow the purple dot as closely as possible. The desired trajectories randomly switched between circular motion and figure-8 motion, as shown in Figure 2.

After following the visual cue for a random amount of time, between 1.5 and 3.5 seconds, the visual tracking component would disappear and the tactile cue would be applied to indicate a direction and distance to move. Two seconds after the initial haptic cue was first displayed, the haptic stimuli were removed, and the participant was instructed to rest before starting the next trial.

D. Experimental Procedure

Twenty-two participants (10 female, 12 male) aged 18 to 40 were recruited for this study and provided informed written consent before participation. The protocol for this research study was approved by the Pennsylvania State University Institutional Review Board, under IRB number STUDY00020703.

All participants completed 5 trials for each unique combination of the sixteen illusionary angles indicating the direction of motion, four velocity magnitudes, and two movement conditions—completing a total of 640 trials in a session. The order in which these combinations of independent variable tested was determined by generating the list of 128 possible combinations and repeating these combinations five times. Using a random number generator, the order of the trials was randomly selected—effectively shuffling the ordered list of trial conditions that was generated for each participant. This process is outlined in Figure 2. This randomization allowed us to avoid capturing effects due to increasing familiarity with the stimulus and test setup or confounding the effect of fatigue with the impact of the trial conditions. The timing of the stimulus was randomized to occur between 1.5 and 3.5 seconds after the start of the trial to avoid anticipatory movement and would remain active while participants executed the indicated motion. The total trial length ranged from 3.5 to 5.5 seconds. Participants completed trials over approximately a 1 hour time window, though only about 30 minutes of that time was actual data collection. The remainder of the time was breaks between trials while the experiment was reset and any additional breaks requested by the participant.

Before data collection began, participants were familiarized with the testing setup. The speed and angle cues were demonstrated individually. For the speed cue, participants performed several practice movements with feedback on their speed error. During testing each stimuli is presented at a constant intensity for two seconds. All participants responded to the haptic cue within the two second time limit. Participants received short breaks between trials and were offered additional breaks frequently to avoid fatigue.

E. Data Analysis

A polar velocity vector was calculated by taking the numerical derivative of the Cartesian positions recorded during the last 0.5 seconds of each trial. The velocity vector was converted to polar form, with the radius representing the speed and the angle being the direction. Only the latter part of the movement was used to avoid differences due to varying reaction times under static and voluntary movement conditions. The error between the angle and magnitude of the velocity vector and the angle and magnitude of the desired motion was computed. A non-parametric, multi-factor, repeated measures Aligned Rank Transform (ART) ANOVA [31] was used to analyze the effect of starting condition, desired angle, and desired magnitude on each of the error measures. Post Hoc corrections to the results of the ART ANOVA were performed were performed using Benjamini-Hochberg [32] false discovery rate method to adjust the p-values.

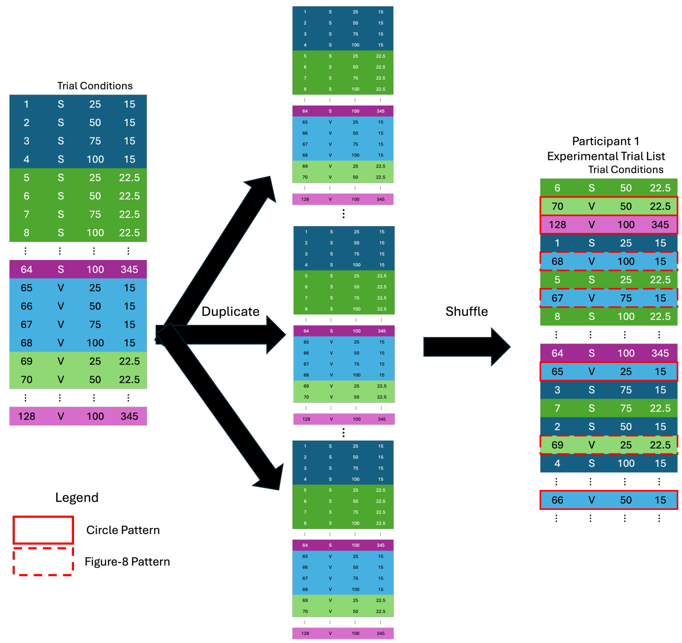

Fig. 2: This schematic shows how the set of unique trial conditions was set, duplicated 5 times such that each participant completed 5 trials per combination. The order of the list of duplicated trials was shuffled with a random number generator. For voluntary trials, half of the trials were randomly assigned to have the participant track a figure-8, and in the other half, participants tracked a circular trajectory.

