

Verbal Outperforms Cartesian Tactile Guidance in Telementored Needle Insertion Training

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Abstract—Needle decompression is an urgent medical task to remove excess air in the chest, often performed by individuals who lack training. Inspired by prior work, our sleeve uses our best performing 3D guidance cue strategy to date, Cartesian feedback, to give online directional cues in 3D space. The tactile cues are felt as strokes in the left, right, forward, and backward direction, or pulses on the top or bottom of the hand to indicate down or up motion, respectively. The goal of this study is to evaluate if haptic cues given in an online way could outperform verbal cues for needle placement. Our between-subjects experiment revealed that verbal cues in fact outperformed the tactile guidance cues, having respective median error values of 1.00 mm and 1.17 mm between the mentor and trainee positions. These results indicate that the efficacy of simple Cartesian tactile guidance reduces when it is applied in an online way, specifically in the case of simple desired motions in Cartesian space.

I. INTRODUCTION

Trauma remains a leading cause of death in the United States [1], [2]. Up to 50% of deaths due to trauma occur within one hour of arrival to the hospital and 30% occur within 24 hours. Improving training for first responders is a critical aspect of improving outcomes in rapid intervention.

Needle decompression (ND) is a fundamental skill to treat traumatic injuries. This procedure relieves excess air near the lungs and requires precise needle placement. If the procedure is done correctly, the odds of 24-hour mortality decrease by 25% [3]. Some possible causes of ND failure include anatomical obstructions, needle misplacement, and lack of drainage. Furthermore, a failed procedure could result in repeated pneumothorax, cardiac tamponade, life-threatening hemorrhages, and hematoma, among other morbidities [4]–[6]. These human-generated failures can be avoided with better equipment and training. With ND failure rates as high as 76% [7], [8], patients and clinicians would benefit from improved training systems, as well as options for online guidance during needle decompression.

Although many robotic systems for needle insertion have been proposed, none are suitable for online guidance in emergency settings due to size, power constraints, and significant setup time. Rather, we aim to develop an emergency guidance system that can be used for training or telementoring of a needle decompression task. This paper presents a low cost

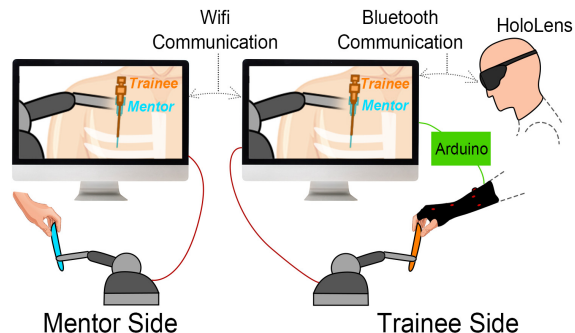


Fig. 1: Diagram of the envisioned telementoring system, including the trainee and mentor. Needle insertion force is applied and perceived through the grounded haptic devices. The mentor guides the trainee along an ideal insertion path via the vibrotactile guidance sleeve. The trainee’s real environment is also shown to the mentor.

sleeve that uses vibrotactile guidance cues to inform a first responder of a mentor’s recommended insertion motions. This sleeve has been tested in multiple studies [9]–[11]. Each of the studies evaluated three different configurations of the motors, both in terms of actuator positions, as well as actuation sequences. We found that the best performing configuration depends on the complexity and purpose of the application. The most recent and most relevant study proved 96.8% accuracy of following cues in a 3D Cartesian space. Still, this work was limited in that only one cue is provided per insertion. Therefore, in this paper, we extend the work in [11] by adding a human mentor to provide online guidance through continual cue delivery during insertion.

II. BACKGROUND

Haptic technology is paramount to the success of medical robots, especially in telemedicine where visual and audio feedback may be of lower quality than reality. Tactile feedback, specifically, has proven beneficial in several medical applications, such as reducing surgical grasping forces [12], conveying tissue force information [13], [14], and even reducing mental workload in complex navigation tasks [15].

