Teleporting through virtual environments: Benefits of navigational feedback and practice

Jonathan W. Kelly[1*], Nicole Powell[2], Melynda Hoover[2] and Stephen B. Gilbert[2]

[1*]Department of Psychology, Iowa State University, 1347 Lagomarcino Hall, 901 Stange Rd., Ames, 50011, IA, USA.

[2*]Virtual Reality Applications Center, Iowa State University, 1620 Howe Hall, 537 Bissell Rd., Ames, 50011, IA, USA.

*Corresponding author(s). E-mail(s): jonkelly@iastate.edu;
Contributing authors: nrpowell@iastate.edu; mhoover@iastate.edu; gilbert@iastate.edu;

Abstract

Virtual environments (VEs) can be infinitely large, but movement of the virtual reality (VR) user is constrained by the surrounding real environment. Teleporting has become a popular locomotion interface to allow complete exploration of the VE. To teleport, the user selects the intended position (and sometimes orientation) before being instantly transported to that location. However, locomotion interfaces such as teleporting can cause disorientation. This experiment explored whether practice and feedback when using the teleporting interface can reduce disorientation. Participants traveled along two path legs through a VE before attempting to point to the path origin. Travel was completed with one of two teleporting interfaces that differed in the availability of rotational self-motion cues. Participants in the feedback condition received feedback about their pointing accuracy. For both teleporting interfaces tested, feedback caused significant improvement in pointing performance, and practice alone caused only marginal improvement. These results suggest that disorientation in VR can be reduced through feedback-based training.

Keywords: Virtual reality, Locomotion interfaces, Teleporting, Spatial updating, Navigation, Feedback

1 Introduction

Many virtual reality (VR) systems allow the user to explore the virtual environment (VE) by physically walking and turning, which requires no training because it leverages human experience with real world locomotion. But walking is only possible within small areas due to physical space limitations (e.g., obstacles) in the user's real environment. Locomotion interfaces are needed to enable movement through larger spaces. These interfaces commonly focus on translation (i.e., change in position) while allowing for full body rotation. However, interfaces that also enable virtual rotation without real body rotation are well suited to certain situations and individuals (e.g., a user seated on an airplane, or a user with mobility impairment).

One popular locomotion interface for VR is teleportation, also referred to as jumping [2]. To teleport, the user selects a position (and sometimes an orientation) in the VE and is instantly repositioned at the selected location. The teleporting interface is popular in part because it is easy to use [3, 14] and does not typically contribute to cybersickness [6, 14, 16, 22].

A defining characteristic of the teleporting interface is that it lacks some or all body-based and visual self-motion cues that normally accompany movement through the real world, which can cause disorientation [13, 21]. In one study [4], participants performed a triangle completion task in which they traveled two outbound path legs before attempting to point to the path origin. Triangle completion is a commonly used test of spatial updating: the process of updating self-location during travel [18]. Triangle completion performance was best when the outbound path was traversed by walking, worse when teleporting to translate and using the body to rotate (herein referred to as partially concordant teleporting), and worse yet when teleporting to translate and rotate (herein discordant teleporting; also see [5, 8, 9, 11]). The current study explored whether practice and feedback when teleporting would lead to improvements in navigation, as measured through triangle completion.

A few studies have investigated whether spatial updating is related to experience. In one study [15], participants repeatedly turned counterclockwise without vision until they believed they had rotated by a specified angle. Practice rotating 45 degrees without feedback (i.e., without any indication of their accuracy) led to improved accuracy for 45 degree rotations as well as 30 degree rotations. Practice with feedback led to greater improvement than practice alone, both for the 45 degree rotation and the 30 degree rotation. It therefore seems possible that practice and feedback on the triangle completion task could lead to performance improvement, since accurate spatial updating during rotation is a key component of the triangle completion task. However, this possibility has not been tested.

Other research has compared spatial updating performance by movement experts, such as dancers and gymnasts, with that of non-experts. The rationale behind these comparisons is that dancing and gymnastics both emphasize good control over body movements as well as awareness of one's position and orientation in space, which may be associated with superior spatial updating performance. One study [20] compared triangle completion performance by gymnasts and non-gymnasts. Blindfolded participants walked two outbound path legs before attempting to walk to the path origin. Response direction was more accurate among gymnasts compared to non-gymnasts, although response distance was comparable between groups.