F. Sensitivity-Adjusted Perceptual Models

The perception of haptic cues can be affected by a variety of factors including tactile masking, tactile suppression, level of skin contact and presentation location on the body. While these factors can all play a role in our perception, their actual effect can vary greatly from person to person, reducing the quality of haptic feedback. We assess the possibility of using a data-driven approach to mitigate various factors by fitting perceptual models to the data and computing the angle and speed errors based on the data-driven models.

Using the models presented by Luzhnica et al. [28], the cued angles, $v \in [0,1]$, and user responses, $y \in [0,1]$, were normalized. The intensities, I_i of the tactors were normalized using the maximum and minimum amplitude of the PWM signal. We extend Luzhnica's model to include skin squeeze as well as vibrotactile sensations. The squeeze intensity, I_{sq}, was normalized by the maximum allowed servo angle.

Given a pair of tactors $i \in \{a,b\}$ actuated at intensities I_i at a known location $x_i = i$, the location of the phantom sensation can described as $x_p \in [0,1]$. In this experiment, we consider linear [24] and power [26] models. In the linear model, the phantom sensation location, x_p, is proportional to the relative stimulation intensity I_a. While in the power model, the phantom sensation location, x_p, is proportional to the square of the intensities. These models can be generalized for vibrotactile displays containing more than two tactors with perceptual sensitivity changes depending on the location of the stimulus [33]. For vibrotactile displays with N tactors $0 < i \leq N$ and M segments between the tactors and known intensities I_i and I_{i+1}, we can estimate the within-interval phantom sensation location x_p between tactors i and $i+1$ using the linear model, (eq. 1) and power model, (eq. 3). Using (eq. 5), estimated value of x_p, and number of segments between tactors M, we can compute the estimated location of the phantom sensation across all tactors as $v \in \{0,1\}$.

The spatial variation of perceptual sensitivity can be accounted for by scaling the intensities I_i using location specific factors $s_i \geq 0.5$ and can be applied to both models as shown in (eq. 1) and (eq. 3). We extend both models to predict the speed response, x_s, based on the squeeze intensity, I_{sq}, of the $N+1$ actuator using a similar relationship. We set up both a linear and power relationship between the speed response and the squeeze intensity as shown in eq. 2 and eq. 4. To account for the interactions between the angle and speed responses, we included an interaction term composed of the product between angle and speed response and a weight, W, as shown in eq. 6.

$$x_p^{ls} = \frac{s_{i+1}I_{i+1}}{s_i I_i + s_{i+1}I_{i+1}} \tag{1}$$

$$x_s^l = s_{N+1}F + s_{N+2} \tag{2}$$

$$x_p^{ps} = \frac{s_{i+1}^2 I_{i+1}^2}{s_i^2 I_i^2 + s_{i+1}^2 I_{i+1}^2} \tag{3}$$

$$x_s^l = s_{N+1}^2 * I_{sq}^2 + s_{N+2} \tag{4}$$

$$v = \frac{x_p - i}{M} \tag{5}$$

$$interaction = W x_p x_s \tag{6}$$

The optimal values for these sensitivity factors were found by minimizing the mean squared error between the user response and the predicted response as in (7), where y_i is the user response at stimulation intensities $I_1^i, ..., I_N^i, I_{sq}$ and $v(S, I_1^i, ..., I_N^i, I_{sq})$ being the response location estimated by the models at intensities $I_1^i, ..., I_N^i, I_{sq}$.

