Teleporting through virtual environments: Effects of path scale and environment scale on spatial updating

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Fig. 1. Perspective views of the small (left) and large (right) VEs. Also shown are the two teleporting interfaces: partially concordant teleporting (left) and discordant teleporting (right). Both images show the location of the yellow post while standing at the location of the green post when traveling a large path.

Abstract—Virtual reality systems typically allow users to physically walk and turn, but virtual environments (VEs) often exceed the available walking space. Teleporting has become a common user interface, whereby the user aims a laser pointer to indicate the desired location, and sometimes orientation, in the VE before being transported without self-motion cues. This study evaluated the influence of rotational self-motion cues on spatial updating performance when teleporting, and whether the importance of rotational cues varies across movement scale and environment scale. Participants performed a triangle completion task by teleporting along two outbound path legs before pointing to the unmarked path origin. Rotational self-motion reduced overall errors across all levels of movement scale and environment scale, though it also introduced a slight bias toward under-rotation. The importance of rotational self-motion was exaggerated when navigating large triangles and when the surrounding environment was large. Navigating a large triangle within a small VE brought participants closer to surrounding landmarks and boundaries, which led to greater reliance on piloting (landmark-based navigation) and therefore reduced—but did not eliminate—the impact of rotational self-motion cues. These results indicate that rotational self-motion cues are important when teleporting, and that navigation can be improved by enabling piloting.

Index Terms—Navigation, Spatial cognition, Virtual reality, Teleporting

1 Introduction

Virtual environments (VEs) are almost always larger than the tracked physical space. Therefore, complete exploration of the VE requires a locomotion interface other than, or in addition to, real walking. The increasing popularity of virtual reality (VR) for home entertainment has contributed to the proliferation of locomotion interfaces [1, 4]. One particularly popular locomotion interface found in almost all VR applications is teleporting (also referred to as jumping). To teleport, the user aims a hand-held controller at the intended location on the ground and is then instantly transported to that location after clicking. In the most common implementation of the teleporting interface, the user physically rotates their body in order to rotate in the VE and teleports to translate. In another less common implementation, the user teleports to translate and rotate. In all cases, teleporting leads to partial or complete discordance between movement through the VE and self-motion cues normally associated with walking, and this discordance can cause disorientation [10].

A growing body of evidence indicates that removal of self-motion cues normally associated with walking negatively affects performance on spatial cognitive tasks [5, 6, 10, 23, 25, 29, 32, 34]. The current project explores the spatial cognitive consequences of interface discordance when teleporting and specifically focuses on whether such consequences characterize both small- and large-scale movement, and whether environmental cues mitigate the consequences of teleporting.

Spatial updating is the process of mentally tracking self-location and self-orientation during locomotion. Spatial updating failure is synonymous with disorientation (i.e., loss of awareness of one's location and orientation relative to the environment). Research in spatial cognition indicates that spatial updating is informed by two primary processes: path integration and piloting. Path integration and piloting are two methods for solving the same spatial updating task, yet they rely on different mental representations. Path integration integrates self-motion cues over time, whereas piloting uses remembered locations of visible landmarks to determine self-location. Path integration and piloting provide independent estimates of self-location and self-orientation, and are typically combined during navigation [9, 30, 35].

2 Related Work

This section first reviews previous work related to two processes that support spatial updating: path integration and piloting. Next is a de-

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scription of the concordance framework, which defines locomotion interfaces on the basis of concordance between movement through the VE and movement of the user's body. Last is a review of research on the teleporting interface as it pertains to spatial updating.

2.1 Path integration

Path integration is the process of integrating body-based self-motion cues (vestibular stimulation, proprioception, and efference copies of motor commands) and visual self-motion cues (optic flow) over time in order to estimate self-location. Triangle completion—a common task used to evaluate the accuracy of spatial updating—involves guiding the participant along two legs of an outbound path before asking the participant to point or walk to the remembered location of the path origin. Path integration enables reasonably accurate triangle completion performance, at least over relatively short distances [19]. But successful path integration requires accurate estimates of both distances traveled (translation) and angles rotated, and because errors in both measures are cumulative, and cannot be corrected without piloting cues, errors necessarily increase with travel distance [22]. Manipulation of the presence of various self-motion cues indicates that the contribution of visual self-motion is negligible when body-based cues are available, and that the presence of body-based self motion reduces triangle completion errors by over 30% compared to vision-only conditions [19]. In sum, path integration enables reasonably accurate spatial updating over short distances, and body-based cues are more important to path integration than are visual self-motion cues.

Research on the relative importance of rotational and translational self-motion cues for path integration has produced equivocal results. In a triangle-completion study [23], participants traversed an outbound path while experimental conditions manipulated the availability of rotational and translational self-motion cues, both visual and body-based, along the outbound path. Performance with body-based rotational and translational cues but without vision was better than performance with vision but without any body-based cues. Furthermore, performance with vision plus rotational body-based cues was just as good as when all body-based cues (but no visual cues) were present. These results suggest that rotational body-based cues are necessary for accurate path integration, but translational body-based cues are not needed.

In a related study [34], participants performed a foraging task in which they searched virtual boxes while looking for target objects. Re-checking a box was considered evidence of spatial updating failure (i.e., disorientation). Participants experienced visual self-motion in all conditions, and experimental conditions manipulated the presence of rotational and translational body-based cues. Consistent with the aforementioned triangle completion results [23], performance with rotational and translational body-based cues together was better than performance without any body-based cues. However, performance with only rotational body-based cues was not better than when no body-based cues were present. These results indicate that rotational body-based cues are insufficient for accurate spatial updating, and that translational cues are necessary.

The reason for the equivocal results obtained through the triangle completion task [23] and the foraging task [34] is unclear. It is possible that simple tasks such as triangle-completion do not benefit from translational body-based cues, whereas more complex movements and tasks require translational cues. It is also possible that a triangle completion condition in which all self-motion cues (visual and body-based) were available would produce even better performance than the blindfolded walking condition or the body-rotation condition, but such comparisons are not available in the literature.

2.2 Piloting

Whereas path integration maintains a running estimate of self-location based on self-motion signals, piloting uses distances and directions to previously encoded landmarks to identify self-location and to navigate toward previously visited goals [14, 15]. Unlike path integration, piloting requires a cognitive map, that is, a representation of landmark locations held in memory.

The are two primary uses of piloting. The first use of piloting is to recover self-location after complete disorientation, which, by definition, reflects failure of the path integration system. The second use of piloting is in conjunction with path integration. In some cases, piloting is used to reset estimates of self-location when path integration accrues a sufficient amount of noise [41]. In other cases, piloting cues are combined with path integration in a statistically optimal way, whereby estimates of self-location based on piloting and path integration are weighted based on their reliability [9, 30, 35]. Whether piloting cues are used to reset path integration or are combined with path integration, remembered directions to landmarks are regularly used to identify self-location and to progress toward navigational goals.

