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Directional Perception of Force in a Virtual Reality Environment

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ABSTRACT Force feedback during teleoperation and in Virtual Reality (VR) environments is becoming increasingly common. We are interested in understanding the impact of motion on the directional accuracy of force perception, as observed in a VR environment. We used a custom force-feedback system that pulled a handle with a force of 1.87N at various angles in front of N=14 subjects. The virtual environment showed a curved wall, which corresponded to the locations from which the force could physically originate. Subjects selected where they perceived the force to originate from with a virtual laser pointer and by orienting their head. We compared several conditions: the subject held the handle still; the subject moved the handle back and forth toward the center of the wall; the subject moved the handle back and forth across their body; and the subject moved the handle back and forth toward where they thought the force was originating. Subjects were able to localize the force with an average accuracy of 1-10 degrees depending on the force's location, which is better than previous studies. All conditions had similar accuracies. Subjects had the best precision when they followed the force as compared to either of the other conditions with movement. As a secondary objective, we compared the accuracy of a hand-held controller and the head-mounted display (HMD); the HMD was 2.4 degrees more precise than the hand-held controller.

INDEX TERMS Force perception, force localization, virtual reality, teleoperation, haptic feedback, force feedback.

I. INTRODUCTION AND RELATED WORK

As robots become more advanced, the number of robots deployed for dangerous tasks such as minesweeping, underwater investigation, space exploration, and handling reactive materials is increasing [1]. Teleoperation of robots enables humans to perform tasks in dangerous environments while remaining at a safe distance [2], [3]. Teleoperation also has the advantages of flexibility and failure recovery over fully autonomous systems [4]. The effectiveness of teleoperation can be greatly improved if users are able to receive realistic haptic feedback [5], [6]. However, achieving this requires a good understanding of human haptic perception capabilities [7].

Similarly, haptic feedback systems in Virtual Reality (VR) systems are becoming more prevalent. For purposes such as training of surgery or other skilled tasks, or for rehabilitation, fully immersive systems with realistic haptic feedback are beneficial [8]–[10]. This too requires a good understanding of human perceptual abilities.

Our study is motivated by applications where a force is applied at some direction to the user. Examples of this include surgical systems, where it is important to know the direction a tool is pushing on the body, or robotic manipulation, where a robot may be interacting with objects with unknown environmental forces on them or that may not be visible to the user, for example if they are in a crevice or bag.

Several previous studies have examined how well people can determine the direction of forces on the tip of their index finger, using a Phantom haptic device. Tan *et al.* [11] studied force discrimination, applying reference forces perpendicular to the fingertip in various directions and determining if the subjects could distinguish between a reference force and a test force in a different direction. They found that subjects were correct with an average threshold of 33°, independent of direction. In the experiment, the subjects' fingers moved

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somewhat due to the applied forces, with an average of 10mm and a maximum of 21.3mm. Thus, potentially proprioceptive sensors in the finger could be giving information to the user. A second study found a threshold of 25.6° for a test condition that was similar to those in the first experiment [12].

Meanwhile, other studies investigated the precision and accuracy of force direction perception with entire hand and arm. Van Beek *et al.* [13] applied forces parallel to the ground to a handle held by subjects, and studied both the effects of force magnitude and direction. All subjects had their hand fixed with the same geometry and no hand movements were allowed. Results showed that force magnitude does not impact the directional perception and that this applies to both left- and right-handed people. With the hand stationary, the error between the physical force and perceived force was large, with a difference as much as 60° and an average of roughly $10^\circ - 15^\circ$. Furthermore, an anisotropic force magnitude and directional perception error pattern was found. This error was not caused by arm geometry as all subjects had their arm in the same pose.

A follow-up study [14] found that this anisotropic error was subject-based. For half of the subjects, subjects had a self-consistent error pattern over time and the error pattern was unique to each subject. Van Beek was unable to explain the cause of the error pattern, but determined that subject-based internal factors contributed to it.

The force perception accuracy of horizontal forces was also studied by [15] with a force-producing joystick. During the test, the joystick randomly produced a reference force and test force in pairs. All test forces were either ±5°, 10°, or 15° away from the reference force, and subjects were asked to determine if the test force was to the left or right of the reference force. Results showed that with a 5° difference, subjects identified the direction with close to 50% accuracy (i.e. they guessed randomly), and with a difference of 10° they achieved 69% accuracy. The highest accuracy was 82.7% with an angular difference of 15°. They found that force directional perception was not uniform, further supporting the anisotropic error pattern mentioned previously. The results also showed that tests with forces coming from the center had higher accuracy compared to the sides.

A few studies examined force reproduction, and found high accuracies. Experiments by Gwilliam *et al.* [16] examined how well people could reproduce a force's direction when they held onto a force-producing joystick handle. The handle produced a force, then the subject had to duplicate it. They found that the mean error was around 1 degree but the standard error was 22.9°. In their study, the force was pulsed and much shorter than in other experiments mentioned here, with a total duration of 800 ms. Toffin [17] studied the relationship between physical force and perceived force by doing a matching task. Subjects experienced a reference force and then immediately after felt a test force, the angle of which they could change with a knob until it aligned with the reference force. They found a very small average error of $< 1^\circ$, with individual subjects having average errors up to 4°.

Yet another category of studies examined the effect of arm geometry on force directional perception. Onneweer [18] conducted several studies about this. Onneweer tested the force reproduction in both magnitude and direction for four different arm postures in 8 different force directions. An anisotropic, elliptical perception distortion was found for both direction and magnitude perception, with the major axis of the ellipse (least-accurate direction) crossing the hand and the shoulder joint. This elliptical distortion supported Van Beek's findings, but contradicted Elhajj's findings, which showed that the direction connecting the hand and shoulder should be the most accurate direction. Onneweer also investigated the relationship between the elbow joint angle and force reproduction error. The force reproduction ellipse changes as arm posture changes rather than the force magnitude. This indicates that the arm geometry affects both the direction and magnitude force reproduction error. Tanaka [19] did a similar experiment but studied the shoulder joint's effect on force perception. The result is consistent with Onneweer's findings: the directional perception of hand changes according to the angle of the shoulder joint. Asymmetric elliptical magnitude distortions were found with the major axis, being the least accurate, crossing the hand and shoulder joint.

The studies described thus far were conducted with the arm stationary. However, we are interested in the impact of hand movement on force perception. Yang *et al.* [20], [21] did several studies about the force direction just noticeable difference (JND) during hand motion. Subjects held a stylus attached to a Phantom force feedback device in their hand, with their arm fixed. Subjects moved the pen left to right at a constant speed while determining if they could notice differences between pairs of a test force and reference force in the frontal plane. The test procedure was very similar to the experiment done by Tan *et al.* [11], and the results showed a perception threshold of 32°, similar to the finding by Tan. They also found that the hand movement speed did not seem to impact the result.

Amemiya *et al.* [22] examined the force direction perception of the hand with a vibrating puck rather than applying a physical force. Two experiments showed that both rotational and translational limb movement used to explore the force direction improved the precision of directional force perception. In contrast, a different group found that exploratory motion impaired tactile sensitivity [23].

In summary, there have been many studies related to force feedback perception and reproduction with the arm, hand, and fingers. These studies focused on different aspects such as the JND of different joints, the force direction and magnitude accuracy, or the arm geometry. Based on these findings, it appears that, first, proprioceptive sensors in the body could potentially be giving information to the user. Second, magnitude does not affect the force localization accuracy. Third, asymmetric distortions exist and arm geometry is an important factor in this distortion. Fourth, there are subject-based error patterns, and the force perception error can vary quite a lot.

