Perception of and Response to a Haptic Device as a Function of Signal Complexity

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***Abstract*—Haptics devices have been developed in a wide range of form factors, actuation methods, and degrees of freedom, often with the goal of communicating information. While work has investigated the maximum rate and quantity of information that can be transferred through haptics, these measures often do not inform how humans will use the devices. In this work, we measure the differences between perception and use as it relates to signal complexity. Using an inflatable soft haptic display with four independently actuated pouches, we provide navigation directions to participants. The haptic device operates in three modalities, in increasing order of signal complexity: Cardinal, Ordinal, and Continuous. We first measure participants' accuracy in perceiving continuous signals generated by the device, showing average errors below 5^o. Participants then used the haptic device in each operating mode to guide an object towards a target in a 2-dimensional plane. Our results indicate that human's use of haptic signals often lags significantly behind the displayed signal and is less accurate than their static perception. Additionally signal complexity was correlated with path efficiency but inversely correlated with movement speed, showing that even simple design changes create complex tradeoffs.**

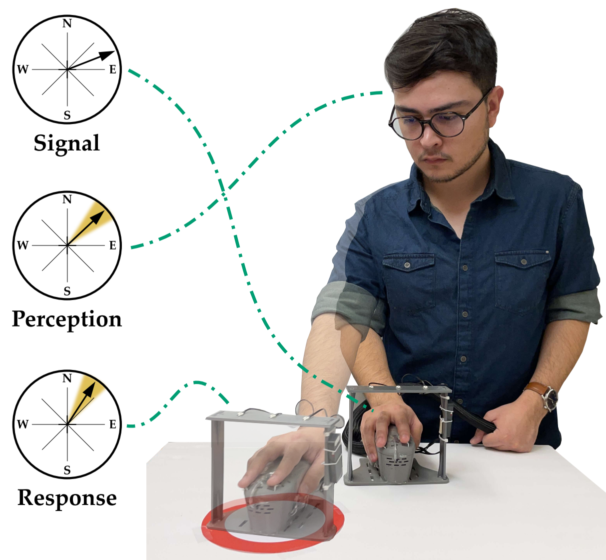

Fig. 1. The holdable haptic display renders signals to provide navigation assistance through a 2-dimensional space to find a target. The person perceives the signal using their hands, and the brain interprets it. The person then reacts to the signal by moving the object. In this study, we explore how the perception of haptic signals varies when humans (1) are asked to interpret them only, and (2) are asked to interpret and react to them.

I. Introduction

Haptic devices have emerged as an attractive option for communicating information to users in a non-intrusive and easily interpreted way. Applications have ranged from guidance [1]–[12], to sensory replacement [13], to hands-free alerts [14], and more. Alongside this expansion of applications, we have seen a rise in form factors, including wearable devices (hand [15], [16], finger [17]), holdable devices [18], [19], and touchable devices [20], and a rise in actuation technologies, such as vibrational (piezoelectric) [21], dielectric elastomers [22], pneumatically actuated soft composite materials [15], [18], [23], mechanical indentation [24], and shape change [25], [26]. However, while it may often be easy to describe the information needing to be transferred, designing a haptic device and haptic signal to accomplish that task remains a complex problem, one involving considerations of design, perception, information transfer, and cognition.

Within this arena, a number of works have been dedicated to understanding how the encoding of information in haptic signals, including the transfer rate and complexity of information, affect perception [27]–[31]. Haptics devices have achieved information transfer rates of up to 7 bits/s, with tens of unique, distinguishable signals/patterns in certain circumstances [32], [33]. Recent works have suggested using perceptual illusions and multiple perceptual dimensions (with a few levels per dimension) to increase these rates [30], [34]. However, generally accepted guidelines suggest that there is an optimal transfer rate for humans below this maxima, in the range of 2 to 3 items/s [35], [36]. Human perception of these signals has been studied extensively, from analyzing the human somatosensory elements involved in perception [37]–[39] to investigating the effects of haptic illusions and pseudo haptics [34], [40]. In navigation contexts, perception of signal encoding has been explored in actuator density and location [5], [6], [8], [11] and frequency modulation of vibration signals [7], [9], [10]. Despite these works focusing on a specific task, navigation, they still focus on perception studies generally removed from that task when determining the best encoding,