2.3 Concordance framework for locomotion interfaces

The concordance framework [10] categorizes locomotion interfaces for VR on the basis of the concordance (i.e., agreement) between movement through the VE and movement of the body. The emphasis on body motion, rather than visual motion, is consistent with spatial cognitive research showing that body motion is critical to spatial updating even when visual motion is present [23, 34], and that visual motion has a negligible effect on spatial updating when body motion is present [19] (see Section 2.1 for more detailed analysis of this literature). Under this framework, locomotion interfaces are categorized as concordant, partially concordant, or discordant.

Walking through the VE is **concordant** because all body-based self-motion cues normally associated with walking are present when moving through the VE. Likewise, any locomotion technique that preserves the full set of body-based cues would also be considered concordant (note that most treadmills do not meet this criterion, as described below). Redirected walking [3], whereby users are steered away from physical obstacles by subtle separation between real and virtual rotation, could also be considered concordant in cases in which redirection is below perceptual thresholds for detection [16, 37].

Teleporting to change location but rotating the body to change orientation—by far the most common form of the teleporting interface—is **partially concordant**, because some aspects of movement through the VE (i.e., rotations) are concordant with self-motion and others (i.e., translations) are discordant. Another partially concordant interface is treadmill walking, whereby proprioceptive and kinesthetic cues associated with stepping indicate self-motion, but vestibular cues that normally signal linear and angular acceleration are absent. Only an omni-directional treadmill that preserves linear and angular acceleration cues [36] would be considered concordant, and only then if the corrective movements used to return the user to the treadmill center were below perceptual detection thresholds. Another partially concordant interface is scaled translational gain [17, 39], in which the user's stride length in the real world is exaggerated in the VE. In this case, body-based cues associated with self-motion are present, but they indicate velocities and accelerations that are smaller in magnitude than those experienced in the VE.

Teleporting to change location and orientation—a less common form of the teleporting interface—is **discordant** because movement through the VE is completely discordant with movement of the body, which is stationary. The most common discordant interface is joystick navigation. Driving interfaces in which the seated driver (without a motion base platform) controls forward motion by pressing pedals or buttons and rotation by turning a wheel are also discordant.

VE users commonly switch between modes of locomotion, for example, by walking when space permits and teleporting to travel larger distances that would otherwise be tiring to walk or would lead the user into a real obstacle. Other locomotion interfaces also involve switching between concordant and discordant modes of locomotion. One such example is resetting [40], whereby users walk freely until reaching a boundary, at which point the display is frozen while position and/or orientation is reset. In this way, walking and turning through the VE is typically concordant, but rotation/translation required during resetting is discordant.

2.4 Teleporting interfaces and spatial updating

The teleporting interface has gained popularity quickly since VR became mainstream for home entertainment in 2016. Researchers have already begun to identify the advantages and disadvantages of teleporting compared to other locomotion techniques. Except where noted, past research has exclusively studied partially concordant teleporting, whereby the user rotates with full self-motion cues but translates with no self-motion cues.

No research to date has directly evaluated the importance of body-based self-motion cues when teleporting while holding visual self-motion constant. Such research would require comparison of teleporting with a condition in which participants walk but do not receive visual input until reaching the end of the path. Instead, research has evaluated the importance of body-based and visual self-motion cues together. In one study [10], participants performed a triangle completion task in which the outbound path was traversed by walking, partially concordant teleporting, or discordant teleporting. Partially concordant teleporting lacks self-motion cues associated with translation, but provides all self-motion cues associated with rotation. Discordant teleporting lacks both rotational and translational self-motion cues. Pointing errors were smaller for walking compared to partially concordant teleporting, and smaller for partially concordant teleporting compared to discordant teleporting. This pattern of results across the three levels of interface concordance occurred in a featureless VE and in a rich indoor VE that enabled piloting, indicating the generality of the result. These results reflect the importance of both rotational and translational self-motion cues (c.f. [23, 34], in which only rotational or translational cues were beneficial). Given the negligible contribution of visual self-motion cues when body-based self-motion cues are also present [19], it stands to reason that availability of body-based self motion cues was the primary difference between interfaces.

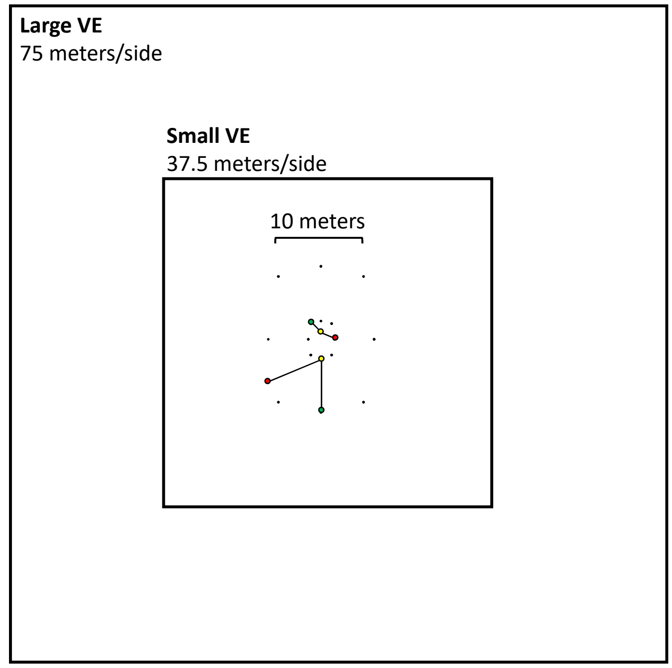

Fig. 2. Overhead view drawn to scale showing possible path start locations (small black dots; the inner ring shows small path start locations, and the outer ring shows large path start locations) and two sample paths (marked by lines connecting green, yellow, and red circles). Walls of the small and large VEs are also shown.

3 Spatial Updating Experiment

3.1 Overview

To date, only one study [10] has examined the role of body-based cues when teleporting. One shortcoming of that study is that the inclusion of a walking condition necessitated small triangles (the length of each triangle leg ranged from 1.5-1.8 meters). In contrast, teleporting is useful for traveling longer distances within the surrounding space. Therefore, the current study evaluated whether the previously-reported importance of body-based rotation when teleporting over short distances also characterizes travel over longer distances.

Manipulation of travel distance is straightforward in an empty, endless VE because the visual experience of the scene is unaffected by travel distance. However, in a more representative VE with boundaries and landmarks, larger travel distances bring the navigator closer to the surrounding landmarks and boundaries, which could allow for more accurate piloting. Therefore, the current experiment also manipulated the size of the surrounding VE to determine the relative contributions of path integration and piloting when teleporting over small and large distances.

