2020

Individual Differences in Teleporting through Virtual Environments

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Abstract

Virtual reality (VR) allows users to walk to explore the virtual environment (VE), but this capability is constrained by real obstacles. Teleporting interfaces overcome this constraint by allowing users to select a position, and sometimes orientation, in the VE before being instantly transported without self-motion cues. This study investigated whether individual differences in navigation performance when teleporting correspond to characteristics of the individual, including spatial ability. Participants performed triangle completion (traverse two outbound path legs, then point to the path origin) within VEs differing in visual landmarks. Locomotion was accomplished using three interfaces: walking, partially concordant teleporting (teleport to change position, rotate the body to change orientation), and discordant teleporting (teleport to change position and orientation). A latent profile analysis identified three classes of individuals: those who performed well overall and improved with landmarks ("Accurate Integrators"), those who performed poorly without landmarks but improved when available ("Inaccurate Integrators"), and those who performed poorly even with landmarks ("Inaccurate Non-Integrators"). Characteristics of individuals differed across classes, including gender, self-reported spatial ability, mental rotation, and perspective-taking; but only perspective-taking significantly distinguished all three classes. This work elucidates spatial cognitive correlates of navigation and provides a framework for identifying susceptibility to disorientation in VR.

Disciplines

Cognition and Perception | Cognitive Psychology | Ergonomics | Human Factors Psychology

Comments

This is a pre-print of the article Cherep, Lucia, Jonathan Kelly, Anthony J. Miller, Alex Lim, and Stephen B. Gilbert. "Individual Differences in Teleporting Through Virtual Environments." *PsyArXiv*. (2020). DOI: 10.31234/osf.io/b6cyd. Posted with permission.

Individual Differences in Teleporting through Virtual Environments

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This manuscript is currently under review as of 12/16/2020 and has not yet been published.

Author Note

Pre-registration as well as videos, data, supplementary analyses, supplementary figures, and experiment code are available on the Open Science Framework (doi:10.17605/OSF.IO/XC8V5). This material is based upon work supported by the National Science Foundation under Grant No. CHS-1816029. Preliminary results are described in Cherep, Lim, Kelly, Miller, and Gilbert (2020).

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Abstract

Virtual reality (VR) allows users to walk to explore the virtual environment (VE), but this capability is constrained by real obstacles. Teleporting interfaces overcome this constraint by allowing users to select a position, and sometimes orientation, in the VE before being instantly transported without self-motion cues. This study investigated whether individual differences in navigation performance when teleporting correspond to characteristics of the individual, including spatial ability. Participants performed triangle completion (traverse two outbound path legs, then point to the path origin) within VEs differing in visual landmarks. Locomotion was accomplished using three interfaces: walking, partially concordant teleporting (teleport to change position, rotate the body to change orientation), and discordant teleporting (teleport to change position and orientation). A latent profile analysis identified three classes of individuals: those who performed well overall and improved with landmarks ("Accurate Integrators"), those who performed poorly without landmarks but improved when available ("Inaccurate Integrators"), and those who performed poorly even with landmarks ("Inaccurate Non-Integrators"). Characteristics of individuals differed across classes, including gender, self-reported spatial ability, mental rotation, and perspective-taking; but only perspective-taking significantly distinguished all three classes. This work elucidates spatial cognitive correlates of navigation and provides a framework for identifying susceptibility to disorientation in VR.

Keywords: spatial cognition, individual differences, teleporting, virtual reality, navigation

Individual Differences in Teleporting through Virtual Environments

Modern virtual reality (VR) systems allow the user to walk and turn to explore the virtual environment (VE). However, the ability to walk through the VE is limited by real obstacles, such as walls and furniture. Therefore, exploration of all but the smallest VEs requires a locomotion interface that separates movement through the VE from movement of the user's body. The most popular locomotion interface is teleportation (Boletsis, 2017). To teleport, the user positions a marker within the VE and is then instantly transported to the selected location typically without accompanying visual or body-based self-motion cues. The popularity of the teleporting interface is most likely due to its ease of use (Bozgeyikli et al., 2016; Langbehn et al., 2018) and reduced cybersickness compared to interfaces that include smooth visual motion without movement of the body (Rahimi Moghadam et al., 2018).