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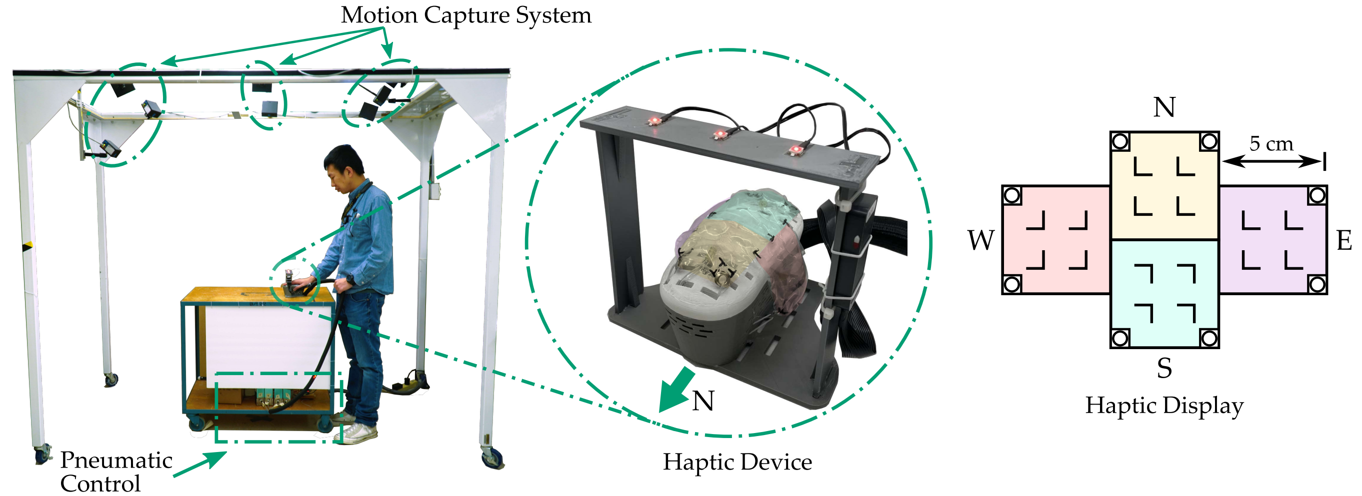

Fig. 2. (Left) The experimental setup consists of a motion capture system mounted on a frame, and a table containing the pneumatic control system and holding the haptic device. (Center) The haptic device consists of a 3D-printed holdable base and a soft wrapped haptic display. (Right) The soft wrapped haptic display consists of 4 individually actuated haptic pouches (one for each cardinal direction) made of thin, heat-sealable TPU film.

stopping short of interrogating if the increase in perception and information transferred will actually translate to an increase in performance at the target task [26].

The rate-distortion theory suggests that "the goal for perception should not be perfect identification, but rather the minimization of error" [41]. The objective of designing haptic signals must be centered on providing stimulus that, although it may not be perfectly perceived, provides enough cues for humans to understand the signal's meaning and respond accordingly. With this philosophy in mind, we formulate the following question: When does increasing the information encoded in a signal enhance human performance in using these signals? And can human perception of signals reliably predict performance with those signals?

In this study, we take a step back from haptic device design to address these questions. By comparing sets of haptic signals with different encoding complexity, both in static and reactive perception scenarios, we seek to understand the differences between human perception of and human use of sensory feedback. To do so, we conduct a navigation guidance task, in which participants receive direction signals encoded in different levels of complexity. Navigation tasks allow study of variations in spatial mapping and/or temporal encoding since direction signals can easily be rendered in different modalities to represent the same information. While some navigation guidance studies have explored the influence of encoding in signal perception [5], [7], [8], few compare the reactive perception of the "best" modality to the other tested modalities. By comparing different modalities in both static and reactive tasks, our work provides an enhanced picture of the differences between perception and use as it relates to signal complexity. In the remainder of this paper, we first present the haptic device and experimental set-up that will be used to measure human perception and performance. We then describe the human perception experiment and results in Section III and the navigation experiment in Section IV. We end with a discussion of the results in Section V and concluding remarks that can be drawn from them.