Having prehospital applications in mind, tactile feedback could also be superior to kinesthetic feedback when it comes to portability, wearability, and cost. In other guidance tasks, researchers have achieved path-following accuracies as high as 99.4% in the case 2D tactile guidance [16], and mixed yet insightful results have been found in the 3D case that seem to indicate the design of intuitive 3D tactile guidance cues is more nuanced than one might expect [11], [17]–[20]. According to a recent meta-analysis, tactile feedback

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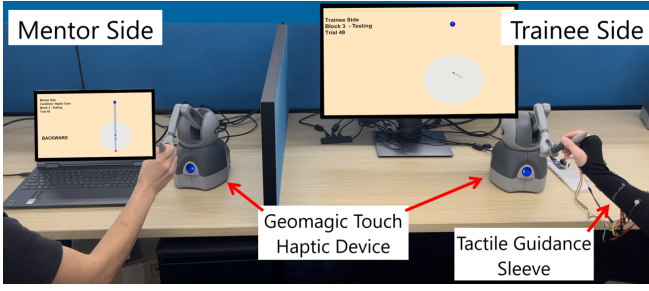


Fig. 2: Experimental set-up. A mentor follows a path shown in their virtual environment. The trainee relies solely on guidance cues to follow the mentor along the same path.

does not perform significantly better or worse than auditory feedback [21]. Considering both the prior art, along with our own results [11], we hypothesize in this study that online tactile guidance cues will perform equally well to verbal guidance. If proven correct, the results would imply that traditional verbal training can be reasonably replaced with our tactile guidance sleeve.

Westebring et al. found that haptic interactions in needle insertion training are limited in one of two ways: either they cannot provide real-time interaction due to computational costs, or they provide real-time interaction with low accuracy [22]. Furthermore, this means that mentor-trainee bidirectional interaction has yet to be done both online and accurately. To address these issues, this paper presents a telementoring haptic system that aims to achieve online, bidirectional interaction between a medical mentor and a medical trainee practicing needle insertion (Fig. 1). We demonstrated accurate haptic feedback from the trainee to the mentor in our previous work [23] and now present the complimentary study where we evaluate tactile guidance that informs the trainee of a mentor's suggested directions of motion as they follow an insertion-like trajectory.

III. TELEMENTORING SYSTEM DESIGN

To enable 3D guidance in multiple directions, our system has three components: (i) mentor and trainee kinematic data collection, (ii) interactive virtual environments, and (iii) a sleeve for delivering tactile guidance. Figure 2 shows the realized system where the mentor side and the trainee side are almost identical with the exception of a tactile guidance sleeve worn by the trainee.

A. Kinematic Data Collection

Communication between the mentor and trainee is accomplished with Geomagic Touch haptic devices and a virtual reality environment. A virtual model of the haptic styluses are rendered in the virtual environment as described in section III-B. The mentor's objective is follow a path in the virtual environment with the tip of their stylus. The trainee's objective is to follow the mentor using guidance cues; doing so ideally results in their stylus tips being at the same position along the path. To provide guidance, it is necessary to capture position data from the haptic devices. We collect position data at 50 Hz, the default loop update

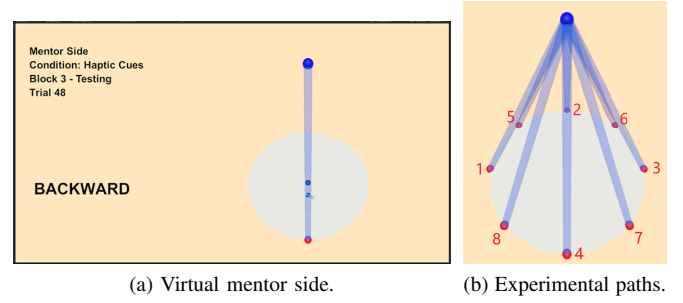


Fig. 3: The mentor follows one of eight possible paths (b) in their virtual environment (a).

rate in Unity, the programming environment used in this experiment. The method of providing guidance is further explained in section IV-A.