However, there have been few studies that involve movement. No prior work has been conducted that includes movement of the whole arm, including the wrist, elbow and shoulder while determining force localization accuracy. We are interested in understanding the effects of motion on the directional accuracy of force perception. Potentially, people may be able to triangulate the location from which a force is originating if they can feel the force pulling in different directions on their hand. Practically, it is frequently impossible to remove all arm motion when conducting force feedback with the hands. If arm movement improves accuracy, then it should be facilitated during teleoperation for better haptic communication. Conversely, if arm movement reduces accuracy, teleoperation systems could seek to eliminate this effect. Thus, we studied the directional accuracy of force perception during motion using the whole arm.

Furthermore, we also investigated the effects of subjects' being able to move their hand following the direction from which they perceived the force to be originating. We theorized that even beyond just triangulating, users may be able to hone in on the force's direction by exploring several directions, and thereby gain a better sense of the force's location as compared to moving their hand in a pre-specified pattern. This scenario is applicable in situations such as shared manipulation of objects by two people or by people and robots, where the two parties need to achieve a common goal and information can be transmitted haptically through contact with the object.

In our experiment, we used a virtual reality (VR) environment to both provide forces to users and measure their feedback. In the VR environment, the user can choose the direction from which the force originates by pointing to it directly. In this manner, the user's selection of the force direction is naturally correlated with the physical space, as opposed to their choosing a direction on a computer screen like many previous studies. Also, we asked the user to look at where the force was originating from, and we collected head position, for an alternate way of force localization. Compared to previous studies, ours is the first to use a VR environment. For comparison, in previous studies, there have been two popular methods of testing force feedback: distinguishing between a test and reference force, and reproducing a force. The first method allows the measurement of a user's perception precision and accuracy only indirectly, while the second method involves proprioceptive skills, which might affect the result unexpectedly. With VR, our test method improves on each of these issues.

Thus, in this paper, we tested several hypotheses:

1) H1: A VR environment will lead to better accuracies for force perception as compared to other means of selecting the force direction.
2) H2: Pointing with the head (i.e., looking toward the direction of force origination) will result in the same accuracy as pointing with a controller held in the hand but have better precision.
3) H3: Being able to move the hand to different locations and triangulate while experiencing a force will result in better force perception accuracy than holding the hand stationary.
4) H4: Being able to move the hand toward the perceived force origination point repeatedly will result in better force perception accuracy than both holding the hand stationary and moving in pre-specified patterns.
5) H5: Subjects' confidence in where the force originates will be correlated with their actual accuracy.

II. METHODS

A. SUBJECTS

A convenience sample of $N = 14$ individuals was selected. They were 21.0 ± 1.4 years old, 7 were male, and 7 were female. All subjects were volunteers associated with Virginia Tech. On the scheduled day for testing, subjects signed the consent form before participating in the study. This process was approved by the Virginia Tech Institutional Review Board (IRB# 17-904).

B. EXPERIMENTAL APPARATUS

We developed a custom force-feedback apparatus to display physical forces to a person (Figure 1A). The system includes a 1m-long swing arm that rotates about a central pivot point; at the far end of the swing arm a winch ("Force Winch," close-up in Figure 1B) winds a string up around a spool, creating a controlled force on the string. The string is connected to the top and bottom of a 2.54 cm diameter PVC pipe which the user holds in the center. The string was attached in a way such that forces on the string pulled the handle evenly and did not introduce any torque. The moving winch is composed of a Maxon EC 4pole 30 100W motor directly connected to a spool of diameter 21 mm. This provides forces on the string of up to 1.87 Newtons. A second winch ("Positioning Winch") is similar but includes a gear ratio of 6.25:1 between the motor and spool using a timing belt. This winch is connected to the swing arm with a string, and is used to control the position of the swing arm, moving it to different locations. Since the Positioning Winch can only provide tension in the string, a second string is connected to the opposite side of the swing arm, which extends over two pulleys and connects to a weight. This provides a constant force to the left opposing the force from the stationary winch, which pulls to the right.

An HTC Vive virtual reality system was used to create a virtual display for the participant and also to track the positions of everything in the experimental setup. Subjects wore an HTC Vive head mounted display (HMD), held an HTC Vive controller in their non-dominant hand, and held the PVC pipe handle in their dominant hand. In addition to an HTC HMD, subjects also wore overhead-style hearing protection to isolate any audio distractions. Three HTC Vive trackers were used to track the PVC handle, swinging arm pivot point, and Force Winch guiding hole, respectively. For convenience, we refer to these three trackers the "handle tracker," "pivot tracker," and "winch tracker" (see Figure 1A).

Subjects were seated in an upright chair which was positioned far enough back so that the handle's strings would clear

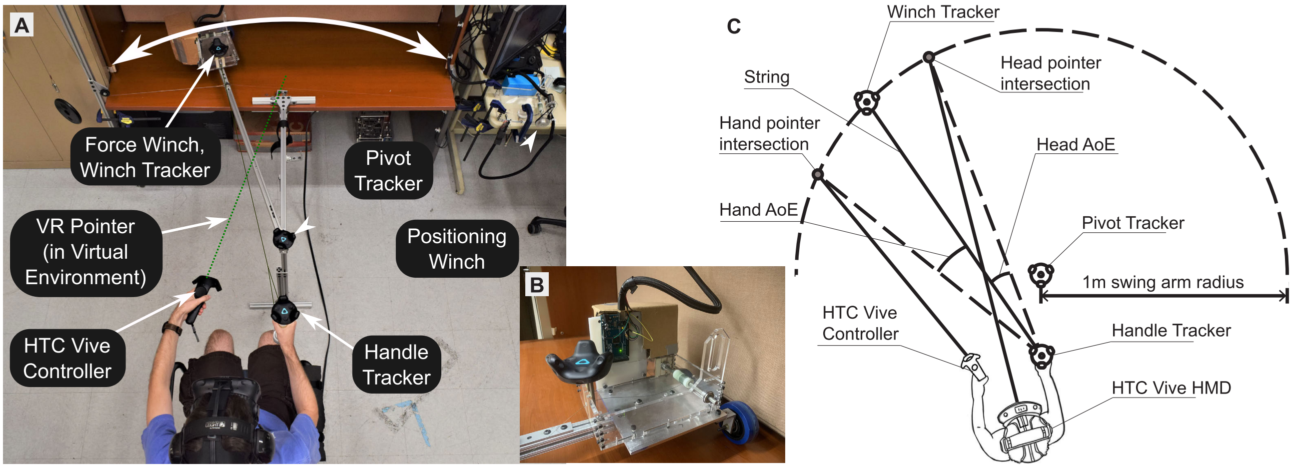

FIGURE 1. A, Overview of the system used in the experiment. B, Close-up of the Force Winch. C, An overview of all tracking devices and how hand and head AoEs were calculated. All AoEs were calculated by using the string as ground truth. Clockwise offset will produce a positive AoE while counter clockwise offset will produce a negative AoE. Both ray casts from head and hand were recorded when user press and released the trigger button on the HTC Vive controller. In the diagram, as drawn the subject has a Head AoE that is positive while the Hand AoE is negative.