II. Device Design and Experimental Setup

This section describes the design of the holdable haptic device with variable signal encoding and the experimental setup used to test the device. The haptic device renders signals in different spatial mapping modalities (described below), allowing us to measure responses to signal complexity. Our setup, with a state-of-the-art motion capture system, allows us to analyze human responses to haptic signals by observing performance in a navigation task.

A. The Haptic Device

The haptic device consists of a 3D-printed holdable base and a soft wrapped haptic display (Fig. 2). The holdable base shape is modeled on a computer mouse to 1) allow the hand to conform around it and 2) provide enough space to wrap the haptic display while maximizing the contact area with the hand. A 3D-printed frame around the device holds LED markers for the motion capture system. All 3D-printed parts were manufactured using a MakerBot Method printer and PLA filament (MakerBot, Brooklyn, NY).

The actuators are made of two layers of thin, heat-sealable thermoplastic polyurethane (TPU) film (Durefelex PT7511. Covestro, South Deerfield, MA) sealed using a linear heat sealer (H-89 Foot-Operated Impulse Sealer. ULINE, Pleasant Prairie, WI). These film actuators are similar to previously developed soft haptic pouches [18], [42]–[44]. The haptic display consists of four independently actuated haptic pouches arranged to match the cardinal directions when mounted on the holdable base. Each of the haptic pouches has an air inlet made of clear soft PVC plastic tubing secured to the pouch using viscoelastic adhesive tape (MD-9000. Marker Tape, Mico, TX). A series of lines with gaps was patterned into each pouch using the linear heat sealer to create texture and reduce inflation volume, similar to previous device designs [43]. Grommets installed in the corners of the display were used to mount to the 3D-printed base using elastic cord.

Four pressure regulators (one for each pouch) with built-in sensors and exhaust (QB3. Proportion Air, McCordsville, IN) provided pressure to the display. These were controlled using an Arduino Uno via Python code. The haptic display can inflate to 3 psi (20.68 kPa) at a bandwidth of 2.1 Hz (determined through experimentation). The haptic display was operated in three different spatial mapping modalities:

- **Cardinal modality**. Four binary signals corresponding to the cardinal points only (e.g., N inflated to 3 psi).
- **Ordinal modality**. Four signals corresponding to each of the cardinal points, as well as four signals representing the ordinal points (i.e., NW, NE, SW, SE), for a total of 8 different signals (e.g., SW is S and W inflated to 2 psi).
- **Continuous modality**. Combinations of the pressures in neighboring pouches corresponding to continuous angles. For signals close to the cardinal points, a deadband of $\pm 15°$ was implemented to avoid rendering small pressure values that slowed responsiveness.

The modalities represent different encoding features for spatial mapping, from continuous to discrete and from single actuator per signal to multi-actuator per signal. For the Cardinal and Ordinal modalities, the closest discrete signal to the desired (continuous) direction was selected as the rendered signal.

B. The Experimental Setup

The setup consisted of a motion capture system (Impulse X2E System. PhaseSpace, San Leandro, CA), composed of eight linear detector-based cameras mounted on an 2.43 x 1.35 x 2.05 m frame over a 0.92 x 0.58 x 0.81 m table. This allows for real-time tracking of active LED markers at 960 Hz with 3 ms latency, tracking the position and orientation of the 3D-printed holdable base. The setup is shown in Fig. 2.

III. Exp 1: Static Directional Accuracy

We first measured how humans perceive directional signals from the device under ideal circumstances. Participants identified haptic cues in the continuous modality and related them to directions, showing the directional accuracy for users.

A. Procedure

For this experiment, participants were asked to interpret haptic signals and relate them to a direction based on cardinal references. The directional haptic signal set comprised the 4 cardinal and 4 ordinal directions and 16 intermediate directions (4 in each quadrant), for a total of 24 different haptic signals. Signals were separated by $15°$ increments, from 0 to $345°$, where 0° is North, and 180° is South, as shown in Fig. 3. Due to time constraints, each signal was shown to the participant once, and they were asked to identify the corresponding direction in degrees. The presentation order of the haptic signals was randomized for each participant. Before beginning, the participants were guided through a demo, showing the device rendering different direction signals. After completing the demo, the experiment started by inflating the device with the first signal to show. The participant was asked to verbally identify the signal direction without moving the device. After answering, the device deflated to a zero-configuration before displaying the next signal. These steps were repeated until all 24 signals were tested.