Another study [1] compared performance by dancers and non-dancers on a VR-based triangle completion task in which the outbound path was traversed by walking, teleporting, or joystick locomotion. On all three forms of locomotion, no significant differences were found between dancers and non-dancers. However, follow-up analyses indicated that engagement in spatial activities (e.g., sports, arts, and crafts) predicted task performance across all participants.

Another study [19] found that experienced dancers performed better than non-dancers at a task in which they walked a short distance through a VE before pointing to multiple previously memorized locations. The task was somewhat more complex than triangle completion, as there were multiple locations to be remembered and the path included more turns. The researchers also found that completing a months-long dance class led to significant gains in task performance by the non-dancers (i.e., those who were initially non-dancers prior to the class), suggesting a causal relationship. It is unclear why dancers performed better than non-dancers in this study and not in the previously described study [1]. Both studies used similar criteria for defining dance expertise. It is possible that task differences between the experiments (e.g., remembering one versus multiple locations) were important.

In summary, there is some evidence that movement expertise gained through dancing, gymnastics, and other spatial behaviors is associated with spatial updating performance [1, 19, 20]. Furthermore, body rotation practice and feedback both cause improvements in accuracy [15]. It is therefore plausible that practice and feedback on a triangle completion task in VR will both lead to improvements. This may be particularly true when triangle completion involves body movement, as when walking or using an locomotion interface that preserves at least some body movement, such as the partially concordant teleporting interface (teleport to translate but turn the body to rotate). It is less clear whether practice and feedback will lead to similar improvements when using a locomotion interface that does not include body movement, such as the discordant teleporting interface (teleport to translate and rotate).

Participants in the current study performed a triangle completion task using one of two teleporting interfaces that differed in available rotational self-motion cues. The first block of trials was performed without feedback. The second block of trials included performance-based feedback for participants in the feedback condition, whereas participants in the no feedback condition continued the task without feedback. The third block of trials was performed without feedback. If performance improves through practice alone, then participants in the no feedback condition should perform better in the third block compared to the first block. If performance benefits from feedback, then the improvement from the first block to the third block should be larger in the feedback condition compared to the no feedback condition. It was expected that performance with both teleporting interfaces would benefit from feedback. No prediction was made regarding the effect of practice alone, nor whether improvement would be greater for one interface compared to the other. The research design, hypotheses, and analyses were pre-registered on the Open Science Framework: https://osf.io/hgf6p/.

2 Method

2.1 Participants

The target sample size was 76 total participants, corresponding to 19 participants in each of 4 between-participant conditions. Sample size was estimated by conducting a power analysis (G*Power v3.1) with the following parameters: one-tailed paired samples t-test between two dependent means, corresponding to the comparison between pre-feedback and post-feedback trials, Cohen's d = .6, alpha = .05, minimum power needed to detect an effect = .80. Effect size was chosen because a medium-to-large effect size would be useful for practical application of the result as a training tool, but a small effect would limit the practical value of a potential training tool. The total participant number was closely monitored during recruitment, but could not be perfectly controlled (e.g., a participant recruited through social media might sign up after the target sample was reached).

Eighty-seven participants (72 men, 11 women, 3 other, 1 declined to state) were recruited through Prolific (an online work site) or social media advertisement. Participants were paid $10 for completion of the study. To be eligible, participants had to be 18 years or older and currently residing in the United States. They also had to have a compatible HMD (Oculus Rift, Oculus Rift S, Oculus Quest, HTC Vive, HTC Vive Pro, or Valve Index) connected to SteamVR. Data from three participants (2 male participants and 1 female participant) were removed as outliers (see Results). Thus, the total sample size was 84 participants. The sample size in each of the four conditions ranged from 19 to 22 participants.

Participants in the feedback condition were recruited first and were randomly assigned to one of the two locomotion interfaces. Participants in the no feedback condition were recruited after data from the feedback condition were collected, and those participants were also randomly assigned to one of the two locomotion interfaces.

2.2 Design

The study followed a 2 (interface: partially concordant teleporting or discordant teleporting) by 2 (feedback condition: feedback or no feedback) by 3 (block) mixed design. The interface and feedback conditions were manipulated between participants and the block was manipulated within participant.

All participants completed 48 trials of a triangle completion task. Trials were split into three blocks: 12 trials in Block 1, 24 trials in Block 2, and 12 trials in Block 3. Participants in the feedback condition received feedback about their performance on each trial during Block 2, whereas participants in the no feedback condition did not receive feedback. No feedback was provided in blocks 1 and 3. For participants in the no feedback condition, there was no difference between trials in blocks 1, 2, and 3 (other than the number of trials in each block).