B. Virtual Environment

The mentor and trainee interface with the same virtual environment, created in Unity. Like the physical set up, the virtual world has two sides. The mentor side (Fig. 3a) contains a virtual model of the mentor stylus, a proxy of the trainee's stylus tip, and task-specific objects including a visible path and a circular "table" where targets lie. The experiments tests eight paths (Fig. 3b), where only one path is shown per trial. We leveraged the Unity Experiment Framework (UXF) which provides easy-to-use functions for building experiments and collecting data [24].

C. Tactile Guidance Sleeve

Our previous study found that 3D Cartesian space cues performed other cues tested with 96.3% accuracy when one cue was given at a time during a 3D needle-insertion task, where possible target locations were also shown to the subjects [11]. Therefore, we used the cartesian space configuration of vibration motors for this experiment. This configuration has six vibrational motors (Fig. 4). Motors 1 and 6 are placed on the dorsal and palmar side of the hand, 5 cm from the wrist. Motor 2 is placed on the wrist, above the arm. Motors 3, 4, and 5 are placed 9 cm from the wrist, along the length of the arm, where motor 3 is on the top of the arm in line with the wrist and motors 4 and 5 are 5 cm to the left and right from motor 3 respectively.



Fig. 4: Guidance sleeve with numbered vibrotactile motors

TABLE I: Guidance direction according to motor actuation sequence

Guidance Direction	Motor Sequence
Left	4, 4, 4
Right	5, 5, 5
Forward	3, 2, 1
Backward	1, 2, 3
Up	6, 6, 6
Down	1, 1, 1

Other commonalities with the previous study include an elastic compression sleeve, the type of vibrotactile motor (ROB-08449, Sparkfun), velcro attachments, an arduino micro for motor control, and a ribbon cable for a compact wiring. Differences in the design relate to cue delivery. The functionality of the sleeve also evolves with the addition of a mentor. Rather than providing a single cue per insertion, our application of the sleeve is online such that cues are triggered continually as the trainee performs a single "insertion". Thus, in our experiment, we study the efficacy of online delivery of tactile cues during a 3D needle-insertion task.

IV. METHODS

A. Providing Guidance Cues

Our experiment is designed to study haptic guidance cues in comparison to the control, verbal guidance. In our system, guidance is directive meaning that the experimental participant (acting as the trainee) must first recognize the guidance cue provided by the experimenter (acting as the mentor) and respond with the appropriate motion. Directions of guidance are in Cartesian space. Hence, there are six directions of guidance: left ($-x$), right ($+x$), forward ($-y$), backward ($+y$), down ($-z$), and up ($+z$), where forward is equivalent to the participant moving the stylus away from themselves. Every guidance cue lasts 0.66 seconds, and there are 0.34 seconds between cues; therefore, one cue is fired per second. Additionally, a single guidance cue can represent only one direction. Table I lists each direction with the corresponding motor sequence. For verbal feedback, the six possible guidance cues are "left," "right," "forward," "back," "down" and "up." We avoid an inconsistent cue rate by pre-recording the verbal guidance cues and triggering the audio at one cue per second. Haptic guidance is provided through the vibrotactile sleeve (Figure 4). For both conditions, the direction of guidance at each cue is determined by the direction of maximum difference of position between the mentor stylus and the trainee stylus. For this study, we did not add an additional experimental condition of both verbal and haptic cues as the objective is to find the simplest and most effective cue to not overload multiple sensory channels.

B. Experimental Protocol

A total of 14 novices participated in the study; 7 participants randomly received haptic guidance cues while the other 7 received verbal guidance cues. Participants did not have physical and cognitive impairments and signed a consent form which was approved by the Institutional Review Board of the University of Texas at Austin (UT IRB #STUDY00000287). None of the haptic participants were left handed. The purpose of the experiment was to determine the efficacy of tactile guidance, through which a mentor directs a trainee in following paths inspired by ND methods. The experiment compares the haptic and verbal modalities in a between-subjects manner where one group of participants is given only haptic guidance cues and the other group is given only verbal guidance cues; the experiment is identical in every other aspect.