B. Results

We recruited 10 participants (5 female, 0 non-binary, 5 male, average age 22.2 years, age range 19 - 25 years) from the Purdue University community. All participants completed the study after giving informed consent. The Purdue Institutional Review Board approved the study protocols (IRB #2022-1720). Fig. 3 summarizes the results. Participants identified cardinal directions (N, S, E, W) with high accuracy (error: $\bar{x} = 0°$, $\sigma = 2.265°$). For the continuous signals, participants successfully identified the correct quadrant of the signals in most cases, but had larger errors on average. The mean response for each signal was within $15°$ of the true value, often skewed in the direction of the nearest cardinal point (Fig. 3(a)). This was especially true for error signals in the NW and NE quadrants, which were drawn towards the North, as shown by the opposite sign mean error and error bars for these quadrants (Fig. 3(b)). Participants gave a greater range of responses for signals corresponding to the SW and SE quadrants. For example, answers for the signal corresponding to $150°$ (error: $\bar{x} = 6.5°$, $\sigma = 19.727°$) ranged from 120 to 190°. Using a Friedman test (for non-parametric data), we determined that the quadrant location had a significant effect on error ($Fr(3) = 7.880$, $p = 0.049$). Post hoc Wilcoxon analysis revealed a significant difference in the errors observed between NW and the southern quadrants ($p < 0.05$).

IV. Exp 2: Active Perception and Response

For the second part of the experiment, participants moved the holdable haptic device in a 2-dimensional space from an initial position to a target. The device actively rendered direction signals based on the target direction, and the participants had to use these signals to locate the target.

A. Procedure

In this experiment, participants interacted with the three different signal modalities (Section II-A): Continuous, Ordinal, and Cardinal. Each modality was tested over 3 trials to 20 different targets (ten medium-distance and ten long-distance) for a total of 60 trials. The medium targets are placed within a 15 cm radius of the center of the table, and long-distance targets are outside this radius (Fig. 4). The trials were blocked by modality; the order of the blocks and of the 20 targets in each block were randomized for each participant. The participants were guided through a demo of the experiment before beginning. For each trial, participants placed the device in the starting position (middle of the table). A beeping sound indicated that the device would start rendering signals, and that participants could begin. Once participants reached the target, a beep indicated completion of the trial. Participants were