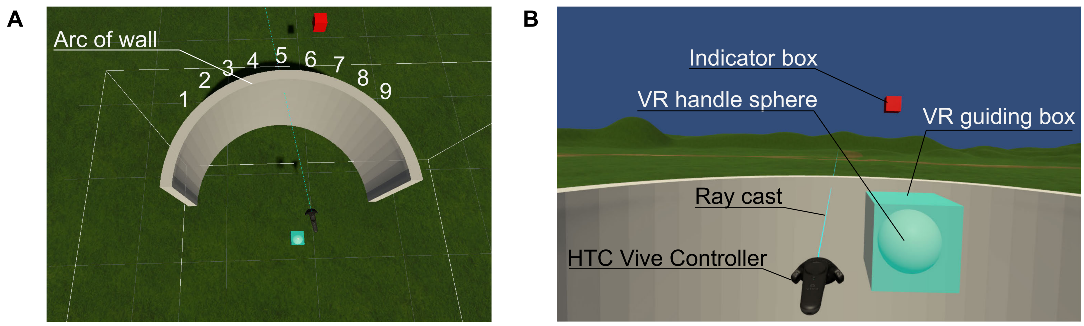

FIGURE 2. A, Top view of the VR environment in experimental conditon 1 (Stationary condition). From top to bottom, the objects are: indicator box; arc of wall; HTC Vive controller with ray cast; VR guiding box with VR sphere in it. During the Stationary condition, subject was required to maintain the VR sphere, which is the location of the handle tracker, inside the VR guiding box. The VR guiding box is a different shape and orientation for other conditions. B, First person view in the VR environment. The Indicator box turns green to signal the start of the trial and turns red once a selection is made. A selection is made by pointing the ray cast from the HTC Vive controller toward the arc and pulling then releasing the trigger. The head orientation, as measured by the VR headset, was recorded when the trigger was released.

the pivot tracker when the subject's arm was fully extended. Subjects were placed so that their dominant hand was directly behind the pivot of the swing arm. During the experiment, the force winch exerts a very small unnoticeable force on the PVC handle at all times to keep the string in tension. When forces are applied, the force gradually ramps up to 1.87 N within 2 seconds to pull the PVC handle. There are nine preset positions (Figure 2A): $\pm 32°$, $\pm 24°$, $\pm 16°$, $\pm 8°$, and $0°$, where $0°$ is perpendicular to subjects' chests. The swinging arm system can reach all preset positions within $\pm 3°$ of error. This $\pm 3°$ error is not carried through the analysis and calculations, as we only use the position measured by the winch tracker during our analysis.

1) VIRTUAL ENVIRONMENT

Unity is used to run the virtual environment. Inside the virtual environment (Figure 2), an arc of wall was placed with the center of the arc aligned with the pivot tracker position, and with the same radius as the swing arm. The purpose of this wall is to represent all possible positions the force could come from. The wall extended past the physical swing arm's range of motion so as to not bias the subjects when the force came from the limits of the swing arm's range of motion. The Vive controller held in the subject's non-dominant hand was set to emit a virtual laser beam. The subjects pointed this at the wall to indicate where they thought the force was originating from. Also color-changing 10 cm indicator box is placed above the virtual wall, in front of the subject to communicate with them about the state of the test.

Trackers were not visible inside of the virtual environment except for an 8cm diameter white sphere overlaid on the handle tracker, which was shown for several of the experiments (section II-C). For the first experimental condition, a blue cube was used to indicate the location where they should hold their hand (Figure 2B). For experimental conditions 2 and 3, a semi-transparent rectangular box with dimensions of $10\,\text{cm} \times 10\,\text{cm} \times 50\,\text{cm}$ was placed inside of the virtual environment for guiding the arm motion (Figure 3). The position of the box was placed before the beginning of the experiment by measuring the arm span and height of

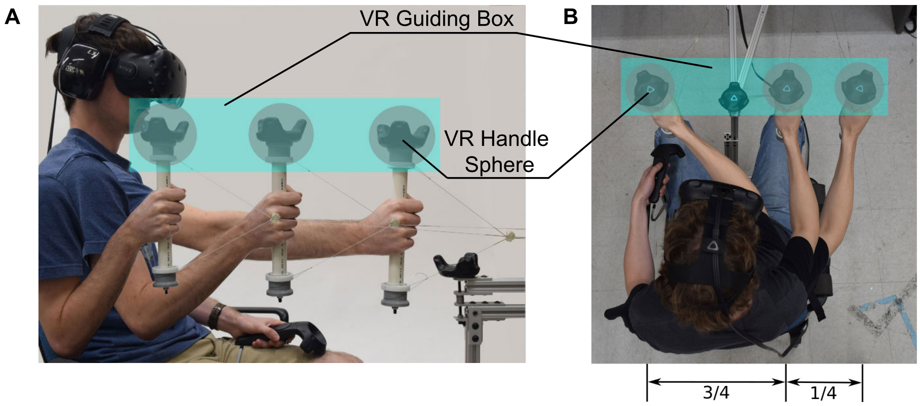

FIGURE 3. A, Vertical motion with overlaid guiding box in Condition 2, Vertical movements. The box was positioned in front of the participant's shoulder. The same approximate motion is done for the Follow condition, but without a guiding box, and the subject may move their arm to their left and right according to where the force is originating. B, Horizontal motion in Condition 3, Horizontal movements.

individual users. Details about placing the guiding box are explained in section II-C.

C. EXPERIMENTAL PROCEDURE

1) COMMON EXPERIMENTAL PROCEDURES

Subjects underwent a half-hour instruction and practice session to acclimate them to the various test conditions. The system randomly moved between three positions, $\pm 15°$ and $0°$, during the practice session. $\pm 15°$ were not positions used during the actual experiment while the $0°$ position was also in the actual experiment. No feedback was given on the accuracy of the subjects' guesses at any point.

During both the practice session and actual experiment, the test procedure was as follows. The swing arm moved to the next test position, with minimum (undetectable) force in the string. Next, the force was applied and the indicator box turned green. While the indicator box was green, the location of all VR trackers was recorded at 90 Hz. The subjects then took as much time as they desired to experience the force. When they felt ready to make a decision where the force was originating, they pointed the laser beam extending from the Vive controller at the wall, then clicked the trigger on the controller. The location where the laser beam intersected the wall is the decision point. To maximize pointing accuracy for each subject, subjects are free to choose the way of pointing that worked the best for them, such as resting the controller on the armrest or reaching out with the laser beam. Subjects were also instructed to look at the location they perceived the force to be originating from while making a decision, and their head position was recorded as well. When the subject clicked the trigger, the indicator box turned red, and the location recording stopped. The experimental operator then switched the force off, commanded the swing arm to move to the next position, and then the sequence repeated. If an undesired decision was made, subjects could express that to the experiment operator, who marked it to be ignored later in the data processing.

For each experimental condition, all 9 positions were tested 5 times each, resulting in 45 tests that were presented in a pre-randomized sequence. Subjects had control over the force exposure time, decision making, and the length of breaks between each condition. Each condition took roughly 12 minutes on average.

2) SPECIFIC EXPERIMENTAL CONDITIONS

There were four different experimental conditions as follows:

a: CONDITION 1: STATIONARY HAND

In this condition, subjects held their hand stationary while they experienced the force. Subjects placed their dominant hand at shoulder level height and rested their elbow on the chair's arm rest. Subjects were told to resist the force and minimize motion created by the force, holding the white sphere corresponding to the top of the handle within the blue cube. The cube was positioned close enough to the subject that it was largely out of the wearer's field of view; any relative motion between the sphere and cube was thus difficult to see so the subject could not rely on it as a cue.

b: CONDITION 2: VERTICAL MOVEMENTS

In this condition, the effects of moving the hand away from the body and toward the center of the wall were explored. The blue rectangular guiding box was placed at subject's shoulder height and adjusted to cover most of the hand motion as they extended and retracted their arm (Figure 3A). The length and position of the box was adjusted such that when the subject's arm was fully extended and fully retracted, the white sphere was at either extreme of the box; the adjusted length was between 40 and 60 cm.