The experiment is composed of three blocks: pretraining, training, and testing. During pretraining, participants are trained on the fundamental directions of guidance. Thus, the participant follows six paths each one being starting at a central point (0,0,0) and ending at a target that is 5 mm from the start point in a single fundamental direction. The pretraining block consists of 24 trials, corresponding to 4 total trials per path. In trials 1-6 and 13-18, the paths are visible to the trainee. For the remaining trials, the trainee relies solely on the guidance cues to follow the mentor and consequently reach the target.

The next two blocks use the eight path options shown in Figure 3b. The paths, as with the whole system, were designed to be clinically relevant. They also take after the 8 paths in [11] for control and comparison purposes. Therefore, each path has the same starting point (0,0,6.25) mm and a straight path to one of eight targets on a 12.5 mm circle 6.25 mm below the start point.

During training, the participant becomes familiar with following guidance cues along eight paths. In the first eight trials, the trainee is able to see both the path and the mentor in order to observe the pace at which the path is to be followed and to associate guidance with ground truth. In the second eight trials, the trainee practices following the guidance cues without seeing the path or the mentor. During testing, the eight paths are tested three times each in a random order. For all testing trials, the trainee can see only the start point; they cannot see the path, the target, nor the mentor.

C. Data Acquisition and Analysis

All data was collected through the UXF. Importantly, for each trial, data collection was triggered when the trainee touches the start point, and collection ends when the mentor touches the target. Measurements included stylus position, guidance cue labels, "help" invocations, and time.

We characterize the effectiveness of tactile guidance through the following metrics: error between the mentor and trainee positions, recall of correctly followed guidance cues, and individual-perceived workload of completing the task. We chose to calculate root mean squared error between the mentor and trainee positions. To compare the trainee's direction of motion with a given guidance cue, we extracted and labeled the direction of maximum velocity. Also, for each condition (haptic or verbal), we characterized randomness of motion by calculating Cohen's kappa of confusion matrix data between the guidance cues and the trainees' actual directions of motion. Lastly, at the end of the experiment, the participant completed a NASA-TLX survey [25] to evaluate perceived workload under each condition.

V. RESULTS AND DISCUSSION

In this section, we present results pertaining to error vs. condition, path completion time, and direction; recall and Cohen's kappa of cued direction vs. actual trainee direction; and perceived workload surveyed through the NASA TLX.

Figure 5 presents a boxplot of the error for haptic and verbal subjects. Overall, it can be seen that verbal subjects performed with less error (median: 1.00 mm, Q3: 1.46) with