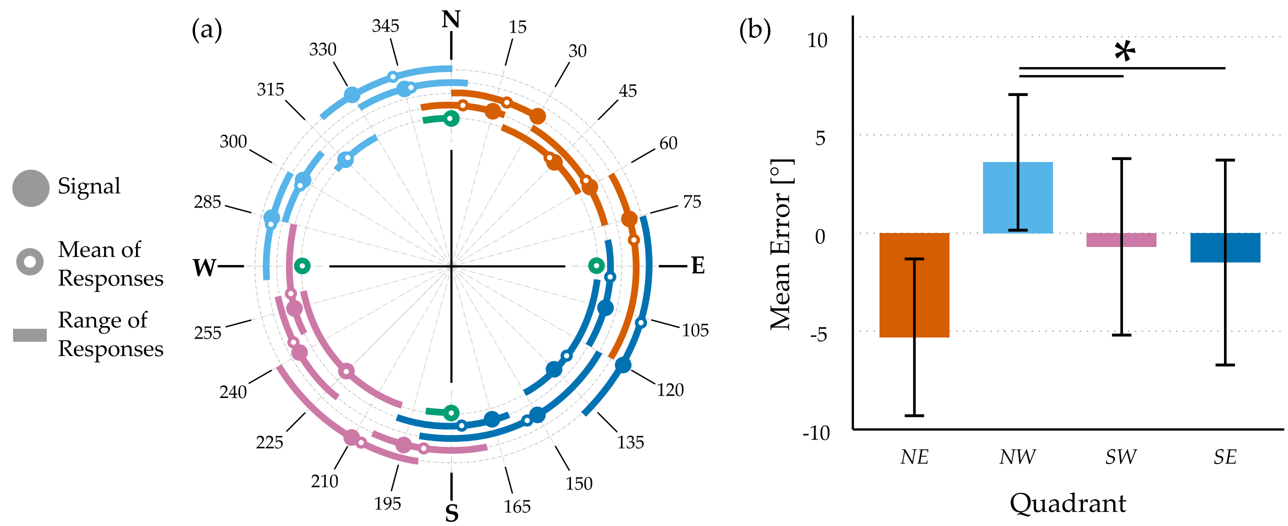

Fig. 3. Exp 1: Directional Accuracy results. (a) Plot showing the mean and range of responses for each tested signal. Each signal corresponds to a 15° increment, from 0 to 345°. The mean response for each signal was consistently within 15° of the true value. Responses corresponding to cardinal directions (N, S, E, W) were very accurate (error: $\bar{x} = 0°$, $\sigma = 2.265°$). (b) Mean error for each of the quadrants. Signals corresponding to the NW and NE quadrants tend to be located toward North, while signals in SW and SE quadrants showed more variance. Error bars represent 95% confidence intervals, and an $*$ indicates statistically significant comparisons.

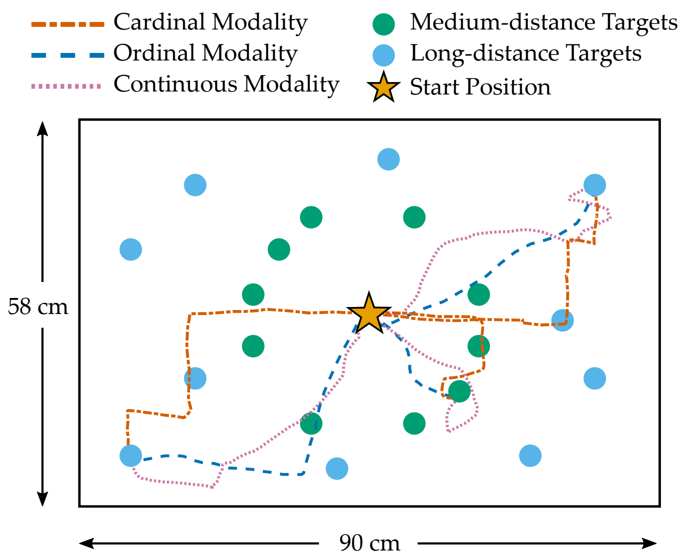

Fig. 4. Location of starting position and targets for Exp 2: Active Perception and Response. Participants were tasked to find the targets based on the haptic feedback provided by the holdable device. The haptic signals were updated in real-time according to the device's position, captured by the motion capture system. The haptic feedback was provided in three different modalities: Cardinal, Ordinal, and Continuous. We show examples of the trajectories followed by participants using the different modalities. Each modality influenced the paths participants used when guiding the object.

offered a break after each modality block, and an end survey asked questions about their perception and interpretation of the signals and their strategies to find the target.

B. Numerical Results and Observations

Participants completed this experiment directly after completing the perception experiment. Two quantitative measures were used to understand the results of this experiment: *Time* and *Motion Path Efficiency*. The effects of the modalities on time measures and path efficiency were evaluated by non-parametric analyses, since distributions were not normally distributed according to Shapiro-Wilks test.

For *Time*, two measures were computed: the time spent to reduce the distance to the target by 50% (T_{50}), and the total time to reach the target (T_T), in seconds. Fig. 5 shows the mean and 95% confidence intervals for these time measures. While the Cardinal modality show the slowest time to 50% of the distance (T_{50}) ($\bar{x} = 6.12s$, $\sigma = 2.37s$) compared with the Ordinal ($\bar{x} = 5.67s$, $\sigma = 1.90s$) or Continuous ($\bar{x} = 5.71s$, $\sigma = 1.92s$) modalities, these these small differences did not reflect on the total time T_T and Friedman tests revealed that modality had no significant effects on time measures ($Fr(2) = 1.221$, $p = 0.543$ for T_{50} and $Fr(2) = 3.110$, $p = 0.211$ for T_T). This analysis was performed on the aggregation of medium and long-distance target trials, which potentially increased the data's variance, hiding potentially significant differences. As such, we also analyzed time measures separately by medium and long distance trials. Friedman tests on the separated data showed no statistically significant differences between modalities for both T_{50} ($p = 0.415$ for medium, $p = 0.683$ for long distances) and T_T ($p = 0.249$ for medium, $p = 0.991$ for long distances).