Subjects were required to move in full strokes (from fully extended to fully contracted or vice versa) within the guiding box at least 6 times before making a decision. Subjects were allowed to move their hand at a self-selected comfortable speed.

c: CONDITION 3: HORIZONTAL MOVEMENTS

In this condition, we examined the effects of a person moving their hand laterally back and forth in the frontal plane (horizontal movement). To guide the movements, the guiding box was placed horizontally, going from side to side in front of the subject, at shoulder level (Figure 3B). The box was placed such that one end was aligned with the subjects' non-dominant shoulder, and then the opposite end extended past their dominant shoulder, such that 3/4 of the way down the box was directly in front of their dominant shoulder. This position and length covered a large range of horizontal hand motion. Other than this, subjects again completed at least 6 strokes and followed the same constraints as in the Vertical condition.

d: CONDITION 4: FOLLOWING THE FORCE

In this condition, we investigated the effects of subjects' moving their hand back and forth from the perceived force direction. Here, the guiding box was disabled. Subjects were instructed to try move their hand toward the direction where they though the force was originating. Subjects were required to have at least 6 full strokes (3 forward and 3 back) before making a decision, and were allowed to move their hand at a comfortable speed.

D. DATA ANALYSIS

Data was recorded the entire time the indicator box was green, allowing subjects' motion to be analyzed. The positions and orientations of all devices at the last frame (when the Vive controller trigger was pulled) were used as the subjects' decision.

1) ANGLE OF ERROR PRECISION AND ACCURACY

Two pointing devices were used and recorded in each of the conditions. The head pointer was recorded by the HTC Vive HMD, while the hand pointer was recorded by HTC Vive controller. The Angles of Error (AoEs) of both pointers (head and hand) were calculated as follows, also shown in Figure 1C: First, a ray extending from the pointer was extended until it intersected the circle of the wall. This location was used as the decision location. For the hand pointer, the ray was the laser shown to the user in the virtual environment. For the head pointer, the ray was an invisible line extending from the front of the HMD (see Figure 1C).

The angle between the decision location, Handle Tracker (which was near the shoulder), and Winch Tracker was used as the AoE. In other words, the vector between the winch tracker and handle tracker is the physical direction of the force, while the vector between the handle tracker and decision point is the perceptual direction of the force. The AoE is the angle formed by these two vectors, in the plane of the experimental setup. Positive AoEs correspond to the subject guessing to the right of the true force, while negative AoEs correspond to the subject guessing to the left of the true force.

Note that the AoEs for both the head and hand depended on the location of the Handle Tracker. In the Vertical, Horizontal, and Follow conditions, the Handle Tracker was not always in exactly the same location at the end of each trial since the participant had just finished moving their hand back and forth. However, each participant held it in nearly the same location in front of their shoulder when making their decision.

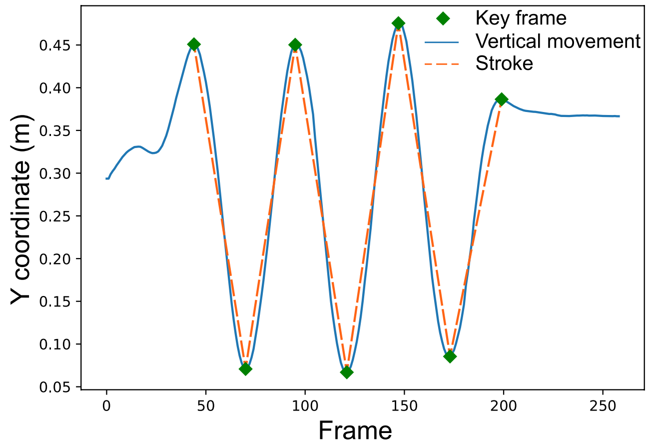

FIGURE 4. Y coordinate of the hand tracker vs. frame number. Key frames were selected by identifying local maxima and minima, and represent the fully extended and retracted positions. Strokes were formed by connecting each of the two key frames.

We generated precision and accuracy for each pointer, per position per subject. Precision was calculated by taking the standard deviation of the AoEs and accuracy was calculated by taking the mean of the AoEs. In this manner, precision is a measure of how tightly the guesses are clustered, and accuracy is a measure of how well the cluster of guesses is aligned with the true force direction.

2) MOTION DATA ANALYSIS

Data was also analyzed from when subjects were moving their hand. Stroke key frames were extracted by identifying the local maxima and minima throughout the entire motion, i.e. the positions of the handle tracker at each end of a stroke, and manually verified. An example can be seen in Figure 4. Stroke rays were then formed by drawing a vector through the two stroke key frames for each stroke. Stoke AoE was calculated by applying the same AoE calculation but replacing the pointer ray with stroke rays. The first stroke AoE, last stroke AoE, and mean AoE were used for motion analysis. Additionally, the duration of each stroke, duration of the entire motion, number of strokes and stroke frequency were also analyzed. Range of motion was also analyzed, and was determined by taking the absolute value of the difference between the highest and lowest AoE.

3) SUBJECT CONFIDENCE

We asked subjects to rate their confidence level on a scale of 0-10 on how accurate they thought they did during each condition, to determine if the subjects' perception of their guesses was correlated with their actual performance. This was asked immediately after the experiment was done for each condition.

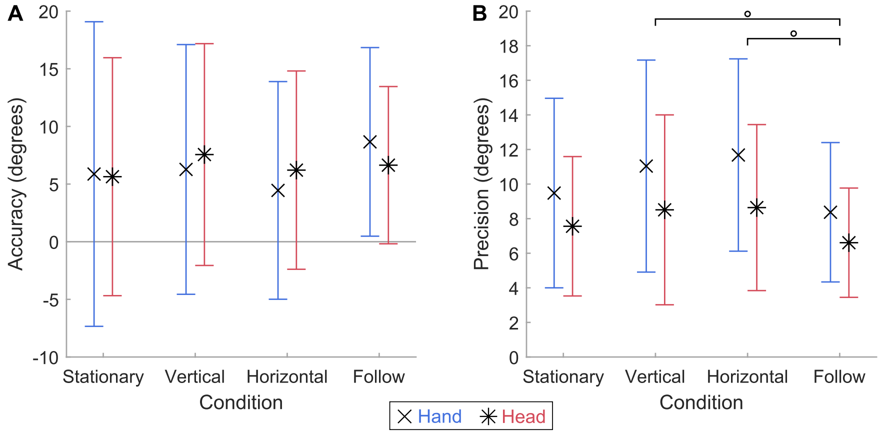

FIGURE 5. A, Accuracy of guesses as a function of Condition. The effect of Condition on accuracy was not significant. B, Precision of guesses as a function of Condition. Smaller numbers for precision indicate that the guesses are more tightly clustered, i.e. have better precision. Brackets indicate significant differences between conditions (combining Head and Hand data).