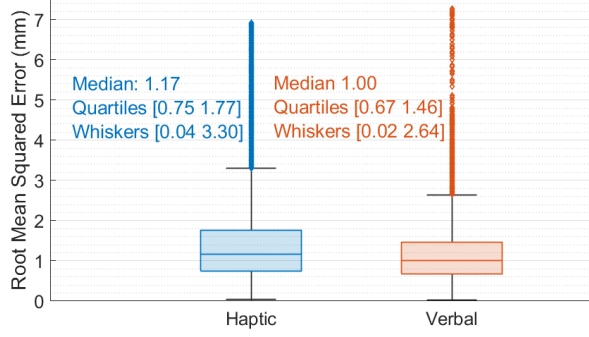


Fig. 5: Error boxplots for haptic vs. verbal subjects

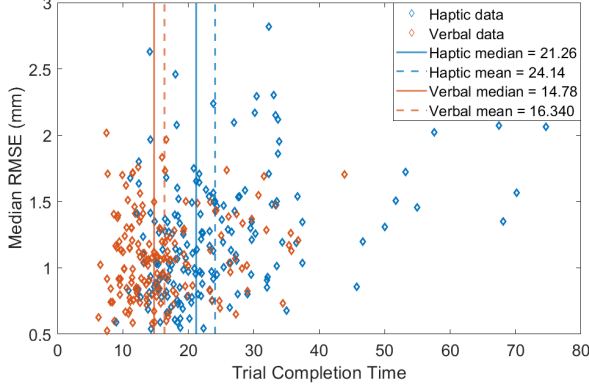


Fig. 6: Trial completion time for haptic vs. verbal subjects

a few outlying exceptions. Further, the haptic distribution not only has a higher median error (1.17 mm), but has a higher third quartile (1.77 mm) meaning that there is more data for larger error values in the haptic distribution in comparison to the verbal distribution. A Lilliefors test yielded $p = 0.001$ for both distributions, which rejects the null hypothesis that either of the distributions are normal. The distributions also have unequal variances ($\sigma_{haptic}^2 = 0.85$, $\sigma_{verbal}^2 = 0.43$); therefore, we conducted a Mann-Whitney U test on the two distributions. Mann-Whitney U test returned $p = 0$; therefore, the differences in the distributions are significant.

One probable reason for the difference in performance is time needed to interpret the cues. Figure 6 shows that on average, verbal subjects completed their insertions 68% faster than haptic subjects ($p = 5.61 \cdot 10^{-17}$ according to the Mann-Whitney U test). In the case of verbal guidance cues, participants hear familiar, unmistakable words, (i.e., left, right, up, down, etc). In the case of haptic guidance cues, the participants must develop an association with motor actuation sequences to a direction of motion. We aimed to make the haptic cues intuitive. For example, in the most difficult case to move forward or backward, we attempted to mimic a saltation illusion [10], [26]. Despite these efforts, there is clear room for improvement.

A feasible idea for improvement is to have *continuous* delivery cues. Our prior work showed that discrete cue sequences were sufficient in the case where only one cue is provided per insertion [11]. Our study reveals that providing cues *continually* but still discretely is not sufficient for a

online guidance. Continuous delivery seems more promising as it better mimicks traditional hand-on-arm guidance. Other ways to improve haptic cue interpretation are increasing the length of training, combining verbal and haptic cues, and considering hand orientation.

Some haptic participants expressed trouble distinguishing certain cue directions from others. In the worst case, a subject reported confusion between left/right cues with up/down cues because of the orientation of her hand and arm while holding the stylus. Poor hand orientation not only increases interpretation time but also results in misinterpretation or misguidance. Figure 7 shows confusion matrices that provide classification measurements of cued direction vs. actual trainee direction. We row-normalized the confusion matrices to get the recall of each cue. In our study, recall can be viewed as the true-positive rate or percentage of correctly followed cues for one given direction. Verbal subjects had higher recall values for every cue direction. "Forward", "Backward", and "Up" were the most confused cues for all subjects. Table II summarizes these results.

TABLE II: Commonly misinterpreted cue directions

Actual Cue	Interpreted Direction	Haptic % Misinterp.	Verbal % Misinterp.
Backward	Down	47.8%	29.7%
Forward	Down	38.8%	34.1%
Up	Backward	26.7%	19.2%

Also, we observed that the most frequent erroneous motion was in the down direction, except for the up cue. Our results shows record of unbalanced data where trainees moved down five times more than they moved in any other cue direction. The principal direction of every path is downward, so it is reasonable for trainees to move down most often. Nevertheless, we calculated Cohen's kappa of the data [27] as a measure of correlation between the cue direction and the trainee's motion. For haptic subjects, $k = 0.329$. For verbal subjects, $k = 0.629$. These results indicate that verbal subjects were more likely to *intentionally* move in the prompted direction while haptic subjects are more likely to move in prompted directions *by chance*.