The *Motion Path Efficiency* (*PE*) is defined as the ratio of the initial euclidean distance between the start and the target and the distance covered by the participant's motion (d_T) [25]. For example, a 50% *PE* indicates a trajectory twice as long as the shortest distance. The *Average Speed* (s_{ave}) of each trial was also computed as $s_{ave} = d_T/T_T$. Fig. 5 shows the mean and 95% confidence intervals for these measures. We observe that participants had less efficient paths while using the Cardinal modality ($\bar{x} = 58.08\%$, $\sigma = 21.45\%$) compared with Ordinal ($\bar{x} = 64.44\%$, $\sigma = 25.02\%$) or Continuous ($\bar{x} = 64.86\%$, $\sigma = 26.27\%$) modalities. A Friedman test confirmed that *PE* was affected by modality ($p = 0.022$). Using Post hoc Wilcoxon analysis, we determined that Cardinal was

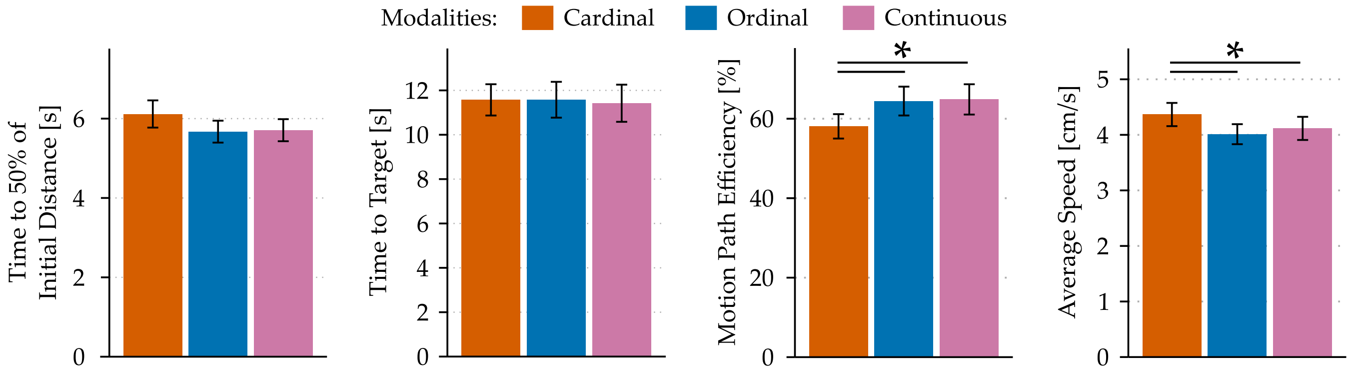

Fig. 5. Exp2: Active Perception and Response results comparing the three modalities in measures of time, path efficiency, and speed. The mean time to reach 50% of the initial distance to target, T_{50}, was greater for the Cardinal modality. However, this difference did not reflect on the mean total time to target T_T. Differences in behavior are again observed in motion path efficiency, *PE*. The Cardinal modality produced the least efficient motions. The *PE* was very similar for the Ordinal and Continuous modalities. Finally, the average speed of motion s_{ave} was greater for the Cardinal modality. Error bars represent 95% confidence intervals, and an $*$ indicates statistically significant comparisons ($p \leq 0.05$).