$$S_0 = argmin \sum_{i=1}^{D} (y_i - v(S, I_1^i, ..., I_N^i, I_{sq}))^2, s_i >= 0.5 \tag{7}$$

Two sets of models were generated with one set being trained against the combined data of every participant and the other set was trained on the data for each individual participant. Each set contained six total models, three were based on the linear equation 1 and the other three were based on the power model equation 3. The three different models were trained on the data containing only the static, only the voluntary motion trials, and on combined data of the static and voluntary movement trials. The data-driven models were evaluate using using K-Fold cross-validation with 10 splits. The model performance was evaluated using the absolute decoding error, which was calculated as $\varepsilon = |y - v|$, where $y \in [0,1]$ is the user response and $v \in [0,1]$ is the phantom sensation location as predicted by the perception models. Comparison of the models was performed using the non-parametric Wilcox-signed rank test, to determine which model, if any, was capable of accurately predicting participant responses.

III. Results

A. Sample Response

Figure 3 shows sample responses to the haptic stimuli under static and voluntary motion conditions. The stimulus is applied in both plots at time t = 0 seconds, indicated by the gray bar. In both trials participants received a haptic cue indicating them to move in a direction of fifty degrees at a speed of 75% of the maximum speed. Under that static condition, a delay of about 0.5 seconds was frequently observed between the display of the haptic cue and the initiation of the indicated movement. In the voluntary motion condition, a delay of 0.3 seconds in movement initiation was observed as indicated by the point in time where the y and z positions diverge. While the voluntary motion condition had a shorter delay in response than the static condition response, we did not have to perform any corrections for this difference as we only examined the last 0.5 seconds of the motions.

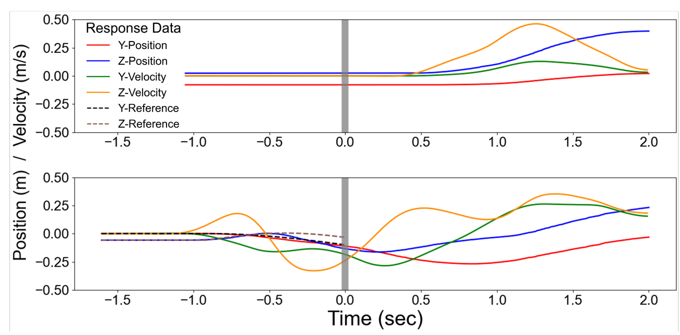

Fig. 3: The top plot shows the participant response during a static trial, where they would remain at rest until the presentation of the haptic stimuli. The bottom plot denotes the participant response during a voluntary motion trial, where they would be following a figure-8 trajectory as indicated on the visual display. The haptic stimulus was applied at t = 0 seconds, as indicated by the gray bar. In both trials the haptic stimulus indicated a direction of fifty degrees at the same speed. In the static response, the participant begins responding to the haptic cue around 0.5 seconds into the trial. The start of their response is clearly denoted by shift to a non-zero velocity. In the voluntary motion response, the participant begins responding to the haptic cue at around 0.3 seconds. The start of the voluntary motion response can be visualized by the point where the y-position diverges from the z-position, indicating a divergence from the figure-8 trajectory.

Figure 4 shows a typical position and velocity response to a fifty degree direction and seventy-five percent speed cue for both a static trial and voluntary motion trial. In the top plots for the static trial, the participants response starts near the zero starting position with an initial velocity of zero in both the y and z directions. Once the haptic cue is presented, the participants begin moving in the direction indicated by the black arrow with an increasing velocity. In the bottom voluntary motion plots, the participants start near the zero position and begin following the voluntary motion pattern until they are presented with the haptic stimuli. Once presented with the haptic stimuli, participants begin attempting to move in the presented direction as indicated by the black arrow. In the static response, participants responded in the same general direction of the desired trajectory. In the voluntary motion response, participants tracked the desired vector with greater precision.