To summarize, participants in the current experiment performed a triangle completion task. The outbound path was traversed through partially concordant teleporting or discordant teleporting (a walking condition was not included because of physical space constraints with larger paths). Path size was either small or large, and the surrounding VE was either small or large. Landmarks were placed near the walls of the VE, and triangles were situated near the center of the VE. In this way, the small triangles remained relatively far from landmarks regardless of VE size, whereas large triangles approached landmarks in the small VE but not in the large VE (see Figure 2).

3.2 Hypotheses

Hypotheses were pre-registered prior to data collection on the Open Science Framework: https://osf.io/83vty/. It was predicted that the discordant teleporting interface would lead to larger errors than the partially concordant teleporting interface, regardless of path size or VE size. This hypothesis is consistent with the notion that rotational self-motion cues are important to spatial updating [23] and is also consistent with past research on the teleporting interface [10].

It was also predicted that the difference in response error between the two teleporting interfaces would be greater when landmarks were far away from the path (i.e., small paths in the small and large VEs, and large paths in the large VE) compared to when landmarks were close to the path (i.e., large paths in the small VE). This was predicted because nearby landmarks (as compared to far landmarks) allow for a greater contribution of piloting to task performance, which could reduce reliance on body-based self-motion cues. In principle, this would lead to a predicted three-way interaction between interface, path size, and VE size. However, anticipating that such an interaction could require a considerable amount of data, it was instead predicted that the two-way interaction between interface and VE size would be significant for large paths, but not for small paths. In other words, for large paths, the difference between the two teleporting interfaces will be reduced in the small VE compared to the large VE, but for small paths, the difference between the two interfaces will not vary across VE size.

Finally, it was predicted that large triangles would result in larger errors than small triangles, particularly in the large VE, where performance is likely to be dominated by spatial updating rather than piloting. This hypothesis is consistent with the notion that path integration error accrues with travel distance, and thus larger travel distances would produce larger errors. It is also consistent with research showing that distance in virtual reality is under-perceived, and that such perceptual errors are proportional to the actual distance (see [12, 33] for reviews), even in modern displays [7, 20].

4 Method

4.1 Participants

Thirty-seven students (19 men, 18 women) at Iowa State University participated in exchange for credit in an undergraduate psychology course. Data from five participants were removed (see Results) leaving 32 total participants (19 men, 13 women).

4.2 Hardware and software

VEs were presented using the HTC Vive head-mounted display (HMD), and participant movements were tracked using the Lighthouse tracking system. One wireless hand-held controller, sold with the Vive, was used by participants to control the teleporting interfaces and to respond at the end of each trial. Images were rendered on a Windows 10 computer with an Intel 6700K processor and Nvidia GeForce GTX 1070 graphics card. Unity software displayed stereoscopic images at 1080×1200 resolution per eye with 100° horizontal × 110° vertical binocular field of view. Images refreshed at a rate of 90 Hz.

4.3 Stimuli

Videos showing the triangle completion task with each interface and in each environment are available on the Open Science Framework: https://osf.io/83vty/. The VEs were built with the Unity game engine, making use of pre-made assets from the Unity Asset Store. Each VE depicted a warehouse and contained several objects arranged along the walls, such as shipping containers, shelving, and wooden crates, with the center of the VE left open to allow free movement. The small and large VEs included many of the same objects and materials, but were not simply scaled versions of the same VE. The small VE (see Figure 1, left) measured 37.5 meters on each side, and the large VE (see Figure 1, right) measured 75 meters on each side.

Paths were marked by vertical semi-transparent posts (1 meter tall, .25 meters in diameter) that appeared in sequence to lead the participant along the two outbound path legs (one such post is shown in both panels of Figure 1). The start of the path was marked with a green post, the end of the first path leg was marked with a yellow post (shown), and the end of the second path leg was marked with a red post. Each post had a blue arrow at its base indicating the direction of the next post in the sequence (the arrow on the red post simply pointed in the same direction as the arrow on the yellow post). The arrows were needed so that participants using the discordant teleporting interface knew their intended orientation, but the arrows were also present when using the partially concordant teleporting interface in order to maintain experimental control.

A virtual replica of the hand-held controller was visible at all times during the task and was co-located with the actual controller held by the participant. When using the partially concordant teleporting interface, the participant selected the intended teleporting location by positioning a white disc (30 cm diameter) with surrounding white ring (75 cm diameter) on the ground plane (see Figure 1, left). A thin red line extended from the end of the controller to the center of the white circle. The participant pressed and held the trackpad button (located on the top of the controller) while moving the controller to manipulate the location of the teleport marker, and released the button to teleport. Rotation was achieved by rotating the body. When using the discordant teleporting interface, the participant selected the intended location and orientation by manipulating a magenta ring (195 cm diameter) with an arrow on one side (see Figure 1, right). A thin red line extended from the joystick to the center of the ring. The participant pressed and held the trackpad button while moving the controller to manipulate the location of the teleport marker and moving the thumb around the edge of the circular trackpad to manipulate the orientation of the teleport marker. Releasing the trackpad button teleported the participant to the selected location and orientation.

After traveling the outbound path, the participant pointed to the remembered location of the path origin by positioning a blue disc (39 cm diameter) on the ground plane. As with the teleporting interfaces, a thin red line extended from the joystick to the center of the disc. The participant pressed and held the trigger button while moving the controller to manipulate the location of the disc, and released the trigger to indicate the intended location.

Both teleporting interfaces included a snapping feature that caused the teleporting marker to lock onto the post when it was positioned nearby. The exact snapping distance varied by path size (20 cm for small paths and 80 cm for large paths. Furthermore, the orientation of the discordant teleporting ring snapped to the orientation of the arrow at the base of the post when it was oriented within 10°, which caused the arrow attached to the post to change color from blue to magenta. The snapping feature was designed to prevent teleporting errors when traversing the outbound path.

Path start locations were arranged in an oblong ring located near the center of the environment (see start locations and sample paths in Figure 2). The first path leg generally led the participant toward the center of the environment, and the second path leg generally led the participant away from the center of the environment.

4.4 Design

The experiment used a 2 (teleporting interface: partially concordant or discordant) × 2 (path size: small or large) × 2 (VE size: small or large) repeated measures design. Trials were blocked and counterbalanced by condition such that half of participants performed all small path trials first and half performed all large path trials first. Within each path size block, half of participants performed all small VE trials first and half performed all large VE trials first. Within each VE size block, half of participants were assigned to use the partially concordant teleporting interface first and half were assigned to use the discordant teleporting interface first.