The path used for the triangle completion task was defined by two outbound path legs, marked by vertical posts. The path angle (i.e., the angle formed by the intersection of the two path legs) was randomly selected on each trial from 24 possible angles ranging from -135° to +135° in 11.25° increments, excluding 0°. The length of each path leg was randomly selected on each trial to be 6.1, 6.7, or 7.3 meters.

2.3 Stimuli

The primary VE was a large 70 by 70 meter warehouse containing shipping containers and cardboard boxes stacked on shelves, all of which were positioned along the room walls, leaving the center of the room open (see Figure 1). The VE was built with the Unity game engine. A practice VE, which was used for participants to familiarize themselves with the interface and task, contained only a rectangular floor outlined by distinct colors on each edge.

The outbound path on triangle completion trials was marked by a sequence of cylindrical posts, each 1 meter tall and .25 meters in diameter. A green post was positioned at the path origin, a yellow post was positioned at the end of the first path leg, and a red post was positioned at the end of the second path leg. An arrow placed at the base of each post indicated the direction of the next post in the sequence. The arrow on the base of the red post pointed in the same direction as the prior arrow. The arrows were necessary to specify the target orientation when using the discordant teleporting interface, but they were also present when using the partially concordant teleporting interface.

When using the partially concordant teleporting interface, the participant teleported to translate and rotated the body to rotate. To use the partially concordant teleporting interface, the participant pressed and held the thumb-pad button on their controller to bring up a small white ring on the ground plane, connected to their controller by a thin red line. While holding the button, the participant positioned the white ring by pointing the controller at the intended position on the ground plane (similar to pointing a laser pointer). The ring snapped to the location of the post when it was within a short distance to ensure that no errors occurred when choosing the teleport location. Releasing the button caused the participant to be instantly teleported to the selected position. Rotations were achieved by physically rotating the body.

When using the discordant teleporting interface, the participant teleported to translate and to rotate. To use the discordant teleporting interface, the participant pressed and held the thumb-pad button on their controller to bring up an oriented purple ring on the ground plane, connected to their controller by a thin red line. While holding the button, the participant positioned the purple ring by pointing the controller and oriented the ring by sliding their thumb around the thumb pad. The ring snapped to the location and orientation of the post when it was within a short distance. Releasing the button caused the participant to be instantly teleported to the selected position and orientation.

2.4 Procedure

The participant first completed a screening questionnaire to determine eligibility, followed by the informed consent form. The participant was then directed to a website with instructions about how to download and run the Unity VR software and how to perform the triangle completion task. The instructions specified that the participant should attempt to remember the location of the path origin (the green post), traverse the outbound path, and then point back to the path origin. The participant was asked to watch a video demonstrating the task with the relevant teleporting interface. The participant was instructed to stand when completing the task, and eye height in the VE corresponded to their standing height (as measured by their tracking system).

The participant then donned their HMD and performed at least two practice trials of the triangle completion task within the practice VE. On each trial, the participant traveled to a sequence of three posts before attempting to point to the unseen location of the path origin. At the beginning of each trial, a green post appeared at the location of the path origin. The participant then teleported to the green post, which disappeared upon their arrival. A yellow post then appeared and the participant teleported to the location of the yellow post, which disappeared upon arrival. Finally, a red post appeared at the location of the path terminus. Upon teleporting to the red post, the participant positioned a small blue circle on the ground plane to indicate the remembered location of the path origin.

After two practice trials, the participant could decide whether to continue practice or move on to