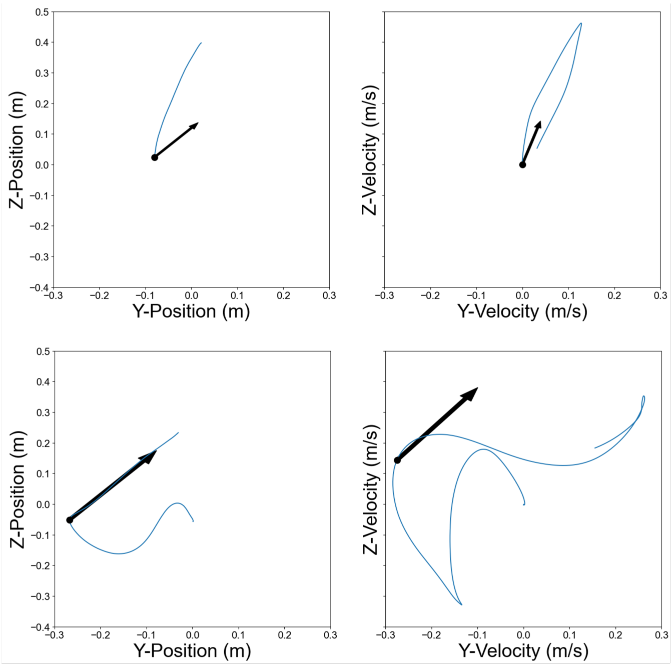

Fig. 4: The top plots show the position and velocity of a typical response during a static trial in the YZ-Plane, while the bottom plots show the typical response during a voluntary motion trial. The black arrow in the plots indicates the haptically cued direction.

B. Statistical Results

The angle error between the velocity angle and the target angle is shown in Figure 5. A non-parametric, three-factor, repeated measures Aligned Rank Transform ANOVA was performed using R [34], to assess the impact of the starting condition, target angle and target speed on angle error.

Angle Error The main effect of target angle ($p = 1.67 \times 10^{-21}, F = 12.120$) was statistically significant. Figure 5 shows that in general participants tended to underestimate the target angle resulting in negative error for trajectories that were rotated clockwise from the target angle. Figure 5 also shows that the angle error was lower for directions in the upper-right quadrant, which indicates that participants were more successful at interpreting cues presented in that location. The interaction effect between the movement condition and target speed ($p = 0.009, F = 4.961$) was statically significant. There was no difference between static and voluntary motion conditions when the target speed was 25% and 75% of maximum speed. For target speeds of 50% and 100% of maximum speed, the angle error was lower when participants received the cue during motion.

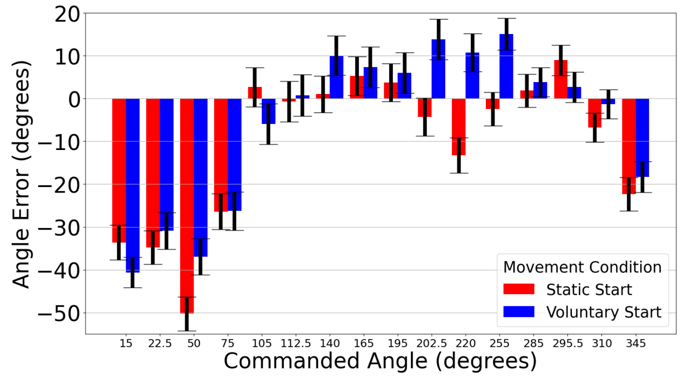

*Fig. 5: **Angle error vs. Target direction:** Participants were able to more accurately interpret and execute target angles that were in the direction of up and to the right. The accuracy of participants interpretation and execution of target angles was not affected by their state of motion.*

The interaction effect between target angle and target speed ($p = 0.013, F = 1.553$) was statistically significant. On the left side of the arm and lower side of the arm (angles between 90 and 310 degrees) there were only small differences in angle error at different target speeds. However, in the regions where angle error was larger overall there were larger differences across target speed. This suggests that the target speed may have further reduced perception of the angle cue on the right side of the participant's arm. The main effects of movement condition ($p = 0.087, F = 4.171$) and target speed ($p = 0.546, F = 0.722$) were not significant. The interaction effect between movement condition and target angle ($p = 0.387, F = 1.068$) and between movement condition, target angle, and target speed ($p = 0.278, F = 1.118$) were also not significant.