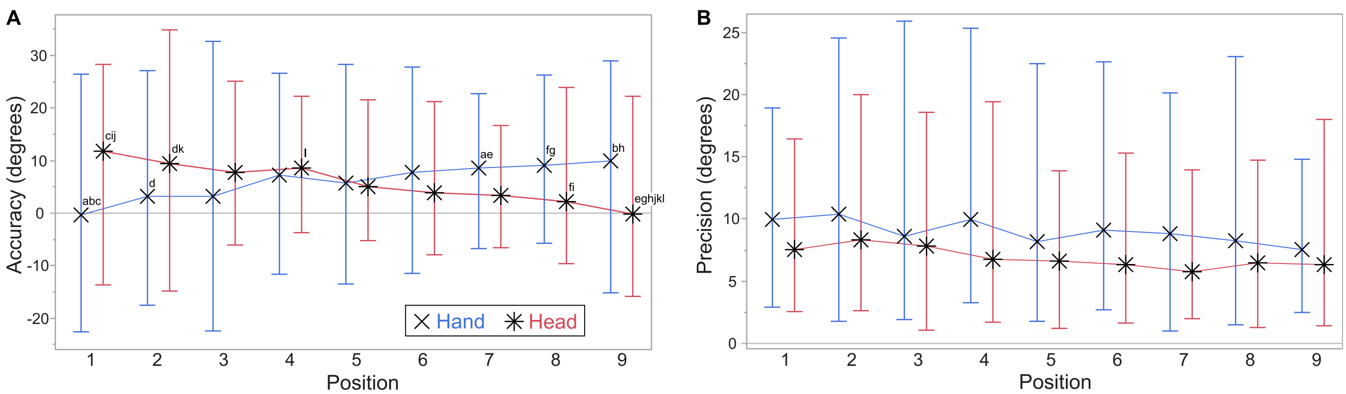

FIGURE 6. A, Accuracy vs. Position for head and hand. The combination of Pointer*Position was significant; letters are used to indicate pairs of (Pointer,Position) values that are significantly different from each other ($p < 0.05$). B, Precision vs. Position for head and hand. No significant differences were found with respect to precision and position.

4) STATISTICAL ANALYSIS

As discussed in the experimental procedures section, there are three independent variables in this study: A: Position (9 positions), B: Condition (4 conditions), C: Pointing device (2 pointing devices). We performed a repeated measures Analysis of Variance (ANOVA) in JMP Pro 14 (SAS, Cary, NC, USA) using a minimum level of significance of 0.05. Both fixed significant effects of independent variables on dependent variable and significant interaction effects were reported. The data was tested for sphericity, and the p-values were adjusted with the False Discovery Rate (FDR) correction [24] to account for the multiple hypothesis tests. Post-hoc analysis of the significant results were done with a Tukey HSD test.

III. RESULTS

A. OVERVIEW

The main results for the experiment are summarized in Figure 5, which shows the accuracy and precision according to Pointer and Condition, and Figure 6, which shows the accuracy and precision according to Pointer and Position. Figure 11 in the Appendix further shows the data grouped by Condition, Pointer, and Position. Two factors were found to have significant effects on precision: Pointer ($F(1,13) = 18.27$, $p = 0.0063$) and Condition ($F(3,39) = 4.80$, $p = 0.021$). We did not find significance for Position, Pointer*Position, Pointer*Condition, Pointer*Condition*Position, and Condition*Pointer ($p > 0.05$). For accuracy, only the effect of Pointer*Position was found to be significant ($F(8,104) = 24.64$, $p < 0.00001$). Pointer, Position, Condition, Pointer*Condition, Pointer*Condition*Position, and Condition*Pointer were not significant ($p > 0.05$).

B. POINTING METHOD

The head was significantly more precise than the hand regardless of condition ($F(1,13) = 18.27$, $p = 0.0063$), but not more accurate ($F(1,13) = 0.00$, $p = 0.98$). Averaging across all conditions, Head had a mean accuracy of $6.51° \pm 8.94°$, and Hand had a mean accuracy of $6.31° \pm 10.66°$, which were not significantly different. In comparison, Head had a mean precision of 7.79° ±4.52°, while Hand had a mean precision of 10.14° ± 5.50°, which were significantly different. Considering the different conditions, the greatest improvement of the Head relative to the Hand was 3.04° in the Horizontal condition and least improvement was 1.76° in the Follow condition. Figures 5B and 6B both show the precision with Head and Hand, allowing the improvements of the Head over the Hand to be seen.

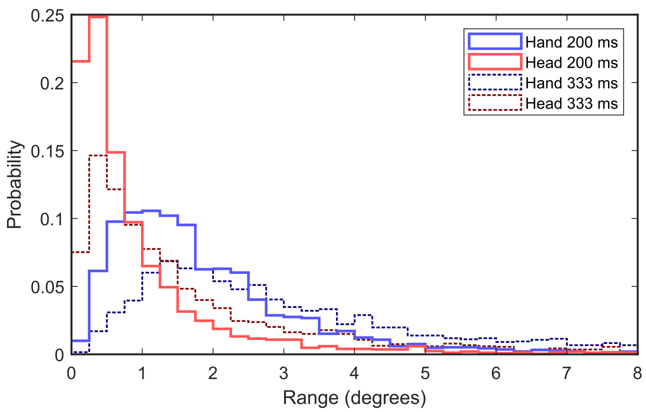

FIGURE 7. Histograms of the range of Hand and Head positions during the last 18 frames (200 ms) and 30 frames (333 ms) before the user pulled the trigger.

Figure 7 shows histograms of the range of the last 18 frames (200 ms) and 30 frames (333 ms) of the Hand and Head positions before the user pulled the trigger on the controller. The Hand had a mean range of 1.94° while the Head had a mean range of 1.00° at 200 ms, while the Hand had an mean range of 4.82° and the Head had a mean range of 2.64° at 333 ms. The difference between the Head and Hand was nearly 1° at 200 ms, and was 2.18° at 333 ms. Both of these are less than the difference in precision between the Head and Hand across all conditions (2.36°), although the 333 ms case is very close. Additionally, the difference between the Head and Hand range continued to increase as the number of frames before the trigger was pulled increased.

C. CONDITION

We found that the condition significantly affected precision ($F(3,39) = 4.80$, $p = 0.0063$) but not accuracy ($F(3,39) = 0.97$, $p = 0.73$). Combining the Head and Hand results, the Follow condition was the most precise, with a standard deviation of 7.52°±3.75°. The Horizontal and Vertical conditions were the worst, with averages of 10.10°±5.37° and 9.73°±5.92°, respectively. The Follow condition was found to be significantly different than the Horizontal ($p = 0.0016$) and Vertical ($p = 0.006$) conditions. The Stationary condition (with an average of 8.51°±4.85°) was not significantly different than any other condition, and the Horizontal and Vertical conditions were not significantly different from each other.

D. POSITION

Position alone was not found to be a significant factor of force perception precision or accuracy ($p = 0.10$ and 0.98, respectively). However, the combination of position and pointing device (Position*Pointer) was significant for accuracy ($F(8,104) = 24.64$, $p < 0.00001$). Both precision and accuracy error patterns as a function of position are shown in (Figure 6).

For precision, both hand and head had roughly the same precisions across all positions. The Hand had precisions between 8.44° − 11.67°, while the Head had precisions between 6.82 − 9.54°.

For accuracy, the hand and head had an almost mirrored bias pattern. The Hand was most accurate at position 1 (1.62° ± 13.15°) and least accurate at position 9 (9.35° ± 10.09°), while the Head was the opposite with the best accuracy at position 9 (0.76° ± 8.85°) and worst accuracy at position 1 (10.65° ± 11.12°). Both hand and head had nearly the same accuracy at position 5 (∼ 6.3 ± 8°). Also, in all cases the average errors were positive, indicating that subjects guessed to the right of where the force originated from in reality. There were many instances where combinations of Pointer and Position were significantly different from each other ($p < 0.05$) at the extremes of position, as shown by the letters in Figure 6.