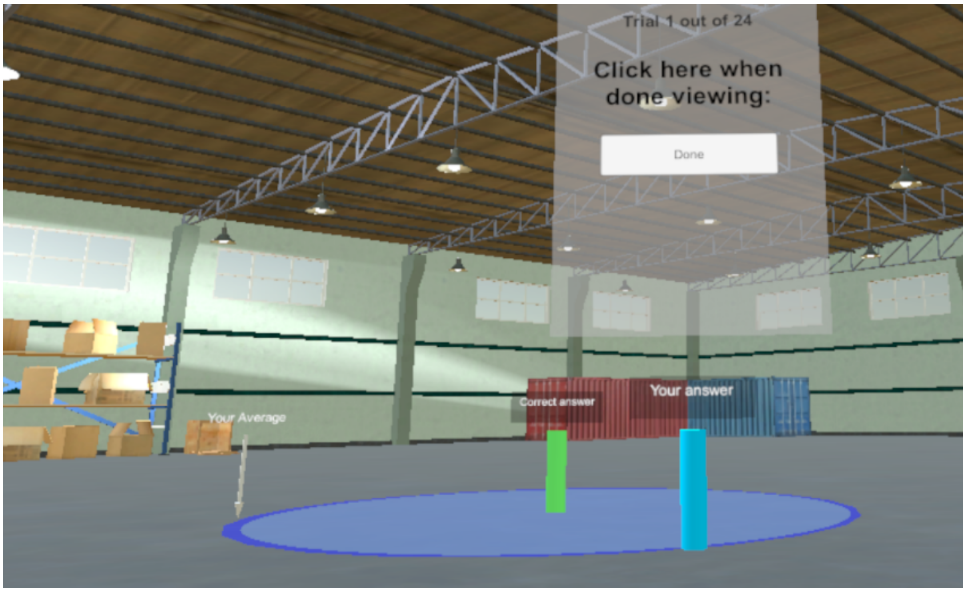

Fig. 1 Participant's view of the feedback provided during Block 2 in the feedback condition. The green post represents the correct location of the path origin. The blue post represents the participant's response on that trial. The blue circle represents the average distance of the participant's response from the path origin based on the preceding Block 2 trials.

the formal experiment. Upon beginning the experiment, the participant completed three blocks of triangle completion trials. Only trials in Block 2 of the feedback condition provided feedback about the participant's performance. Feedback (see Figure 1) was provided by displaying a blue post at the location of the participant's response, labeled "Your answer," and a green post at the location of the path origin, labeled "Correct answer." Additionally, a blue circle was centered on the path origin and the circle's radius corresponded to a running average of the absolute distance of the response from the path origin, averaged across all of the participant's Block 2 responses. This feedback remained visible until the participant clicked to proceed to the next trial.

The participant was prompted after each trial block to indicate whether they experienced any difficulties in the preceding block. The participant was also offered an opportunity to take a break between blocks. Average time for an individual trial was less than 20 seconds. After completing all three blocks of trials, the participant removed the headset and completed surveys about perceived workload, cybersickness, demographics, VR usage, video game experience, and strategies used when performing the task.

3 Results

The primary dependent measure was absolute distance error, defined as the absolute distance between the location of the response and the location of the path origin. Data from three participants were removed due to very large errors (absolute distance error more than 3 standard deviations from the condition mean). Of the remaining 84 participants, average age was 26.2 years (SD = 7.0). When asked about frequency of VR use, the majority of participants (n = 55) indicated that they used VR one or more times per week, with an average VR session length of 76.5 minutes (SD = 55.3). Participants reported playing video games (not necessarily in VR) an average of 35.6 hours per week (SD = 21.8), which is consistent with recent research on HMD owners [10].

Absolute distance errors were not normally distributed so a log transformation was used to reduce skewness [17].[1] The result was a more normal distribution with minimal skewness and similar variances across conditions compared to the untransformed data. Analyses were conducted using the log-transformed data. However, the

[1] A constant value of 0.4 was added to all error values prior to log transformation [7], as this minimized skewness.

figures are presented using untransformed data for ease of interpretation. Equivalent figures showing log-transformed data can be found on the Open Science Framework: (https://osf.io/hgf6p/).

Absolute distance error at the level of individual trials is shown in Figure 2 (discordant interface) and Figure 3 (partially concordant interface). For the purpose of statistical analysis, individual trials within each block were averaged together and analyzed in a mixed-model ANOVA that included one within-participant factor (block) and two between-participant factors (interface and feedback condition). Absolute distance error at the level of block is shown in Figure 4. Mauchly's sphericity test was not significant (p = .190), confirming that the ANOVA assumption of sphericity was met. The main effect of block was significant, $F(2, 160) = 29.576$, $p < .001$, $\eta_p^2 = .270$, with progressively smaller errors from Block 1 (M = 5.998 meters, SE = 0.317) to Block 2 (M = 5.032 meters, SE = 0.247) to Block 3 (M = 4.783 meters, SE = 0.267). The main effect of interface was significant, $F(1, 80) = 18.347$, $p < .001$, $\eta_p^2 = .187$, with larger errors when using the discordant teleporting interface (M = 6.404 meters, SE = 0.361) than the partially concordant teleporting interface (M = 4.138 meters, SE = 0.371). The main effect of feedback condition was also significant, $F(1, 80) = 10.357$, $p = .002$, $\eta_p^2 = .115$, with larger errors in the no feedback condition (M = 5.958 meters, SE = 0.375) than the feedback condition (M = 4.584 meters, SE = 0.357). The only significant interaction was between block and feedback condition, $F(2, 90) = 5.597$, $p = .004$, $\eta_p^2 = .065$. This interaction reflected the larger improvement from Block 1 to Block 3 among participants in the feedback condition compared to those in the no feedback condition, $t(82) = 2.508$, $p = .024$, $d = 0.547$. No other main effects or interactions were significant.