Speed Response A non-parametric, three-factor, repeated measures Aligned Rank Transform ANOVA was also performed on the speed response. The main effect of target speed ($p = 7.72 \times 10^{-8}, F = 24.582$) was statistically significant. In Figure 6, as the intensity of the speed cue increased, participants moved faster, indicating that participants could accurately perceive and interpret the different squeeze intensities and respond accordingly. The interaction between movement condition and target speed ($p = 0.008, F = 5.021$) was also significant. Figure 6 shows that generally the speed response for the voluntary movement condition was larger. The larger response indicates that when participants were already in motion, they tended to overshoot the target speed compared to trials where they started at rest except in the case of the max speed. Figure 6, also shows that participants had a strong tendency to overshoot the desired speed value.

The main effect of target angle ($p = 0.011, F = 2.091$) was significant. Figure 7 shows that the speed response was slower for target angles of 255 to 310 degrees, indicating that in general for direction cues pointing down and to the right, participants were less successful at replicating their response compared to their response in other directions for the same speed cue. The interaction between target angle and target

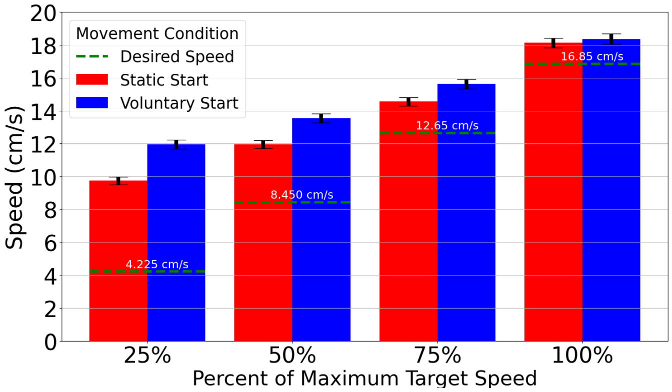

Fig. 6: ***Speed responses vs Target speed:*** *Participants were able to differentiate the different levels of squeeze and increased the speed of their movement when the intensity of the squeeze increased. However, participant responses tended to not closely match the true desired speed value and would overshoot it.*

speed ($p = 0.044, F = 1.403$) was not significant. However, one can see that in Figure 7, generally, the higher speeds corresponded to higher target speeds with a few cases where a pair of adjacent target speeds did not result in different speed responses as can be seen in target angles, 22.5, 75, 112.5, and 220. The interaction effect between movement condition, target angle and target speed ($p = 0.008, F = 1.667$) was significant. The main effect of movement condition ($p = 0.237, F = 1.724$) and the interaction effect of movement condition and target angle ($p = 0.156, F = 1.382$) were not significant.

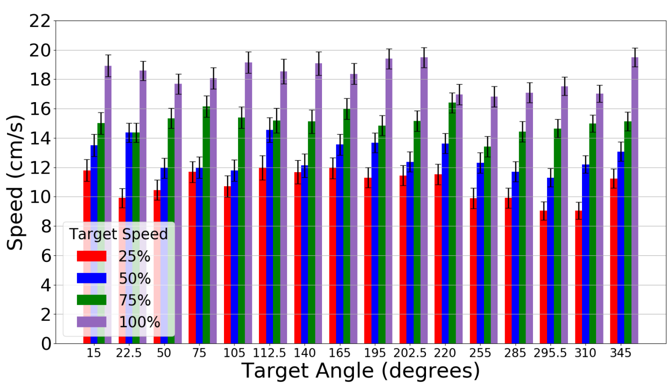

Fig. 7: ***Speed responses vs Target angle:*** *Generally, as the speed intensity increased, participants increased their speed. For target angles between 255 to 310 degrees, participants' speed responses were generally slower than the other directions.*

We compared the absolute decoding error of linear and power models trained on the data aggregated across all participants using eight sample t-tests. In general, we found that both the linear and power models could reduce user response error.