For each combination of interface, path size, and VE size, participants performed blocks of 12 triangle completion trials corresponding to 12 unique turn angles from -135° to +135° in increments of 22.5°, excluding 0°. The order of turn angle presentation was randomized within block. Path leg length was randomly selected on each trial from three possible values (1.52, 1.68, and 1.83 meters for small paths; 6.1, 6.7, and 7.3 meters for large paths).

4.5 Procedure

Each participant received a description of the study before providing informed consent. The participant then donned the HMD and was given verbal instructions about how to use the two teleporting interfaces. Using a grid-like VE, each participant completed at least two practice triangle completion trials without feedback, and could request additional practice if desired. Experimental trials began after practice completion.

A green post appeared at the beginning of each trial, marking the path origin. The participant traveled to the green post using the assigned locomotion interface. Upon arrival, the green post disappeared and a yellow post appeared, marking the end of the first path leg. Upon arrival, the yellow post disappeared and a red post appeared, marking the end of the second path leg. Upon arrival, the red post disappeared and the participant was instructed to point to the location of the path origin (i.e., the green post). During the response phase of the task, the participant was encouraged to rotate the body to face the path origin before pointing. Body rotation prior to response was encouraged with both teleporting interfaces in order to 1) avoid awkward pointing behind the participant and 2) ensure that any performance difference between the two interfaces was solely due to differences in spatial updating during outbound path travel, and not due to differences in response execution. After rotating toward the path origin, the participant held the trigger on the controller while adjusting the response location and released the trigger when satisfied with the response. The trigger release event was used to log the response location and response time. The experimenter then pressed a key to advance to the next trial.

After the experiment was complete, the participant was debriefed about the goals of the study and given credit for participation. Feedback about performance was never provided to the participant.

5 Results and Discussion

Data from four participants were removed due to missing data in at least one condition. Of those four, two were due to early withdrawal after reporting symptoms of cybersickness, one was due to technical failure, and one was due to failure to complete the study in the allotted time. Data from another participant were removed due to mean pointing errors that were more than three standard deviations higher than the group mean. An additional 16 trials (0.5%) were removed from the remaining data due to computer errors and procedural errors.

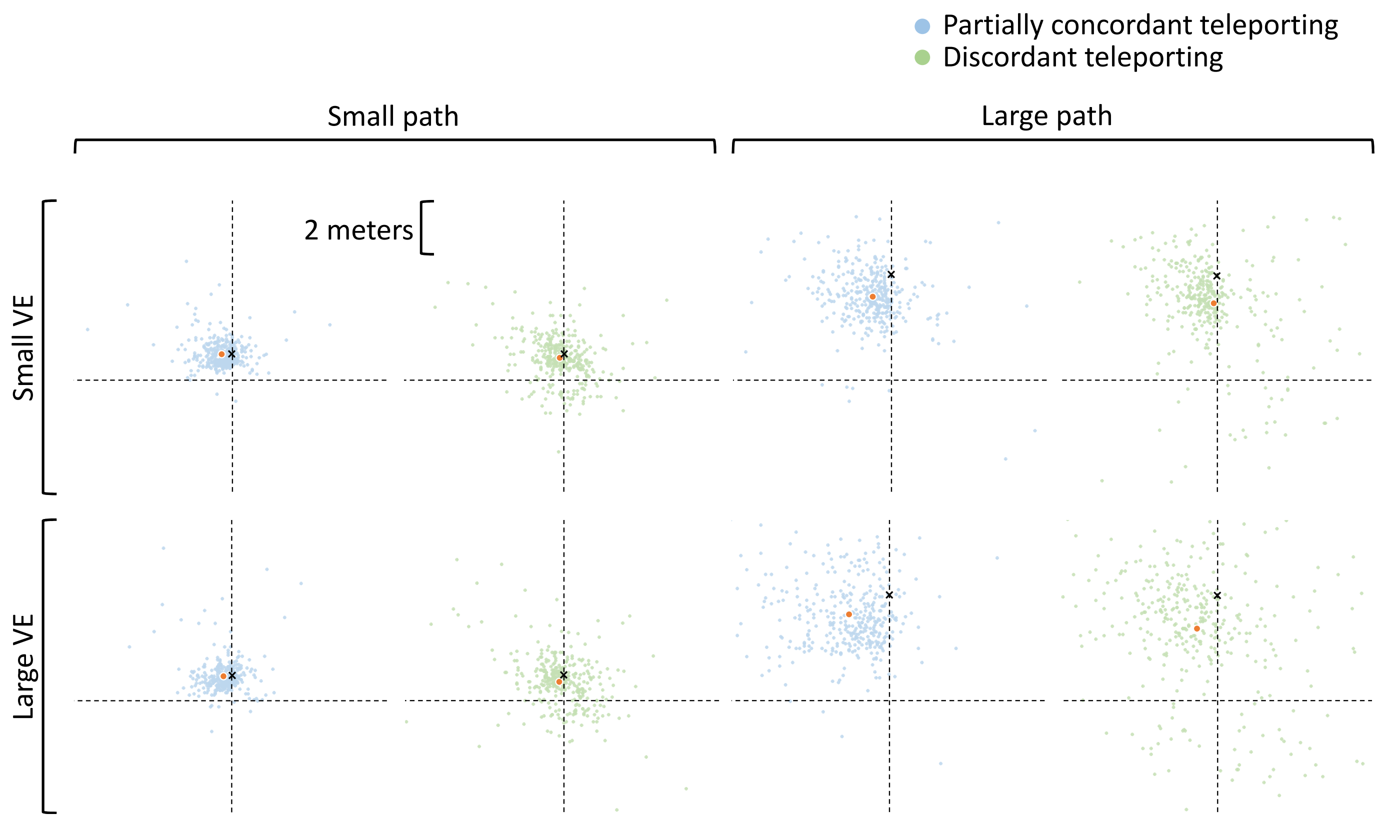

Fig. 3. Scatterplots showing individual pointing responses. The path origin (i.e., the correct pointing location) is marked by a black X. The mean response is marked by an orange circle. The path terminus (i.e., the participant's location at the time of response) is located at the intersection of the dashed lines. Responses for left- and right-turn paths were normalized so that counter-clockwise error reflects under-rotation when turning to face the path origin. A few data points are not shown due to scaling and cropping for publication purposes.

Individual pointing responses are shown in Figure 3. In the analyses below, triangle completion errors are first described in terms of absolute distance from the path origin (i.e., the correct pointing location), which simplifies the data by reducing pointing responses to a one-dimensional error but also captures something especially meaningful: total distance from the target. Absolute distance error could be caused by angular error (i.e., pointing in the wrong direction), axial error (i.e., pointing the wrong distance, such as too long or short), or some combination of angular and axial error. Therefore, subsequent analyses separately describe the angular and axial components of the pointing response in order to elucidate the underlying causes of the absolute distance errors.