Despite the many benefits of teleportation, discordance between movement of the body and movement through the VE comes at a spatial cognitive cost. In particular, spatial updating – the process of updating self-location during travel – is disrupted in the absence of self-motion cues. For example, in a triangle completion task in which the participant travels two outbound path legs before pointing back to the path origin, performance suffers when translation (change in position) is accomplished by teleportation compared to walking and suffers further when rotation (change in orientation) is accomplished by teleportation compared to real body rotation (Cherep, Lim, Kelly, Acharya, et al., 2020; Kelly et al., 2020). These findings are consistent with prior research indicating the importance of walking (Lhuillier et al., 2020), translational (Ruddle & Lessels, 2006) and rotational (Klatzky et al., 1998) self-motion cues to spatial updating. The goal of the current project was to characterize individual differences in spatial updating performance when teleporting.

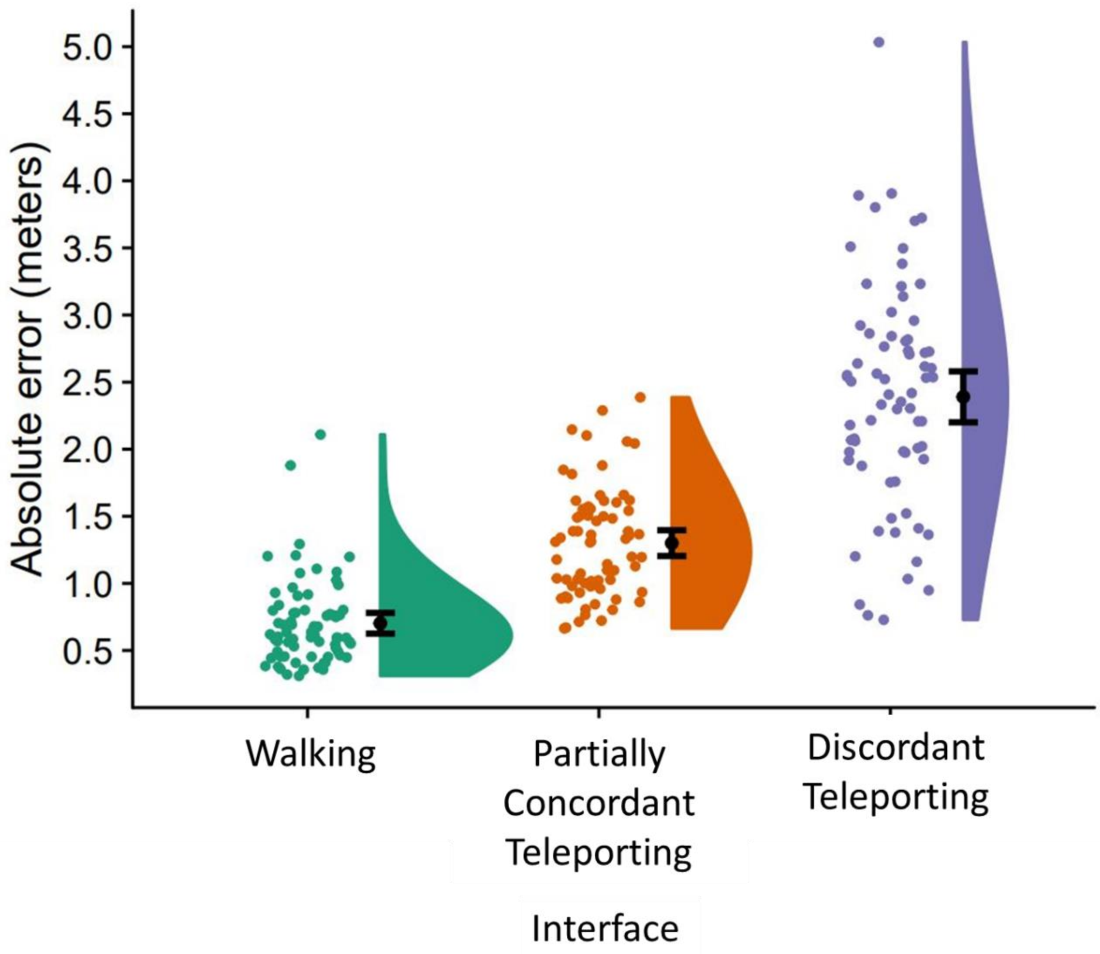

Figure 1. Raincloud plots (Allen et al., 2019) of the pooled triangle completion data from the open field VE from Cherep, Lim, Kelly, Acharya, et al. (2020) (Experiments 1-3). This graph provides individual data points, with mean and 95% confidence intervals, and density plots.

The negative influence of teleportation on triangle completion performance is robust. Figure 1 shows means and 95% confidence intervals (black dots with black error bars) from 72 participants pooled across multiple experiments described by Cherep, Lim, Kelly, Acharya, et al. (2020). Those data were collected using a triangle completion task in a VE that included only a grassy field without visual orienting cues, such as landmarks. When using the **walking interface**, participants walked and turned to travel the outbound path, and therefore received all visual and body-based cues normally associated with translation and rotation. When using the **partially concordant teleporting interface**, participants teleported to translate and used their bodies to rotate. Participants using this interface experienced no translational self-motion cues but full rotational self-motion cues. This is referred to as partially concordant because rotation through the VE was concordant with physical movement of the participant's body, whereas translation through the VE was discordant with movement of the participant's body. When using the **discordant teleporting interface**, participants teleported to translate and rotate, with no accompanying self-motion cues. A more complete characterization of the concordance framework for virtual locomotion can be found in Cherep, Lim, Kelly, Acharya, et al. (2020).