To more closely examine potential improvements caused by practice and practice with feedback, Block 3 errors were compared to Block 1 errors separately for the four combinations of interface and feedback condition. Block 3 errors were significantly lower than Block 1 errors when feedback was provided, and this was true for both teleporting interfaces; discordant: $t(21) = 5.756$, $p < .001$, $d = 1.227$, and partially concordant: $t(21) = 3.720$, $p = .001$, $d = 0.793$. Block 3 errors were marginally lower than Block 1 errors when feedback was not provided, and this was true for both teleporting interfaces: discordant interface: $t(20) = 1.859$, $p = .078$, $d = 0.406$, and partially concordant: $t(18) = 1.886$, $p = .076$, $d = 0.433$.

The NASA Task Load Index (TLX) measured perceived workload along five dimensions. There were no notable differences across conditions. Mean workload (averaged across dimensions) was 8.25 (SD = 5.36) on a 21-point scale. TLX data are provided in more detail on the Open Science Framework (https://osf.io/hgf6p/).

Cybersickness measures revealed an overall mild experience of cybersickness. For example, ratings of nausea on a 1-7 scale averaged 1.95 (SD = 1.36). There were no notable differences in cybersickness across conditions. Cybersickness data are provided in more detail on the Open Science Framework (https://osf.io/hgf6p/).

Free response data on strategies used to perform the task were coded for whether they referred to reliance on environmental cues (e.g., "I tried to remember where the green post was by using the props in the background") and whether they referred to reliance on path-based cues (e.g., "I tried to trace my steps from the directions of the teleports and looked behind to find out where the green post was."). Environment strategies were reported more frequently ($n = 51$) than were path strategies ($n = 23$), but neither varied notably across feedback condition or interface.

4 Discussion

This experiment evaluated the effects of practice and feedback on triangle completion performance using two teleporting interfaces. Practice alone led to a marginal improvement in task performance. Practice with feedback led to significant improvement for both teleporting interfaces. Effect sizes indicate that the effect of feedback is large, and that the effect of practice is small to medium.

Performing triangle completion by teleporting is a complex task with many sub-tasks, any of which could have improved through practice and feedback. Improvements could have occurred in the perception of body movement, similar to studies testing movement training [15] and movement expertise [1, 19, 20]. However, this cannot fully explain the improvements found in the current study, since the discordant teleporting interface involved no body movement. Improvements could