Seeing that confusion is greater in the haptic case, we suspect three possible sources for confusion: alignment of coordinate frames, lack of perception in the virtual environment, and insufficient training. The global coordinate frame of the virtual environment should be aligned with that of the physical environment such that moving the stylus vertical upward, i.e. away from the table, results in a vertical upward motion in the virtual environment. Similarly, the coordinate frame of the vibrotactile motor assembly should be aligned with all other coordinate frames. In future work, we can either control arm orientation using a custom stylus attachment or correct guidance through IMUs and calibration. In addition, online knowledge of hand configuration could additionally help to understand the relationships between the stylus, the hand, and the arm [28].

Another likely cause of confusion is perception in the

Haptic Subjects - Recall (row normalized)										
Cue (desired direction)	Right	51.1%	3.7%	8.6%	2.4%	5.6%	28.6%	→	51.1%	48.9%
	Left	3.2%	54.2%	10.1%	2.9%	6.2%	23.4%	→	54.2%	45.8%
	Back.	6.2%	4.7%	34.4%	4.3%	2.7%	47.8%	→	34.4%	65.6%
	Forw.	7.3%	6.8%	7.7%	30.9%	8.4%	38.8%	→	30.9%	69.1%
	Up	8.5%	5.7%	26.7%	5.3%	36.2%	17.6%	→	36.2%	63.8%
	Down	4.8%	6.5%	7.7%	10.7%	1.7%	68.7%	→	68.7%	31.3%
	Right	Left	Back.	Forw.	Up	Down				
Trainee actual direction										

Verbal Subjects - Recall (row normalized)										
Cue (desired direction)	Right	71.9%	0.4%	1.2%	2.0%	1.2%	23.3%	→	71.9%	28.1%
	Left		78.6%	2.9%		2.1%	16.4%	→	78.6%	21.4%
	Back.	1.7%	2.0%	61.4%	0.7%	4.4%	29.7%	→	61.4%	38.6%
	Forw.	2.2%	1.8%	1.3%	57.5%	3.1%	34.1%	→	57.5%	42.5%
	Up	3.2%	1.9%	19.2%	7.1%	60.3%	8.3%	→	60.3%	39.7%
	Down	1.0%	1.2%	10.0%	2.4%	0.9%	84.6%	→	84.6%	15.4%
	Right	Left	Back.	Forw.	Up	Down				
Trainee actual direction										

Fig. 7: Confusion of cue direction vs actual trainee direction. The percentages are a measure of recall and the two right-most columns summarize the recall for each cue direction. The red boxes indicate performance worse than chance.

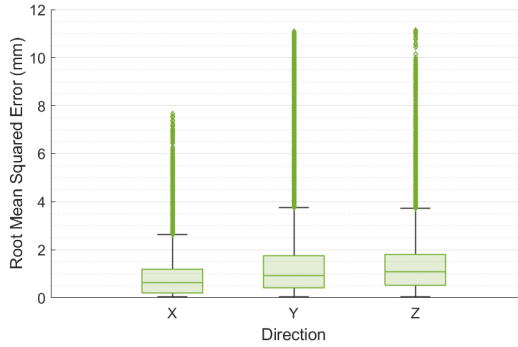


Fig. 8: Error vs. direction for all subjects

virtual environment. Figure 8 shows RMSE of all subjects vs. each direction x , y , and z . Despite most paths having some x -component, error in the x direction is significantly lower than error in the y ($p = 0$) and z ($p = 0$) directions. This is true for both haptic and verbal subjects which points to a shared issue: perspective. In figure 9, the top view clearly shows that both the mentor and the best performing subject deviate from the paths especially paths 1 and 3 where there is no y -component, just x - and z -components. The front view is visually very similar to what is shown in the virtual environment and poses an illusion of being on the path when in reality there is some deviation. Perspective is a research topic on its own; some ideas for improvement in perspective include strategic lighting and reference planes.

Lastly, results from the NASA TLX survey reveals a notable difference in the perceived workload between haptic and verbal subjects (Fig. 10). Haptic subjects had worse ratings than verbal subjects for physical demand, effort, frustration, and mental demand; a better rating for performance; and an equal rating for temporal demand. These results agree with our overall conclusion that verbal subjects performed better in this study than haptic subjects.