Although the mean differences between interfaces are large, individual data points highlight large variability in task performance, especially for the two teleporting interfaces. This variability in individual performance suggests that not everyone is similarly impacted by the removal of self-motion cues when teleporting. The current study sought to better understand this variability by examining the relationship between triangle completion performance and characteristics of the individual.

Despite the large individual differences in the triangle completion task reported by Cherep, Lim, Kelly, Acharya, et al. (2020), there is very little research characterizing individual differences in spatial updating performance. In one of the few examples (Hegarty et al., 2002), participants were led blindfolded along an outbound path before pointing to the path origin. Pointing performance was associated with a self-reported sense of direction, such that those reporting better sense of direction produced lower pointing errors.

Self-reported sense of direction is also associated with the ability to reorient to the environment using visual landmarks (Hegarty et al., 2002; Sholl et al., 2006), in a process known as piloting. In addition to their utility when reorienting after complete disorientation, piloting cues (e.g., landmarks) can be integrated with self-motion cues to produce more reliable estimates of self-location (Chen et al., 2017; Nardini et al., 2008; Sjolund et al., 2018; Zhang & Mou, 2016; Zhang et al., 2019; Zhao & Warren, 2015).

Current Study

The purpose of the current study was to investigate individual differences in spatial updating performance when locomotion is accomplished by walking or by teleporting. Furthermore, the environmental cues available in the surrounding VE were manipulated to evaluate individual differences in the integration of path-based cues (i.e., self-motion cues experienced along the path, as well as information about distance and turn angle provided by the path markers) and environmental cues. Participants performed triangle completion using three interfaces: walking, partially concordant teleporting (teleport to change position, rotate the body to change orientation), and discordant teleporting (teleport to change position and orientation). This task was presented in an enclosed classroom VE replete with landmark objects (e.g., tables and chairs) which served as piloting cues, and in an open field VE with only a ground plane and sky. The primary measure of triangle completion performance was absolute error when pointing to the path origin from the path terminus.