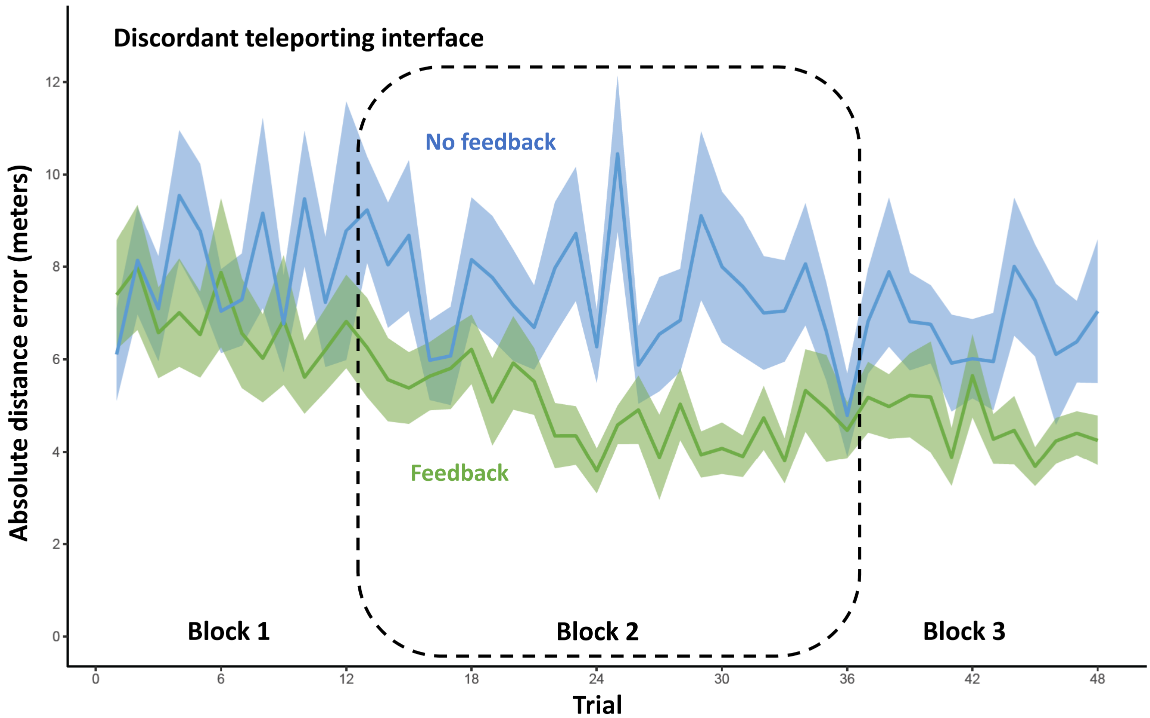

Fig. 2 Trial-level means when using the discordant teleporting interface. Error bars represent +/- 1 SEM. No feedback was provided during Block 1 trials, and thus Block 1 was identical for the feedback and no feedback conditions. Feedback was provided during Block 2 trials, but only for participants in the feedback condition. No feedback was provided during Block 3 trials.

also have occurred at the level of the interface. For example, control of the teleporting interface (e.g., positioning the thumb on the trackpad for the discordant interface) could have improved with practice and with feedback. Improvements in encoding the outbound path could also have occurred as a result of practice and feedback. Additionally, participants could have developed and refined strategies that facilitated task performance. However, subjective reports of the strategies used by participants did not differ between conditions, so if feedback caused a shift in strategies, it was not evident in the self-report data.

Participants were HMD owners, and most (65%) used their HMD at least weekly. The teleporting interface is widespread, and frequent VR users likely have considerable experience with teleporting (although experience with these specific interfaces was not measured). It is therefore possible that VR novices, who lack experience with VR and with teleporting interfaces, would benefit even more from practice and feedback than the experienced VR users tested in the current study. On the other hand, a study measuring triangle completion performance when teleporting found that HMD owners perform with similar accuracy to VR novices [12], perhaps because the typical usage of the teleporting interface is for tasks that require less precise spatial updating than does the triangle completion task, so this remains a question for future empirical study.

The results align somewhat with past research on the effects of practice, feedback, and spatial experience on navigation. In one study, practice rotating the body by a specific amount led to improved accuracy for the practiced rotation angle and another angle, and practice with feedback led to larger improvement [15]. This result appears similar to the current findings, although the effects of practice without feedback in the current study were small and not statistically significant.

In summary, performance-based feedback when using two teleporting interfaces significantly improved navigation performance. Improvement through feedback was larger than that based on practice alone. Furthermore, improvement