E. CENTER POSITION (POSITION 5)

We examined position 5 additionally because in this position, the subject moved their hand directly toward the force in the Vertical condition, even though they did not realize it. Thus, for this position we can compare the Vertical results to those of Follow, where the person nominally also was moving their hand directly toward the force. The difference between Vertical and Follow in this position is that in Vertical, the subject was being guided to move directly toward the force, while in Follow they could choose to move how they wished. The results for position 5 are visible in Figure 11 in the Appendix.

For precision at position 5, the Follow condition was better than the Vertical condition, although the result was not significant ($p > 0.05$). While not statistically significant, the Hand and Head were 5.02° and 2.29° more precise, respectively, in the Follow condition compared to the Vertical condition at position 5. This was consistent with the previously-mentioned result of Condition being an important factor in precision and the Follow condition yielding the most precise results across all conditions.

For accuracy, the Vertical condition was 3.9° better than the Follow condition with Hand but was 0.3° worse with Head, and in both cases the differences were not significant. This was consistent with the condition not significantly affecting accuracy as stated previously.

We also examined the range of angles covered by both the Follow and Vertical conditions. On the average, during the Follow condition overall, each trial had an average range

TABLE 1. The mean and Std. Dev. of all stroke metrics in Follow and Vertical conditions at position 5. These include: Angle of Error for both the Hand and Head; the number of strokes; the duration of time before the trigger was pressed; the stroke frequency; the AoE of the first stroke; the AoE of the last stroke; the range of the AoE of all strokes; and the mean error across all the strokes.

	Vertical (Mean ± Std.)	Follow (Mean ± Std.)
Hand AoE [°]	4.58 ± 16.29	8.09 ± 10.84
Head AoE [°]	6.70 ± 12.87	5.36 ± 8.33
No. of Strokes	6.66 ± 1.20	7.73 ± 2.89
Duration [sec]	7.51 ± 2.97	7.87 ± 3.20
Freq. [Hz]	1.12 ± 0.34	1.03 ± 0.34
First [°]	4.37 ± 2.26	6.49 ± 14.44
Last [°]	4.34 ± 3.22	5.11 ± 18.59
Range [°]	4.65 ± 2.05	28.88 ± 26.52
Mean [°]	4.72 ± 1.95	6.43 ± 11.85

of 26.86° ± 24.71°. For position 5 specifically, this was 28.88° ± 26.52°. For comparison, during the Vertical condition, the range was 8.91° ± 8.88° overall and 4.65° ± 2.05° at position 5. A summary of the various stroke metrics during the Follow and Vertical conditions at position 5 is shown in Table 1.

F. FOLLOW CONDITION STROKE ERRORS AND RANGE

For the Follow condition, we also looked at the stroke AoEs over time to determine if the subjects were systematically exploring the space or narrowing down on a final answer, but we did not find a pattern. The stroke did not get better, nor worse over time. Examples of different stroke motions for a single subject are shown in Figure 8.

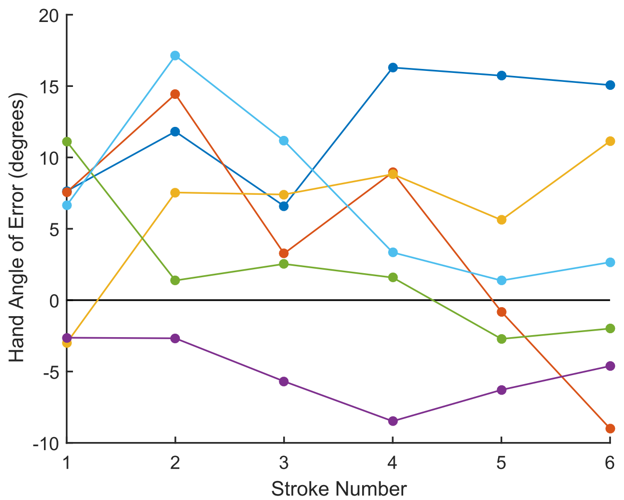

FIGURE 8. Examples of stroke motions for a representative subject. Each line represents a different trial.

We further analyzed the stroke data in the Follow condition to see what, if any, effect the range of motion encompassed by the strokes would have on the subject's accuracy. We grouped the guesses with ranges of $0° - 10°$, $10° - 20°$, $20° - 30°$, and $> 30°$, and compared them. The results are in Table 2. We found that for the Hand, guesses with a $0° - 10°$ range

TABLE 2. The mean and Std. Dev. of the Head and Hand guess accuracy, in degrees, per stroke range in the Follow condition.

Range	Hand Mean ± Std	Head Mean ± Std
$< 10°$	4.58 ± 8.78	4.06 ± 8.89
$10° - 20°$	11.00 ± 12.45	6.74 ± 9.57
$20° - 30°$	9.31 ± 11.15	5.74 ± 9.65
$> 30°$	8.98 ± 12.10	6.55 ± 10.07

had a significantly better accuracy than the other ranges ($p < 0.02$). For the Head, guesses with a $0° - 10°$ range were significantly different than the $10° - 20°$ range ($p < 0.05$) but no other pairs were significantly different.

G. SUBJECT CONFIDENCE LEVEL

The results of the subject confidence questionnaire are shown in Figure 9. Subjects were most confident that they had made a correct guess in the Follow condition, with an average of 7.08 points, and subjects had the least confidence in the Horizontal condition with an average 5.31 points. The second highest rating was 6.08 for Vertical with a standard deviation of 2.18, and the average rating for Stationary was 5.62, with the lowest standard deviation of 0.96. Follow was significantly different than Stationary ($p = 0.0063$) and Horizontal ($p = 0.0012$). However, subjects' ratings of their performance were not correlated with their accuracy ($p = 0.99$) or precision ($p = 0.16$).

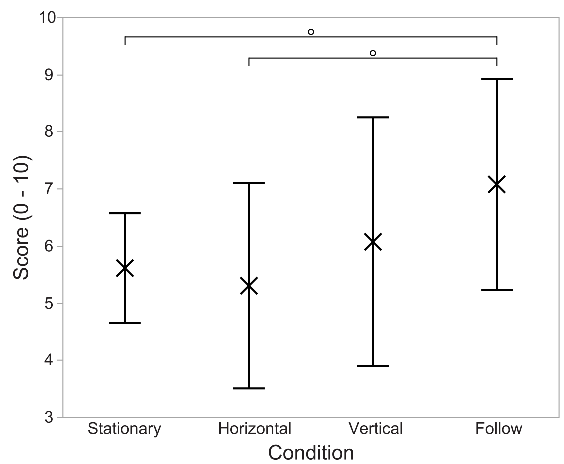

FIGURE 9. Confidence level vs. condition. Brackets indicate pairs of conditions that were significantly different. The *p*-value for Follow-Stationary is 0.0063 and the *p*-value for Follow-Horizontal is 0.0012.

IV. DISCUSSION

Overall, both the Head and Hand had higher accuracies ($1° - 10°$ on average depending on the Position, with $> 85\%$ of all guesses accurate to within $\pm 20°$) than the average numbers found by previous studies. This supports hypothesis H1, that a VR environment would lead to better force perception localization accuracy as compared to other means of selection. The closest comparable set of papers, by van Beek, show average values of 10° − 15° for the two positions in front of the participant [13], [14]. Another paper using a force-feedback joystick also found values in the 10° − 15° range [15], and still others found values around 30° or higher using a Phantom or fingertip force transducer [11], [21], [23]. It is plausible that the higher accuracy in our study is due to the VR environment, allowing people to more directly indicate where they thought the force was coming from, as compared to previous studies where a monitor or other feedback device was used that was not directly connected to the physical environment. Alternatively, our study only presented subjects with forces within a range of 48°, whereas van Beek presented forces within a range of 220°. The smaller range in our study may have contributed to the higher accuracy.