In addition to the triangle completion task, participants completed several measures that might be associated with task performance. Self-report measures of sense of direction were included because they have been shown to associate with spatial updating performance (Hegarty et al., 2002). The selection of additional measures was based on details of the triangle completion task and the interfaces themselves. Both forms of teleportation involve manipulation of an object in space (e.g., discordant teleporting involves positioning and orienting a marker on the ground to select the intended location and orientation). Therefore, a test of mental rotation (Vandenberg & Kuse, 1978) was included to capture this aspect of the task. The triangle completion task also involves changing perspectives when traveling along the outbound path. Therefore, a measure of perspective tasking (Kozhevnikov & Hegarty, 2001) was included. Video game experience has also been associated with improvements in spatial cognition and perception (for a review of the relationships between video game and spatial cognition see Spence & Feng, 2010), with some studies demonstrating relationships between experience in playing action videogames and improvements in mental rotation ability (Feng et al., 2007; Quaiser-Pohl et al., 2006). Therefore, video game experience, experience using VR, and demographic measures were also included.

Hypotheses were pre-registered prior to data collection on the Open Science Framework (doi:10.17605/OSF.IO/XC8V5). Predictions for triangle completion performance followed from previous work on the role of self-motion cues in spatial updating (Cherep, Lim, Kelly, Acharya, et al., 2020; Kelly et al., 2020; Klatzky et al., 1998; Ruddle & Lessels, 2006). Specifically, it was expected that discordant teleporting would exhibit the highest pointing errors, followed by partially concordant teleporting, followed by walking and that this pattern would occur in both VEs. Additionally, errors were expected to be lower in the classroom VE when using the two teleporting interfaces due to the availability of piloting cues, but not when walking (mirroring the findings of Cherep, Lim, Kelly, Acharya, et al., 2020). It was also predicted that the spatial ability measures and video game experience would be significantly related to triangle completion performance.

An exploratory latent profile analysis (LPA) was also used to examine possible classification based on triangle completion performance. Following the identification of class membership, classes were compared based on spatial ability measures, video game experience, and demographics. The LPA did not include robust predictions regarding the number or make-up of classes. However, previous work that statistically grouped individuals based on spatial tasks

(Weisberg & Newcombe, 2016; Weisberg et al., 2014) indicates that three latent classes might be expected: one that performs well on the task, one that performs poorly on the task, and one that falls in the middle.

The contribution of the current study is to provide a framework to describe a range of individuals who vary in susceptibility to disorientation while navigating VEs using teleportation. The results from this study could also provide avenues of future work examining how to mitigate disorientation on an individual basis. Furthermore, individual differences when navigating using teleportation may have general implications for cue integration during navigation.

Method

Participants

199 undergraduate students (97 men, 102 women) from Iowa State University participated in exchange for course credit. Data from 14 participants (9 men, 5 women) were removed due to missing triangle completion data for one or more cells in the experimental design, or missing spatial ability measures. In all cases, missing data was caused by equipment failure or insufficient time. Data from an additional three participants (2 men, 1 woman) were removed as outliers (see Results). Thus, the total sample size for the analyses was 182 (86 men, 96 women).

Materials

Hardware and Software

The HTC Vive head-mounted display presented the VEs, and graphics were generated 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 and reflected the head position and orientation tracked by the Lighthouse tracking system sold with the Vive. One wireless handheld controller, sold with the Vive, was used by participants to control the teleporting interfaces and to respond to each trial.

Spatial measures and Demographics

Santa Barbara Sense of Direction Scale. The Santa Barbara Sense of Direction scale (SBSOD) (Hegarty et al., 2002) assesses a self-report of spatial cognition and has been shown to have good internal reliability (Coefficient α = .88). The SBSOD is regarded as a unitary measure of "large-scale spatial ability" which measures several different environmental-scale tasks, such as learning the layout of new environments or giving verbal navigation directions (Hegarty et al., 2006), and has been used as a measure of self-reported ability of metric knowledge of distances and directions, or "survey knowledge" (Davies, et al., 2017; Ferguson et al., 2015). The SBSOD is a 15-item measure that assesses a participant's "sense of direction." Items are scored on a Likert scale of (1) = strongly agree to (7) = strongly disagree. Sample items include "I am very good at giving directions" and "I am very good at reading maps."