We also compared linear and power models trained using only static trial data, only voluntary motion trial data, and data from all trials, summarized in Tables I, II, III. In all cases, both linear and power models showed promise at reducing the perception error; however, the linear model was more effective at reducing the error for vibrotactile cues and the power model was more effective at reducing the error for squeeze cues. The

	Static		Voluntary		All	
Model	μ	**SD**	μ	**SD**	μ	**SD**
Linear	15.44	10.92	15.33	11.59	8.723	11.04
Power	18.51	11.41	19.18	11.95	11.39	10.04

TABLE I: This table contains the mean and standard deviation of the angle error for each model trained using the combined data from all participants. All the models have the capability of reducing the response error. The linear model trained using the combined static and voluntary motion data had the greatest reduction in the angle portion of the absolute decoding error.

significant differences between the various models shown in Table III, show that training the models using only static or only voluntary motion results in less effective compared to training the models using both the static and voluntary motion data. The statistical comparisons also show that there is a significant difference between the linear and power models, but no difference between training with static motion data or voluntary motion data for the linear model.

	Static		Voluntary		All	
Model	μ	**SD**	μ	**SD**	μ	**SD**
Linear	2.597	1.510	2.822	1.678	7.220	1.512
Power	4.480	2.835	4.549	2.880	3.710	2.054

TABLE II: This table contains the mean and standard deviation of the speed response for each model trained using the combined data from all participants. All the models have the capability of reducing the response error. The power model trained using the combined static and voluntary motion data had the greatest reduction in the speed portion of the absolute decoding error.

Model	ε_{SL}	ε_{SP}	ε_{VL}	ε_{VP}	ε_{CL}
ε_{SP}	0.002				
ε_{VL}	0.432	0.002			
ε_{VP}	0.002	0.037	0.002		
ε_{CL}	0.002	0.002	0.002	0.002	
ε_{CP}	0.012	0.002	0.002	0.002	0.002

TABLE III: This table shows the resulting p-values for the non-parametric Wilcox-signed rank test comparing the absolute decoding error of the different models trained using the combined data from all participants. The absolute decoding errors ε, was denoted by the training data: S (static trials), V (voluntary motion trials), or C (both) and the model: L (Linear) or P (Power). There is a statistically significant difference in the absolute decoding error between the static linear and static power models, the static linear and dynamic power, the static power and dynamic power, the dynamic linear and dynamic power, the static linear and linear, the static linear and power, the static power and linear, the static power and power, the dynamic linear and linear, the dynamic linear and power, the dynamic power and linear, the dynamic power and power, and the linear and power models.

IV. Discussion

Prior studies show that increasing the complexity of haptic cues and using multiple cutaneous stimuli can increase the number of distinct cues with a wearable haptic device—potentially enabling higher information transmission via cutaneous stimuli. However, the complexity of such cues, interference between stimuli, and tactile suppression may limit such haptic interfaces, especially when designed to guide motion or improve communication between a robot and human during voluntary motion tasks. Tactile suppression in its simplest definition is a phenomenon that degrades our ability to accurately perceive and interpret tactile stimuli during movement [35]. This phenomenon dominates from shortly before the beginning of a movement and continuing until the motions end, with a peak attenuation at the exact point motion is initiated [21], [22], [36]. Following the results of existing literature, we should expect that in our experiment, participant response accuracy to the haptic cues should be poor or inconsistent under the voluntary motion starting condition. Instead, we found that our main hypothesis was not supported and that in general participant response accuracy was unchanged by voluntary motion. In goal-directed motions, the effects of tactile suppression were absent in areas where tactile information is relevant to the motion [20], which could explain the greater quality of the responses. However, all the tactile stimuli supplied in our study was presented on the participant's forearm, and according to the study by Colino et. al [20], vibrotactile stimuli applied to the forearm would consistently be affected by tactile suppression. These findings suggest that tactile suppression is not a dominant factor in haptic perception accuracy for motion guidance. Our statistical results indicate that the cued angle was the dominant factor affecting perception errors. In this experiment, the indicated angle coincides with unique stimulus locations on the body. This suggests that the stimulus location is among the most important factor affecting haptic perception. This is consistent with other work on tactile perception [23]. This change in perceptual accuracy due to stimulus location is often attributed to varying densities of mechanoreceptors on different arm surfaces [37], or to the spatial differences in perceptual sensitivity around the forearm [33].