Analyses focused on the effects of interface, path size, and VE size. Therefore, data from repeated trials were averaged together prior to analysis. There was no evidence of a speed-accuracy trade-off. The within-participant correlation between absolute distance error (the absolute distance between the response location and the path origin) and latency (the difference between the time at which the participant arrived at the red post and the time that the pointing response was recorded) was significantly positive ($M = .38$, $SE = .06$), $t(31) = 6.25$, $p<.001$. Response error was the focus of the current project, and it was generally more responsive to manipulation of the independent variables than was response latency. The complete data set is provided on the Open Science Framework: https://osf.io/83vty/.

5.1 Absolute distance error

Absolute distance error was defined as the absolute distance (in meters) between the location of the response and the location of the path origin. Absolute distance error (see Figure 4) was analyzed in a 2 (path size) by 2 (VE size) by 2 (teleporting interface) repeated-measures ANOVA. Significant main effects of path size, $F(1,31)=130.97$, $p<.001$, $\eta_p^2 = .81$, VE size, $F(1,31)=45.23$, $p<.001$, $\eta_p^2 = .59$, and interface, $F(1,31)=61.18$, $p<.001$, $\eta_p^2 = .66$, were qualified by significant interactions between VE size and interface, $F(1,31)=5.53$, $p=.025$, $\eta_p^2 = .15$, path size and interface, $F(1,31)=5.08$, $p=.031$, $\eta_p^2 = .14$, and path size and VE size, $F(1,31)=59.66$, $p<.001$, $\eta_p^2 = .66$. The three-way interaction was not significant.

Errors were larger when using the discordant teleporting interface

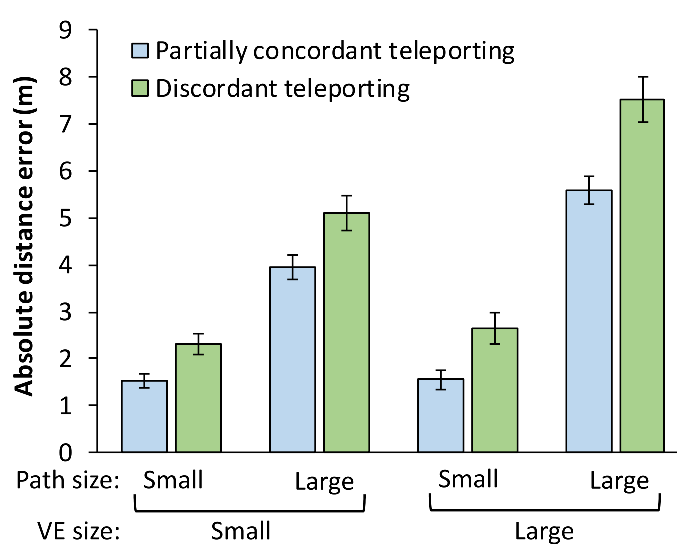

Fig. 4. Average absolute distance error as a function of path size, VE size, and teleporting interface. Smaller absolute distance errors reflect better performance. Error bars represent ± 1 standard error of the mean.

compared to the partially concordant teleporting interface, and this was true for every combination of VE size and path size (p's$<$.001). Furthermore, the difference between the two interfaces was exaggerated in the large VE compared to the small VE, and also exaggerated when navigating large compared to small paths. Errors were also overall larger when navigating large compared to small paths, and this difference was exaggerated in the large VE compared to the small VE.

Despite the non-significant three-way interaction, small and large path data were further analyzed in separate 2 (VE size) by 2 (teleporting interface) repeated-measures ANOVAs to test the a priori prediction that the difference between the two teleporting interfaces would be reduced in the small VE when traversing large paths but not small paths. As predicted, the ANOVA testing large path data showed a significant interaction, $F(1,31)=4.96$, $p=.033$, $\eta_p^2 = .14$, but the ANOVA testing the small paths did not, $F(1,31)=2.12$, $p=.155$, $\eta_p^2 = .06$. These results can be interpreted as evidence that the relative contributions of path integration and piloting shift depending on landmark proximity. Partially concordant teleporting provides self-motion cues that enable more accurate path integration compared to discordant teleporting, and this difference between interfaces is greatest when the role of piloting is reduced (i.e., when landmarks are farther away). To that end, the role of piloting was greater when landmarks were near (large paths in the large VE) compared to far (small paths regardless of VE size, and large paths in the large VE) relative to the outbound path.

To summarize, analysis of absolute distance error supported all three a priori predictions. Errors were larger with discordant compared to partially concordant teleporting, errors were larger when traversing large compared to small paths, and nearby landmarks reduced errors overall and reduced the consequences of interface discordance. However, absolute distance error does not specify whether errors occurred because participants pointed in the wrong direction, or the wrong distance, or both. Therefore, additional analyses explored the specific characteristics of pointing responses that led to these patterns in absolute distance error.

5.2 Absolute angular error

Absolute angular error was defined as the absolute angular distance (in degrees) between the direction of the pointing response and the direction of the path origin. Absolute angular error (see Figure 5) was analyzed in a 2 (path size) by 2 (VE size) by 2 (teleporting interface) repeated-measures ANOVA. Significant main effects of path size, $F(1,31)=19.19$, $p<.001$, $\eta_p^2 = .38$, VE size, $F(1,31)=20.88$, $p<.001$, $\eta_p^2 = .40$, and interface, $F(1,31)=55.13$, $p<.001$, $\eta_p^2 = .64$, were qualified by significant interactions between VE size and interface, $F(1,31)=4.27$, $p=.047$, $\eta_p^2 = .12$, path size and interface, $F(1,31)=8.64$, $p=.006$, $\eta_p^2 = .22$, and path size and VE size, $F(1,31)=20.95$, $p<.001$, $\eta_p^2 = .40$. The three-way interaction was not significant.

Absolute angular errors were larger when using the discordant teleporting interface compared to the partially concordant teleporting interface, and this was true for every combination of VE size and path size (p's$\leq$.001). Furthermore, the difference between the two interfaces was larger in the large VE compared to the small VE, and when navigating small compared to large paths. Angular errors were larger when traveling small compared to large paths, but only in the small VE and not the large VE.

Despite the non-significant three-way interaction, small and large path data were further analyzed in separate 2 (VE size) by 2 (teleporting interface) repeated-measures ANOVAs to test the a priori prediction that the difference between the two teleporting interfaces would be reduced in the small VE when traversing large paths but not small paths. As predicted, the ANOVA testing large path data showed a significant interaction, $F(1,31)=6.32$, $p=.017$, $\eta_p^2 = .17$, but the ANOVA testing the small paths did not, $F(1,31)=1.21$, $p=.280$, $\eta_p^2 = .04$. Paralleling the analysis of absolute distance error, these results show that the role of piloting was greater when landmarks were near (large paths in the large VE) compared to far (small paths regardless of VE size, and large paths in the large VE) relative to the outbound path. When landmarks were near, the increased role of piloting partially compensated for the consequences of using the discordant teleporting interface.