We also found that the Head was more precise than Hand but not more accurate, supporting hypothesis H2. It is likely that the difference in precision was due to noise introduced through the subject's shaking as they pointed the controller at the wall, as compared to pointing with the head. Given the range of the controller as compared to the HMD over the last 200 ms and 333 ms before the trigger was pulled, it is clear that individuals move around the controller much more than they do their heads. It is likely that people are able to orient their heads more stably as compared to their hands, since the hands are at the end of a long kinematic chain (the arm) and thus are more sensitive to small motions anywhere along the length of the arm. This seems to be true even though subjects rested their forearm on an armrest while holding the controller. The variance introduced by the additional controller motion could fully explain the reduced precision with the Hand as compared to the Head, if a slightly longer time window is considered.

Surprisingly, the Head and Hand have opposite trends for error (accuracy) versus position. The Head had a large positive error at the subject's left, which decreased to be close to zero at the subject's far right, while the Hand had the opposite pattern.

It is interesting that both the Head and Hand produced guesses to the right of the true force direction in almost all cases (similar to van Beek's results [13], [14]). In our experiment, nearly everyone was right-handed, and the one left-handed subject showed a similar pattern. One possibility that may explain this effect is if people perceived the virtual wall to be at a different distance in the virtual space than it was in reality. This effect was shown to exist by Konrad *et al.* [25] where people thought a virtual object was slightly closer to them than it was presented in a VR system. Konrad *et al.* only tested locations within an arm's length, but the effect may occur at farther locations as well. While this effect appears to be small ($<$ 5% for distances equal to an arm's length), it may contribute to these errors. Suppose people thought the virtual wall was closer than it was physically, as illustrated in Figure 10. The subjects had their right hand aligned with the center of the arc, so both their left hand (holding the controller) and their head (which held the head mounted display) were to the left of the wall arc center.

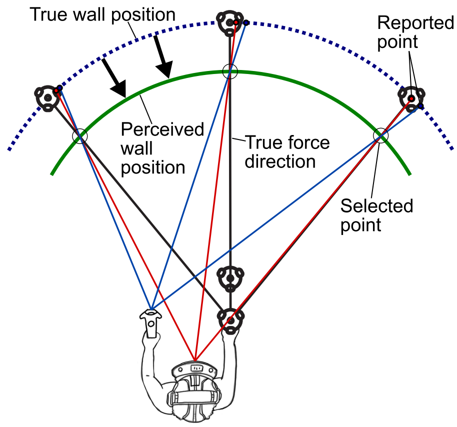

FIGURE 10. Possible explanation of selected locations appearing to the right of the true location. This effect could occur if the wall is perceived to be closer than it actually is, in conjunction with the parallax effect. In the diagram, the blue dashed wall is the true wall position, but it is perceived to be closer to the person (green solid line). Thus, if the person perfectly chooses the correct location on the wall where they believe the force is originating, then the controller and head mounted display both point to the right of the point at which the true force appears (measured at the true wall location). In some positions, there is almost no parallax error (e.g. the Head at the far right position), while it increases in other locations. Note that this diagram is simplistic in that it illustrates the controller and head in fixed locations; in reality, the person will rotate their head and move their wrist to change the locations of the controller and HMD.

If the participants perceive the virtual wall to be closer than it is in reality, then a parallax error will occur and pointing to the location on the virtual wall from which the force originates causes their selections to appear to the right of the force winch and winch tracker. In some locations, e.g. to the very far right, this effect is minimized, while in others it is larger. Note that any perceived distance change of the wall is likely a function of the distance between the wall and the person's head, which was not located exactly in the center of the wall arc, as opposed to a fixed offset as drawn in the figure. Also note that in the figure, the head mounted display and controller are shown in fixed locations for simplicity. In practice, participants rotated their heads and moved their wrists back and forth, so the points from which the Head and Hand rays originated moved around to some extent. These more complex motion patterns in combination with the Head and Hand's different vantage points may be responsible for the opposite trends in the Head and Hand accuracy error patterns (Hand increased with position while Head decreased with position in Figure 6A).

We found that the Condition significantly affected precision, but not accuracy, contradicting both hypotheses H3 and H4. We had hypothesized that the Horizontal and Vertical conditions would lead to improvements in accuracy because the subject would experience the force at a variety of different angles as they completed the motion, and thus be able to triangulate the force's origin better (hypothesis H3). For the Horizontal case, this would be most pronounced at Position 5, where the force would appear to change angle approximately ±14° as the hand moved from one side of its range to the other. For comparison, the Vertical case had the largest angular change at Positions 1 and 9, but with an angular change of only ±4° as the hand moved back and forth. Despite the reasonably large change for the Horizontal condition in Position 5, the Horizontal condition was not significantly different than the other conditions, and indeed almost identical to them with the Head as the pointer. Thus, it appears that the hand's motion may be causing "tactile suppression" [23] and masking any possible benefits of triangulation. This finding seems to confirm the effect of tactile suppression during motion, as found by [23], in contrast to Yang *et al.* [21] who did not observe this effect. It may be that allowing the user to pause at the ends of the travel distance may allow them to triangulate, but this would require further study.

We had also hypothesized that the Follow condition would result in an increase in accuracy, as the subjects could try out several possible guesses and see which felt best (hypothesis H4). However, the Follow accuracy was not any different from the others, and furthermore had the worst accuracy with the hand used as a pointer (though the difference was not significant). We also thought that the Range might be correlated with the Follow condition's accuracy—if people could experience a wider range of angles, perhaps including trials on either side of the true force direction, they might make a more accurate guess. This was also not correct. This can be seen in comparing the Vertical and Follow conditions at position 5: there, the Vertical condition had a range of $4.6° \pm 2.0°$, while the Follow condition had a much larger range of $28.9° \pm 26.5°$. Despite the increased range in Follow, the mean accuracy was about the same as that in the Vertical condition. Further disproving this hypothesis, trials with small ranges ($0° - 10°$) in the Follow condition were correlated with more accurate guesses. We suspect that in these situations, subjects randomly moved toward the true force direction during their first stroke, and then moved in the same direction for subsequent strokes and made a guess close to the average of their strokes. Thus, their small range did not cause them to have a good accuracy, but instead was due to random chance.

The Vertical and Horizontal conditions resulted in the worst precisions, which is likely caused by the motion masking the perceptual signals. However, the Follow condition resulted in a precision significantly better than both Vertical and Horizontal, despite it also including motion. Thus, the ability to explore the possible directions where the force may be coming from does seem to lead to the subjects' solidifying in their head what their guess is, and being able to guess in the same location repeatedly, even if that location is not where the force is actually originating.

Hypothesis H5 was not correct: subjects' confidence levels were not correlated with their accuracy. Follow had the best precision and also was rated highest on the average by participants, but this relationship was not statistically significant. 77% of the subjects (10 of 13) rated the Follow condition as their best performance, despite the Follow condition not actually being more accurate than the other conditions. Future studies could investigate the relationship between force localization confidence and performance in more detail.