VI. CONCLUSIONS

In this paper, we presented a haptic telementoring system intended for needle decompression training. We compared tactile guidance to verbal guidance in a between-subjects experiment. We found that verbal subjects performed significantly better than haptic subjects for all of our metrics.

The error between mentor and trainee stylus positions was lower for verbal subjects by 0.17 mm. Trial completion time was lower by 6.48 seconds. Verbal subjects had better recall and Cohen's kappa values when comparing cue direction to actual trainee motion. Finally, verbal subjects had 10% lower overall workload for the task and experienced lower effort, frustration, mental demand, and physical demand as measured by a NASA TLX survey.

Various studies point to the theory that task complexity lowers performance of tactile devices. Our study concurs with this theory as it revealed decreased accuracy from our previous (simpler) study [11]. We increased complexity of a path guidance task by providing cues in an online matter. Consequently, interpretation time is bounded by the period of a cue sequence (one second) resulting in longer path completion time and greater cue misinterpretation. We believe that performance can be improved by providing more training, enhancing perception of the virtual environment, correcting tactile guidance based on arm orientation, and redesigning the glove to deliver cues continuously.

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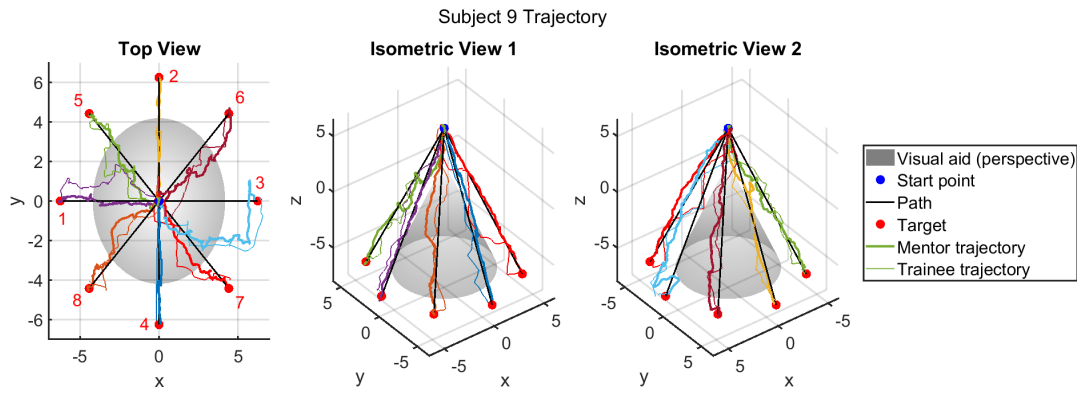


Fig. 9: Trajectories of the best performing subject.

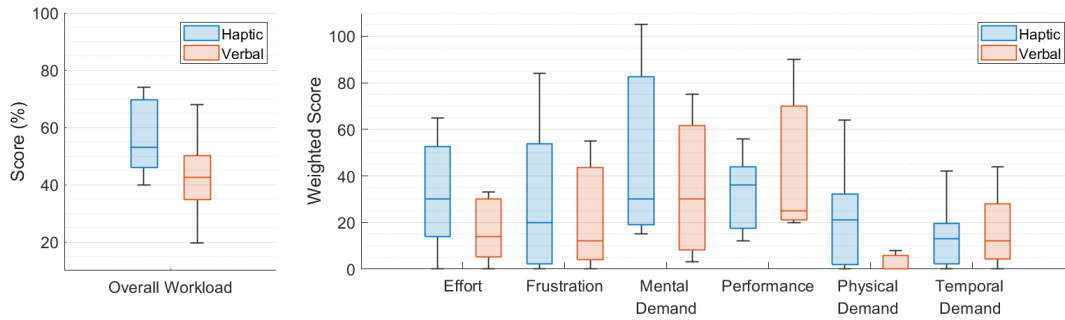


Fig. 10: Workload from the NASA-TLX for haptic vs. verbal subjects

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