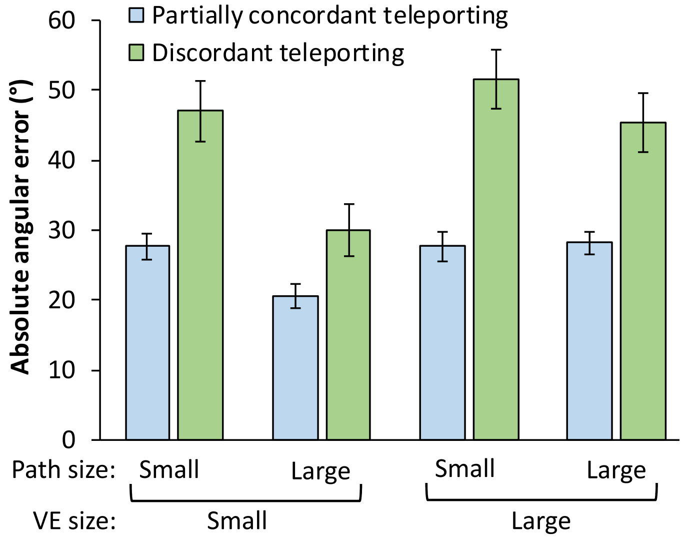

Fig. 5. Average absolute angular error as a function of path size, VE size, and teleporting interface. Smaller absolute angular errors reflect better performance. Error bars represent ± 1 standard error of the mean.

How do the absolute angular error results fit with the preceding analysis of absolute distance error? The results are consistent in that errors were larger when using the discordant teleporting interface compared to the partially concordant teleporting interface. Furthermore, nearby landmarks (i.e., in the small VE with large paths) reduced errors and also reduced the consequences of interface discordance. The most notable difference is that absolute distance errors were larger when navigating large paths and when navigating in the large VE, whereas absolute angular errors were smaller when navigating large paths in the small VE. However, there is no discrepancy here: equivalent angular error after navigating a small path and a large path would correspond to an absolute distance error four times larger for the large compared to small path because the path origin is four times farther away from the path terminus. Therefore, the somewhat smaller angular errors (˜12°) observed in the large compared to small paths within the small VE actually led to larger absolute errors (˜2.5 meters) in the large compared to small paths. Likewise, the approximately equivalent angular errors in the large and small paths within the large VE led to considerably larger absolute errors (˜4.3 meters) in the large compared to small paths.

The absolute angular errors provide a more complete understanding of the absolute distance errors presented in Section 5.1. However, even absolute angular error glosses over an important component of the pointing response: signed pointing error. Specifically, absolute angular error could be caused by variability around the correct pointing direction, or by bias in one direction or the other, or both. Therefore, additional analyses of signed angular error explored the specific characteristics of pointing responses that led to these patterns in absolute angular error.

5.3 Signed angular error

Signed angular error was defined as the distance (in degrees) between the direction of the pointing response and the direction of the path origin. Errors were flipped for triangles with a counter-clockwise turn at the yellow post, such that a negative error reflected under-rotation when turning to face the path origin and a positive error reflected over-rotation when turning to face the path origin (assuming participants rotated the shorter of the two possible turn directions). In this way, signed angular error reflects bias in the pointing response. Signed angular error (see Figure 6) was analyzed in a 2 (path size) by 2 (VE size) by 2 (interface) repeated-measures ANOVA. Main effects of interface, $F(1,31)=63.67$, $p<.001$, $\eta_p^2 = .67$, and VE size, $F(1,31)=8.78$, $p=.006$, $\eta_p^2 = .22$, were significant, as was the interaction between VE size and

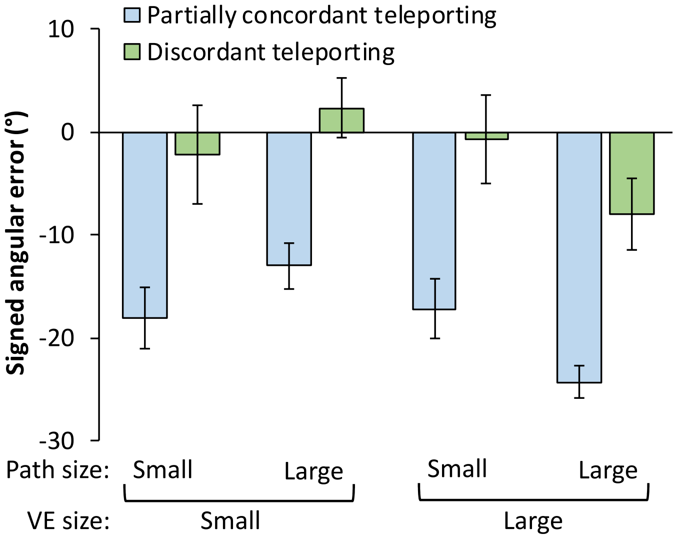

Fig. 6. Average signed angular error as a function of path size, VE size, and teleporting interface. Negative errors reflect under-rotation when turning to face the path origin, and positive errors reflect over-rotation. Errors closer to zero reflect less biased responses. Error bars represent ± 1 standard error of the mean.

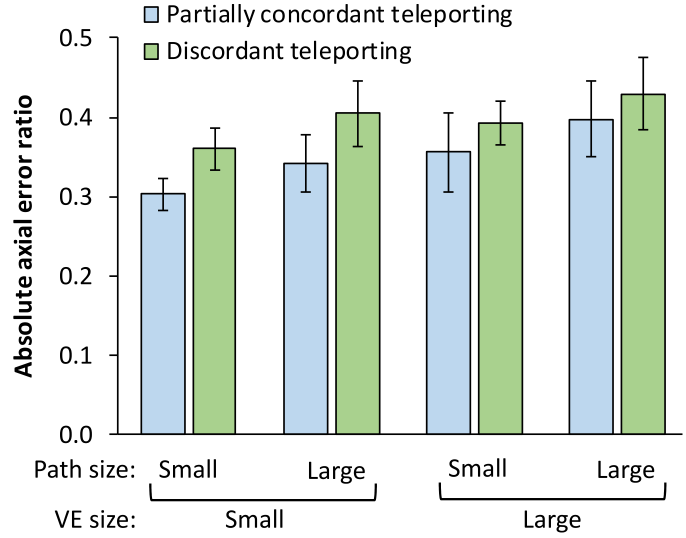

Fig. 7. Average absolute axial error ratio as a function of path size, VE size, and teleporting interface. Smaller ratios reflect better performance. Error bars represent ± 1 standard error of the mean.

path size, $F(1,31)=9.87$, $p=.004$, $\eta_p^2 = .24$. No other main effects or interactions were significant.