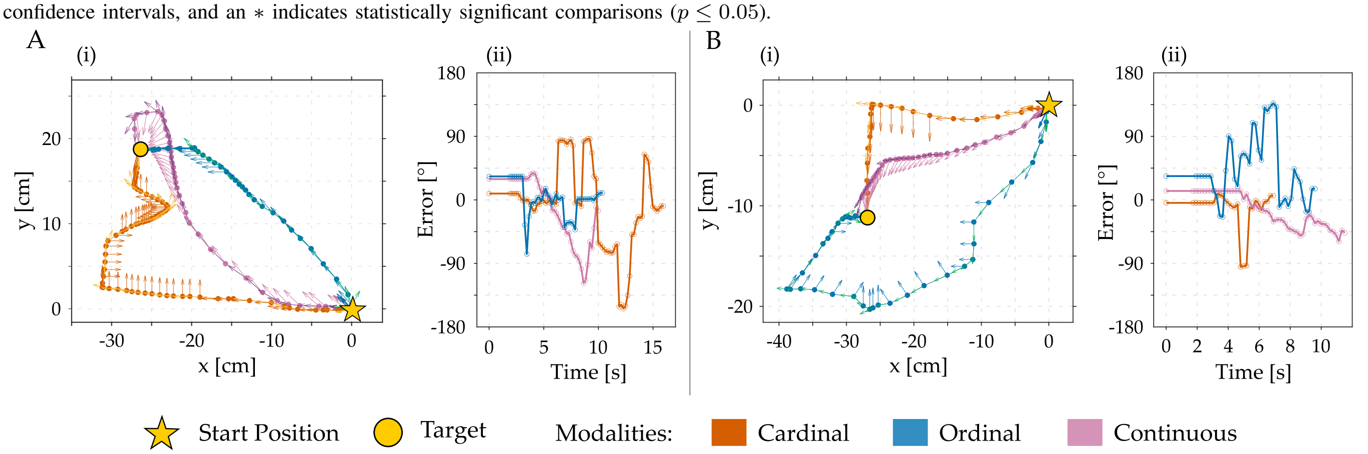

Fig. 6. Trajectory (i) and Angle Error (ii) plots for two targets, A and B. Each of the target plots shows trials performed by three different subjects, each interacting with different modalities. The trajectory plots show two vectors at each trajectory step; the heading angle α_H, tangent to the trajectory, and the instructed direction α_I. Error is computed as the instructed direction minus the heading direction. Clear distinctions in how the haptic rendering modality influences participants' reactions can be observed. For example, the Cardinal modality invites participants to move in straight motions, while Continuous influences smoother trajectories. Generally, participants were able to maintain their direction within $\pm 100°$ of the instructed angle.

significantly different than Ordinal and Continuous ($p < 0.05$). A Sign test (Wilcoxon signed-rank test for non-symmetric sets) determined that the *PE* was also affected by target distance ($p < 0.001$). For s_{ave}, a Friedman test shows that the modality had a significant effect on how fast users moved the device ($Fr(2) = 8.854, p = 0.012$). Post hoc analysis reveals that participants had a greater s_{ave} while interacting with the Cardinal than the Ordinal ($p = 0.006$) and Continuous ($p = 0.032$) modalities. The mean s_{ave} for each modality (Cardinal: $\bar{x} = 4.36\ cm/s$; Ordinal: $\bar{x} = 4.01\ cm/s$; Continuous: $\bar{x} = 4.12\ cm/s$) confirm that the Cardinal modality generally influenced participants to move faster. Participants spent the same total time T_T but had worse path efficiency *PE* for the Cardinal modality. We hypothesize that participants moved faster with this modality and that counterbalanced the lower *PE*.

In addition to measures of time, path efficiency, and speed of motion, we examined how participants reacted to the real-time changing haptic signals in this navigation/guidance task. To do so, we compare the *Instructed Angle* α_I (instruction provided by the haptic device) with the *Heading Angle* α_H (direction in which the participant was instantaneously moving) during the experiment. In Fig. 6, we depict example trajectories of three participants to two targets. Participants were generally able to follow the instructions, and their heading angle α_H generally stayed within $\pm 100^o$ of the instructed angle α_I. We also observe that participants exhibited a delay in their heading angle as the signals provided by the haptic device changed. This phenomenon is most clearly seen in the Cardinal modality since signal changes represent changes in $\pm 90°$, so participants made more drastic trajectory adjustments.

C. Influence of Experimental Order on Performance

Additionally, we analyzed the effect of order (i.e., the 1st, 2nd, and 3rd trial blocks shown) on the performance. The data shows that the mean T_T and s_{ave} for the 1st, 2nd, and 3rd trial blocks had indiscernible differences. Using Friedman tests, we observe that the order had no statistical significance on T_T ($p = 0.384$) nor s_{ave} ($p = 0.122$), suggesting that there were minimal learning affects.