Philadelphia Spatial Abilities Scale. The Philadelphia Spatial Abilities Scale (PSAS) (Hegarty et al., 2010) is a self-report measure that assesses four categories of spatial tasks: static relations, relations among objects, relations within deformed objects, and relations among moving objects. The current study used a 16-item version of the scale (Hegarty et al., 2010). The PSAS has been shown to have good internal reliability (Coefficient α = .87) and have good predictive validity for scores on tests of object transformation, such as the MRT, and a high correlation with the SBSOD. Items are scored on a Likert scale of (1) = strongly agree to (7) =

strongly disagree. Sample items include “I can easily visualize my room with a different furniture arrangement” and “I could clearly imagine what a soda can would look like after it was partially crushed.”

Mental Rotation Test. The Mental Rotation Test (MRT) (Vandenberg & Kuse, 1978) assesses the ability to rotate mental representations of two-dimensional and three-dimensional objects in space and has a test-retest reliability of .83. This test includes 20 items where each item consists of a criterion figure, two correct alternatives, and two incorrect or “distractor items.” The correct alternatives are identical to the criterion except that each alternative has been rotated in space. Responses were scored by each accurate identification of both correct alternatives, with the maximum points possible out of 20. No points were rewarded for partial identification of one correct alternative. Participants were given six minutes to complete the test.

Spatial Orientation Test. The Spatial Orientation Test (SOT) (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001) assesses the ability to perform egocentric perspective transformations and has been shown to have good internal reliability (Coefficient $\alpha = .83$). This test presents the participant with an overhead view of an object array. With the array in view, the participant is asked to imagine standing at one object, facing a second object, and point to a third object from the imagined perspective. Traditionally, the pointing response is executed by drawing a radial line through a circle to indicate the egocentric direction of the third object relative to the imagined perspective. In the current study, this measure was modified for online administration. Rather than drawing the directional response, the participant viewed a circle numbered in minutes (1-60) and selected the number corresponding to the egocentric direction of the third object. Performance on a computerized version of the SOT is similar to the original paper-based version (Friedman et al., 2019). For scoring, responses were converted from minutes to degrees, then the correct answer was subtracted from the participant's response. Absolute errors were then calculated, and if the absolute error exceeded 180˚ it was subtracted from 360˚. Final errors ranged from 0˚ to 180˚, with lower errors indicating better performance. Participants were given five minutes to complete the test.

Video Games. Participants were asked to estimate how many hours they play video games per week day and per weekend day in the last calendar year. Each estimate was multiplied by five and two, respectively, and then summed to yield weekly video game hours. Participants also reported the genre of video games, including VR games. Experience with VR games was coded as 0 = no experience or 1 = experience with VR.

Demographics. Gender was recorded by the experimenter for each participant and was coded as 0 = men and 1 = women.

Stimuli

Virtual environments

The experiment included three VEs: the training VE, the open field VE, and the classroom VE. The training VE contained a grid-like ground texture and no landmarks. The open field VE consisted of an infinite ground plane with grass texture and blue sky (Figure 2, top). The classroom VE was based on a real classroom at Iowa State University (Figure 2, bottom). The walls of the 3D model were textured with photographs from the real classroom. The classroom VE was square with 9.14 m sides and included several 3D models of classroom furniture such as chairs, tables, and a classroom media console.