Under-rotation was evident in the partially concordant teleporting condition but not the discordant teleporting condition. Supplemental analyses (available on the Open Science Framework: https://osf.io/83vty/) indicate that under-rotation was linearly related to turn angle, such that larger turn angles produced greater under-rotation, but only for the partially concordant teleporting interface. Furthermore, under-rotation was more pronounced in the large VE, but only when navigating large paths.

If angular responses in the partially concordant teleporting condition are negatively biased and those in the discordant condition are essentially unbiased, then why are absolute angular errors (Section 5.2) larger in the discordant compared to partially concordant condition? Average signed angular errors near zero reflect the absence of bias, but this says nothing about the variability of individual responses around the mean. Absolute errors reflect both bias and variability in pointing responses, and in this case variability was much larger when using the discordant compared to partially concordant teleporting interface. This large difference in variability across interfaces overwhelmed the difference in bias when calculating absolute angular error. In fact, supplemental analyses of the standard deviation of angular responses (available on the Open Science Framework: https://osf.io/83vty/) are very similar to those based on absolute angular error.

5.4 Absolute axial error

Absolute axial error was defined as the absolute value of the difference between the response distance and the target distance, divided by the target distance. Therefore, smaller errors result in values closer to zero. Absolute axial error (see Figure 7) was analyzed in a 2 (path size) by 2 (VE size) by 2 (teleporting interface) repeated-measures ANOVA. Main effects of VE size, $F(1,31)=5.26$, $p=.029$, $\eta_p^2 = .15$, and interface, $F(1,31)=7.49$, $p=.01$, $\eta_p^2 = .20$, were significant. No other main effects or interactions were significant.

Errors were larger when using the discordant teleporting interface compared to the partially concordant teleporting interface, and when navigating in the large VE compared to the small VE.

5.5 Signed axial error

Signed axial error was defined as the response distance minus the target distance, divided by the target distance. Negative axial error indicates that pointing responses were too short, whereas positive axial error indicates that pointing responses were too long. In this way, signed axial error reflects bias in the pointing response. Signed axial error (see Figure 8) was analyzed in a 2 (path size) by 2 (VE size) by 2 (interface) repeated-measures ANOVA. Only the main effect of path size was significant, $F(1,31)=23.25$, $p<.001$, $\eta_p^2 = .43$, whereby judgments were shorter for large paths than for small paths. No other main effects or interactions were significant. Signed axial errors for large paths were significantly negative (all p's$<.01$), whereas the average of signed errors for small paths did not significantly differ from zero, indicating an approximately balanced mix of negative and positive signed errors.

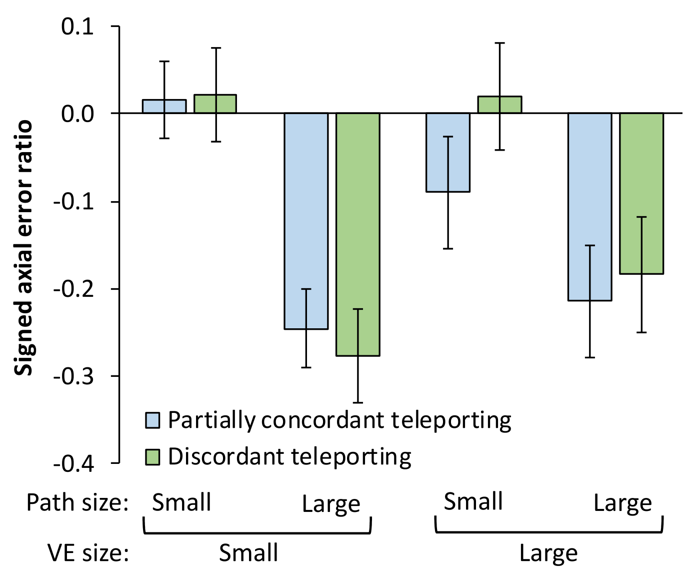

Fig. 8. Average signed axial error as a function of path size, VE size, and teleporting interface. Zero represents perfect performance, negative errors are too short, and positive errors are too long. Error bars represent ± 1 standard error of the mean.

5.6 Response latency

Response latency was calculated as the difference between the time when the participant arrived at the red post and when a pointing re-

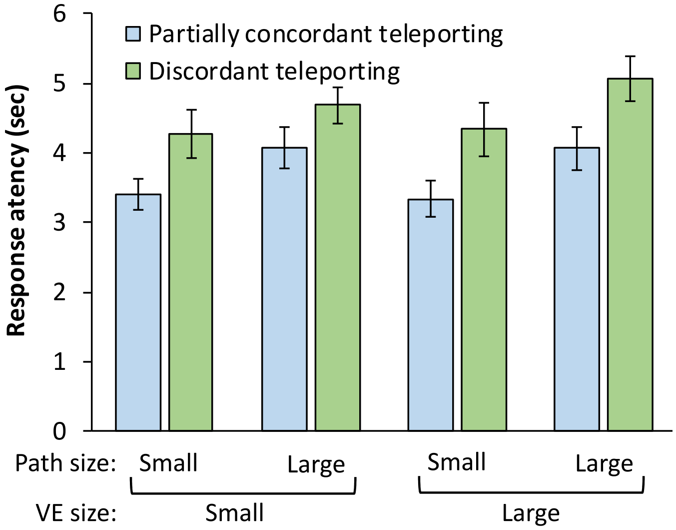

Fig. 9. Average response latency as a function of path size, VE size, and teleporting interface. Error bars represent ± 1 standard error of the mean.

sponse was recorded. Latency (see Figure 9) was analyzed in a 2 (path size) by 2 (VE size) by 2 (interface) repeated-measures ANOVA. Main effects of interface, $F(1,31)=29.70$, $p<.001$, $\eta_p^2 = .49$, and path size, $F(1,31)=12.33$, $p=.001$, $\eta_p^2 = .28$, were significant. No other main effects or interactions were significant. Response latency was longer when using the discordant compared to partially concordant teleporting interface, and response latency was longer after traversing larger compared to smaller paths.

6 Summary and Further Discussion

The purpose of this study was to evaluate the contribution of rotational self-motion cues to spatial updating performance when teleporting across different movement scales and different environment scales. Participants completed a triangle completion task using two locomotion interfaces: partially concordant teleporting, which included all rotational self-motion cues, and discordant teleporting, which included no rotational self-motion cues. Small and large paths, as well as small and large VEs, were used to evaluate whether the importance of rotational self-motion cues varied across those factors.