Perceptual interference (also known as tactile masking), is the phenomenon where our perception accuracy of one stimuli is degraded when in the presence of another [10]. This degraded perceptual accuracy has a greater chance of occurring in multi-sensory devices as they supply multiple types of stimuli simultaneously [38]. In our results, participants responded with a slower speed when presented with directional cues between target angles of 255 to 310 degrees, showing a possible confusion of the intensity of the presented stimuli. In our angle error results for target angles pointing to the right, participants had increased variation in their responses. This increased variation as compared to other directions could be caused by perceptual interference from the interaction of the vibration and squeeze cue. This result falls in line with work done in [15], where a loss of accuracy was found even though vibration and the other stimuli are not being applied at the exact same location.

This study used two data-driven perception models to analyze the possible improvement in perception for the vibrotactile and skin-squeeze feedback in the voluntary motion conditions. Our analysis of the data-driven, sensitivity-adjusted perception models found that there was a significantly better result when training the models using the combined static and voluntary data compared only static or only voluntary motion trials.

While the models used in this paper have shown a potential for great improvement. They may be challenging to implement online in a wearable device due to computation and storage limitations on portable micro-controllers like Arduino or ESP32. The feedback will also be limited by the performance characteristics of the hardware. In the present study, we use ERM tactors, where vibration amplitude and frequency cannot be controlled independently. The quality of haptic feedback might be improved with hardware that can independently control the amplitude and frequency of vibration such as linear resonant actuators. This change would increase perceptual model complexity and likely increase the amount of training data needed. Without appropriate training data, the perceptual model used here could result in poor model performance. More sophisticated learning algorithms might enable online learning with relatively few data points. Further, using more general models—including one capable of switching between attractive and repulsive feedback—may allow for learning and adapting to user preferences and as well as perceptual differences.

V. Conclusions

This paper investigates whether tactile suppression plays a role in the perception of multi-sensory haptic feedback. The feedback information was conveyed using a vibrotactile array for a desired direction and a squeeze band for a desired speed. Our results demonstrated that our main hypothesis was not supported and our ability to perceive haptic stimuli on the forearm accurately is not significantly affected by state of motion, instead stimulus location seems to be the most important factor. Our results also show that sensitivity-adjusted perception models are capable of reducing the impact of stimulus location for a wide range of people. These results provide insight into factors to consider in the design of wearable haptic devices to provide more effective feedback. Specifically, our results demonstrate that voluntary movement need not be explicitly considered in device and control design, but that it should be included in data-driven control methods. By considering these factors, improving and creating wearable haptic feedback devices to further enrich our experience with AR/VR and facilitate effective human-robot interaction in teleoperation is possible.

In addition to compensating for relative decreases in tactile perception across participants or body locations, data-driven control methods could enable more sophisticated adaptation of tactor control to user preferences and task performance. With appropriate training data and algorithmic updates to the tactor control policy, it is possible that for different users or tasks, a unique optimal policy could be learned. For instance, the literature is mixed on whether repulsive or attractive vibrotactile feedback is more effective or if it simply comes down to user preference. Future work will include customization of the tactor control using data-driven approaches similar to the perceptual models we investigate in the present study. Such data-driven approaches may be able to handle both body-location dependencies and preferences with sufficient model complexity. However, the challenge will be developing data-efficient strategies to train these models and adapt them to perturbations to the interface between the user and wearable device.

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