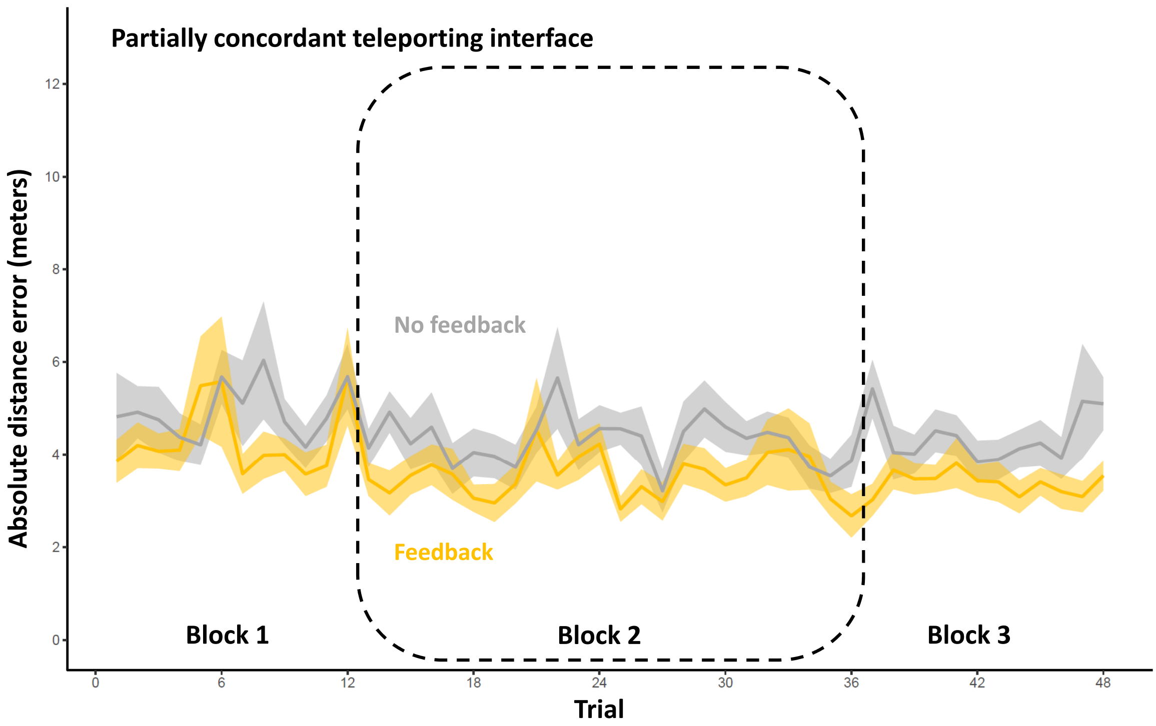

Fig. 3 Trial-level means when using the partially concordant teleporting interface. Error bars represent +/- 1 SEM. No feedback was provided during Block 1 trials, and thus Block 1 was identical for the feedback and no feedback conditions. Feedback was provided during Block 2 trials, but only for participants in the feedback condition. No feedback was provided during Block 3 trials.

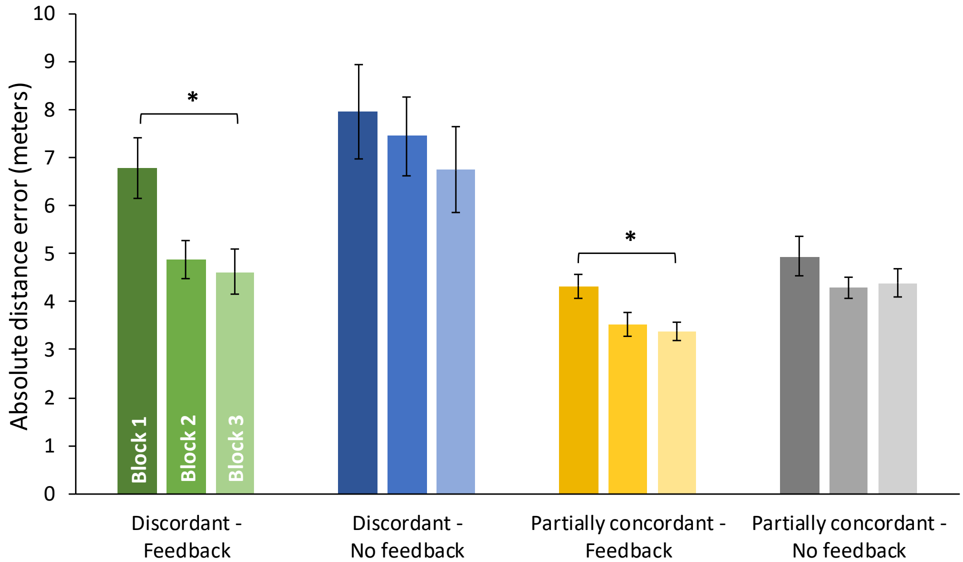

Fig. 4 Mean error as a function of block and feedback condition. Error bars represent +/- 1 SEM. * p <.001

through feedback occurred for two different interfaces varying in the extent to which they include body movement. These findings indicate that tasks requiring precise navigation can benefit from training with a relatively small number of trials.

Data availability statement. The datasets generated during and/or analysed during the current study are available on the Open Science Framework: https://osf.io/hgf6p/.

Supplementary information. Supplemental figures/tables are available on the Open Science Framework: https://osf.io/hgf6p/.

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