The first hypothesis was that the discordant teleporting interface would lead to larger errors than the partially concordant teleporting interface, regardless of path size or VE size, due to the importance of rotational self-motion cues to spatial updating [10, 23]. This hypothesis was supported by analysis of absolute distance errors and absolute angular errors, both of which were higher when using the discordant compared to partially concordant teleporting interface for every combination of path size and VE size. Furthermore, absolute axial errors were larger and response latencies were longer when using the discordant compared to partially concordant teleporting interface.

Past research on the relative importance of rotational and translational self-motion cues for spatial updating has produced equivocal results. A study using the triangle-completion task found that rotation of the body was necessary for accurate spatial updating, but translation of the body was not [23]. In contrast, a study using a foraging task found that translation of the body was necessary [34]. The current results appear to support the importance of body rotation. However, the discordant interface in the current experiment eliminated body rotation and visual rotation. Therefore, this experiment cannot identify the relative importance of body rotation and visual rotation, but given the similarity with the methods and findings of past triangle completion research [23], we speculate that body-rotation is the key factor. Future work applying the concordance framework to a foraging task, or other more complex navigation tasks, would be useful for evaluating whether rotational self-motion cues when teleporting are important only in specific situations or whether they are important across a broad range of navigation tasks.

Signed angular errors indicated that the partially concordant teleporting interface produced an under-rotation bias when turning toward the path origin, although the larger absolute errors for discordant compared to partially concordant teleporting reflect the greater contribution of pointing variability to absolute error. Still, the under-rotation bias is worth considering further. Supplemental analyses indicated that the amount of under-rotation was proportional to the turn angle (the angle at the vertex of the outbound path), such that larger turns led to larger under-rotation bias. Rotational bias in triangle completion has been reported elsewhere, including the finding that bias becomes more negative with increasing turn angle [27]. Although some studies report under-rotation [13, 27], like the current study, others report over-rotation [19, 28]. One study [19] found that rotation bias depended on available cues, shifting from under-rotation with only visual self-motion cues to over-rotation when both visual and body-based self-motion cues are available, but the partially concordant condition in the current study produced under-rotation despite the availability of both body-based and visual self-motion cues. More recent research indicates that the bias is due to error in response execution, rather than error in encoding of the turn on the outbound path [11]. If the response is truly the source of the under-rotation bias, then it is surprising to see that the discordant interface produced no bias, since participants responded in the same way regardless of interface. It is possible, therefore, that the discordant interface produced systematic under-perception of the turn angle which would have led to over-rotation during the response but was negated by the under-rotation response bias. It is worth reiterating that, although the partially concordant interface produced an under-rotation bias that did not occur with the discordant interface, the response variability associated with the discordant interface was so much larger than that associated with the partially concordant interface that absolute errors (absolute distance errors and absolute angular errors) were much larger when using the discordant compared to partially concordant teleporting interface.

The second hypothesis was that the difference between the two teleporting interfaces (partially concordant and discordant teleporting) would be greater when landmarks were far away from the path (i.e., small paths in the small and large VEs, and large paths in the large VE) compared to when landmarks were close to the path (i.e., large paths in the small VE). This hypothesis was supported by analysis of absolute distance errors and absolute angular errors, whereby the difference between the partially concordant and discordant interfaces was unaffected by VE size for small paths, but the difference between interfaces was reduced in the small VE compared to the large VE for large paths. It stands to reason that piloting played a larger role in the small VE with large paths, because the paths brought participants closer to the landmarks and boundaries within the VE. This increased role of piloting diminished the role of path integration, thus reducing the difference between interfaces. It is somewhat surprising that this effect was not found in the axial error data, since piloting should enable better updating of both distance and direction. This does not appear to be caused by ceiling performance, as pointing distance was typically off by 30-40% of target distance. Thus, the engagement of piloting appears to have been primarily for the purpose of identifying self-orientation within the VE, but not self-position. Although the current data did not explain why landmark proximity did not improve pointing distance, we speculate that the objects at the border of the room were too far to be helpful for this purpose, even with the large paths in the small VE. Geometrically, the effectiveness of most distance cues (e.g., binocular convergence and disparity, angular declination, relative size, etc.) is diminished for far compared to near objects. Closer landmarks (e.g., objects scattered within the movement space) might provide more detailed positional information that would facilitate distance judgments.

The final hypothesis was that large triangles would produce larger errors overall compared to small triangles, particularly in the large VE, where performance is likely to be dictated by spatial updating instead of piloting. This hypothesis was supported by the absolute distance errors, but not absolute angular errors. This distinction is not altogether surprising. Considering data only from the large VE, absolute angular errors were equivalent for small and large paths, but large paths were characterized by longer distances between the path terminus and path origin, which led to larger absolute distance errors even though angular errors were comparable. Axial errors indicated a tendency to under-judge distance on large compared to small paths. This appears consistent with past research showing underperception of distance in VR [12, 33], which is typically proportional to actual distance.

The effect of VE size was primarily limited to its interaction with interface and path size, as described above in the second hypothesis. The only exception to this was in the absolute axial error data, where errors in the large VE were overall greater than in the small VE. This may have been related to the lack of contextual size cues in the middle of the large VE as compared to the small VE, as the size of nearby familiar objects can provide information about scale when judging distance.

Research in spatial cognition reveals that individuals differ in their ability to perform spatial tasks. For example, men tend to outperform women on a variety of navigational tasks [2,8,31], and men and women differ in their reliance on available spatial cues. Some of those sex differences appear to be attributable to differences in spatial experience [18, 38] and differences in reliance on available spatial cues [21, 24]. Future research should examine whether characteristics of the user impact navigation in virtual environments, and whether such individual differences warrant different recommendations for interfaces and virtual environments. Furthermore, future research that includes a more diverse sample of participants would indicate whether the current findings generalize beyond the college undergraduate population.

7 Conclusions

The teleporting interface for locomotion in VR is widespread, most likely due to reduction in cybersickness compared with interfaces that place visual motion in conflict with body motion (e.g., joystick locomotion) [26]. Yet, teleporting hinders spatial updating performance, and may produce unacceptable levels of disorientation in certain individuals and applications. The current results indicate that rotational self-motion cues are important to spatial updating when teleporting, and other research points to a similarly important role for translational self-motion cues [10,23]. Furthermore, these spatial cognitive consequences persist across multiple scales of movement, and also across multiple VE scales, suggesting that the consequences of teleporting are quite general.

One encouraging message for VE designers is that piloting cues mitigate the negative consequences of teleporting. Although one might be tempted to litter the VE with additional landmarks in an attempt to further reduce the consequences of teleporting, other work suggests that landmarks per se are not helpful and that spatial boundaries, such as room walls or fences, are necessary [10]. The current experiments cannot distinguish between the contributions of landmarks and boundaries, as both were present in the VEs. Further research is needed to define general guidelines for designing VEs that support piloting as a way to compensate for the lack of self-motion cues when teleporting.

8 Acknowledgments

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