D. Qualitative Results

In qualitative response questions, participants mentioned that the Cardinal modality was easiest to sense. As the complexity of the signals increased, participants mentioned deciding to "cheat" towards whichever pouch was inflated to a greater pressure. A few participants took this strategy to the extreme, expressing that when given more complex signals (Ordinal or Continuous modalities), they would *"completely ignore the less intense signal, and move in the direction of the more intense cardinal direction only"* as if the modality was Cardinal. However, other participants expressed that they *"felt more under control with the Continuous signal, because although (they) had to slow down, (they) felt the constant variation of signals gave (them) more precise instructions."* Participants also mentioned that they often overshot in all modalities and felt the need to move slower when the signals would change more often (as in the Continuous case). Participants also reported interpreting faster changes in signal as proximity to the target, which influenced them to move more carefully to diminish overshoot. When asked which modality they preferred, 4 participants indicated Cardinal, 2 Ordinal, and 4 Continuous, showing that these different strategies may have affected participant preferences.

V. Discussion

Our results indicate that all modalities of signal rendering allowed participants to perform the navigation task, though with different strategies. Despite creating these distinct behaviors in performance, no modality was preferred by a majority of participants. This is especially clear once the participant comments were considered, and these variations in qualitative reasons match the quantitative results. Participants noted how their speed changed as the signal complexity changed and alternately preferred the surety of the cardinal direction or the additional information in the continuous modality.

Examining the effect of signal complexity, there was a clear trade-off in path efficiency and average speed. From the perception experiment, participants were able to identify cardinal signals with near zero error, compared to an average of $\pm 5^{\circ}$ for continuous signals. This difference in perception is reflected in a difference in behavior during the navigation task, where the Cardinal signals are easily followed by participants (Fig. 6) but at the consequence of a less direct path. These difference are reflected in the decreased path efficiency and increased average speed compared to the other modalities.

The Ordinal and Continuous modalities, on the other hand, had comparable measures in terms of speed and path efficiency. Again looking at the perception results, we can see that ranges of responses are similar for the ordinal and other multi-actuator directions, so one might expect that these signals should continually improve performance as more are added. However, moving from Ordinal to Continuous in the navigation does not change participant behavior. This suggests that there are diminishing returns as signals are added, but more work is needed to determine what feature of the continuous signals leads to this effect. Looking at the whole picture, we observe that there exists a trade-off between increasing signal complexity and the accuracy of perception of signals. Our results indicate that when humans must use haptic signals, the mental processing of complex information often produces delays in response.

Additionally, this sense-and-respond process seems to affect the accuracy of apparent perception during use compared to static perception. In other words, considerable differences exist in humans' perception and their ability to use that sensory feedback. Further, the results of our experiments lead us to hypothesize that increasing the information inherent in haptic signals (increasing the complexity and/or the variety of signals) affects the efficiency of the reactions, either slowing down human response or leading to ignored signals.

In the end, all modalities allowed participants to find the targets. However, the different modalities come with their advantages and disadvantages. A complex set of haptic signals may be a better fit for tasks that require a precise human reaction. Conversely, simpler sets of signals may be adequate for tasks that require faster reactions and have loose restrictions on precision.

A. Limitations

We believe that our insights on the differences between the static and active perception of signals are generalizable to other types of haptic devices, not only soft haptic pouches. However, future experiments with other haptic technology may allow us to enhance the transferability of these observations to other haptic technology. Additionally, the haptic display used for these experiments had a low bandwidth. Repeating experiments with a haptic device with better frequency response may allow us to perform a better analysis of the influence of signal complexity in reaction time.

VI. Conclusion

In this paper, we present a study that provides insight on the differences in human perception and human use of sensory feedback in navigation-related experiments. In Experiment 1, participants were asked to identify a haptic cue and relate it to a direction based on cardinal references. The results of this experiment illustrate how humans perceive signals related to cardinal directions. Experiment 2 results helped us analyze how humans perceive and react to these guidance haptic signals rendered in different levels of complexity. The results of these experiments suggest that when humans must react to a signal, the depiction of the signal may be less accurate than when they only have to identify the signal. The results also show that increasing the information inherent in haptic signals affects the efficiency of human reactions. Simple signals are easier to interpret and lead to faster reactions, with reduced efficiency. Complex signals are more difficult to interpret, which slows down reactions, but increases task efficiency, as long as the signals provide additional information that can be accurately perceived. Future work will expand on verifying the insights on trade-offs related to increasing the complexity and/or the variety of signals to other haptic technology, such as vibrotactile feedback, as well as studying these effects in other application areas, like haptic devices for communicating robot learning [42], [43].

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