It is important to note that in our experiment, the applied force (1.87N) was small enough that it did not "pull" the subject's hand in the correct direction. The subject needed to actively move their hand in the direction in which they felt the force. If the force were higher, it is likely that a person would be able to rely on the force driving their hand in the correct direction, and thus they could use their arm's position to make a guess instead of the perceived forces. This would rely on a different set of proprioceptive sensors—mechanoreceptors providing feedback about the arm's position, as opposed to the muscle spindle sensors, Golgi tendon organs, and skin pressure sensors informing the user of the force [26]. In our experiment, subjects likely benefited from sensing their arm's position during the Follow condition, since they moved their hand toward the perceived force direction, whereas they moved their hand in other directions for the Horizontal and Vertical conditions. This may have led to the higher precision for Follow compared to Horizontal and Vertical.

The fact that subjects made more tightly-clustered guesses with the Follow condition, while still having a very similar accuracy pattern to the other conditions, suggests that people have a consistent internal mapping between perceived force directions and their head or body's coordinate frame. However, in most cases this mapping is not well-calibrated, leading to consistent errors in perceived direction. This confirms the results from van Beek [13], [14] who found a subject-based bias in accuracy. In our experiment, no feedback was given to the subject at any point, so they were not able to calibrate this mapping during the course of the experiment. It may be that providing training for this would improve the subjects' accuracy. Interestingly, Elhajj *et al.* [15] found small improvements in accuracy over the course of their experiment. Even with training, we suspect that the precision might decrease by a comparatively smaller amount, since the precision may be a function of the noise in the subjects' proprioceptive sensors.

Our study did have one limitation in that the conditions were always presented in the same order. However, the later conditions were not better in general than the Stationary condition, which would be expected if there were training effects. Thus, we believe the presentation order did not significantly affect our results.

V. CONCLUSION

In this study, we examined the effect of transverse plane motion on the precision and accuracy of force direction perception. We used a virtual reality environment provide an intuitive way for subjects to experience the forces and provide feedback on their direction. Our results showed that enabling a person to move their hand following the direction from which they perceive the force is originating results in a higher repeatability (precision) than their moving their hand in a prescribed horizontal or vertical pattern. However, the accuracy of subjects' guesses was the same in all conditions.

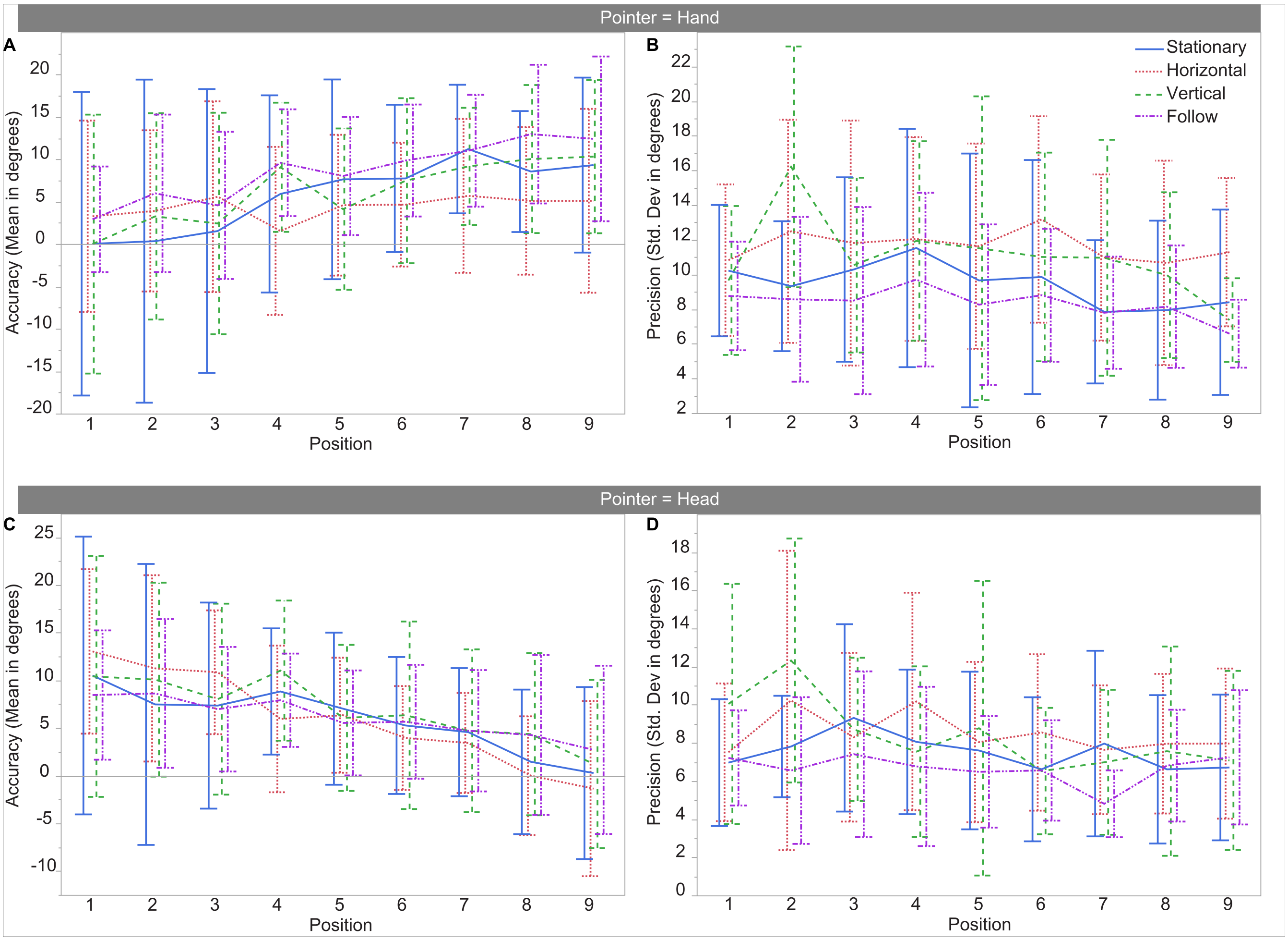

FIGURE 11. Overview of the accuracy and precision for the hand (A,B) and head (C,D), showing each condition and position separately. Within a cluster of error bars at a given position, from left to right the order is Stationary, Horizontal, Vertical, and Follow.

We compared using the head as a pointing device and a hand-held virtual laser pointer held in the non-dominant hand, and found that the head led to a significantly higher precision. We found that subjects' exploring a wider range of angles during the Follow condition did not lead to improved precision or accuracy. Any triangulation the subjects experienced during arm motions did not seem to help either.

There is an opportunity for future studies to investigate which factors lead to differences in accuracy. It may be that providing feedback to subjects could lead to a correction of their internal bias. It would also be illuminating to determine subjects' accuracy if they are allowed to pause their hand at several stationary positions so they can triangulate the force's direction, instead of their moving continuously as was done in the current study. This would eliminate any masking effects from the motion, and possibly lead to a more integrated theory of how the brain combines different proprioceptive signals from the arm. Finally, the questions of why the head and hand have opposite directions of the error versus position trends and why there are subject-specific biases in accuracy remain open. In general, this and future studies may lead to improved algorithms for teleoperation or force-feedback devices, including in virtual reality.

APPENDIX

The data for the experiment, organized by condition, pointer, and position, are shown in Figure 11.

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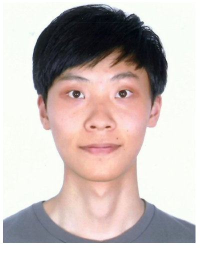

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