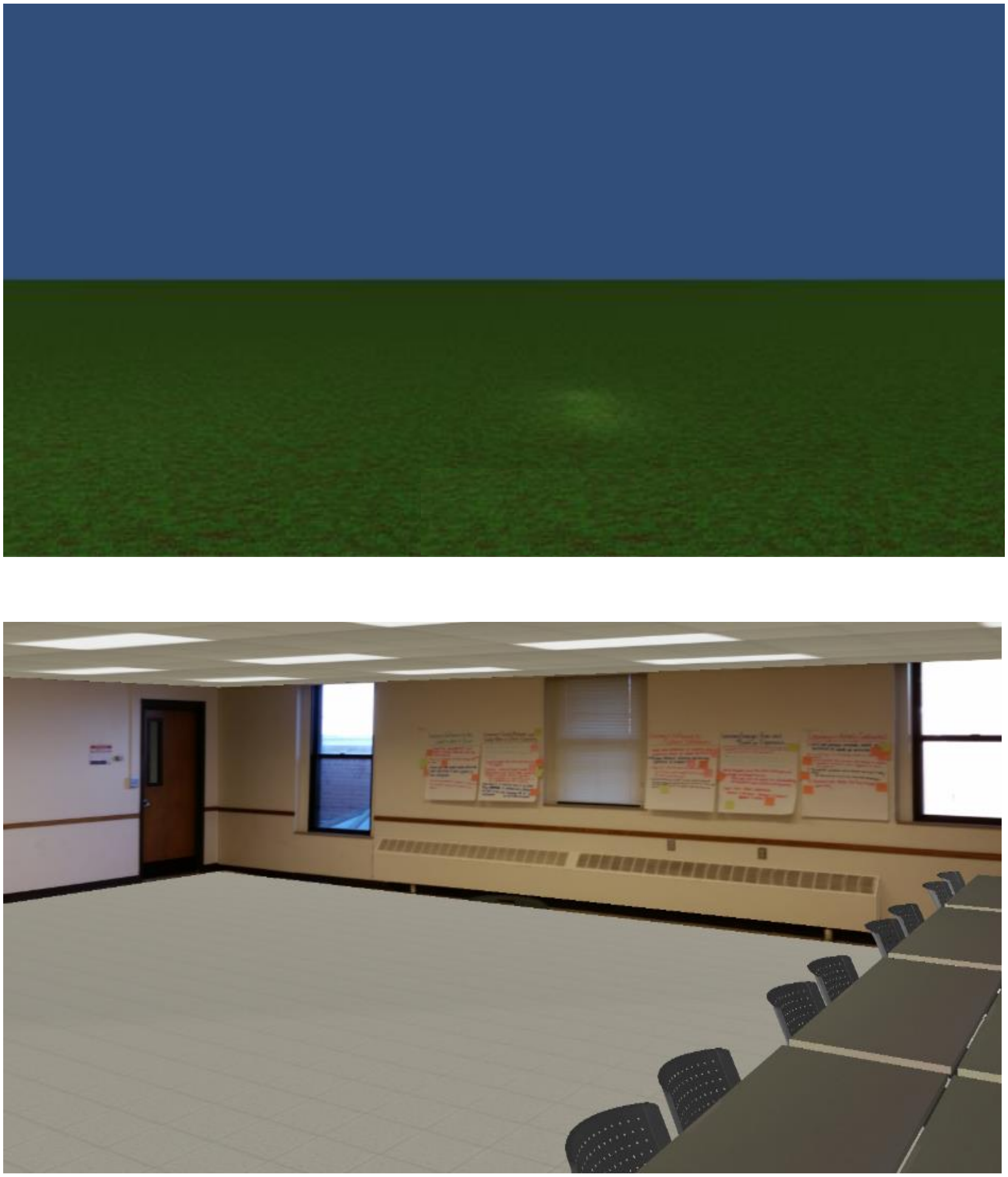

Figure 2. Image of the two experimental VEs: open field VE (top) and classroom VE (bottom).

Three color-coded posts indicated each vertex of the triangular path: a green post marked the path origin, a yellow post indicated the end of the first path leg, and a red post denoted the end of the second path leg. A white arrow located at the bottom of the first and second posts indicated the orientation of the subsequent path leg. For all locomotion interfaces, a virtual replica of the handheld controller was visible to the participant.

Interfaces

For walking, the participant physically walked and rotated to change position and orientation.

To teleport with the partially concordant interface, the participant selected a location on the ground plane by pressing down on the controller's touchpad, which produced a white circle (30 cm diameter) surrounded by a white ring (75 cm diameter) on the ground plane (see Figure 3, top). This white teleport marker was connected to the controller by a red line, and the participant controlled the position of the maker as if aiming a laser pointer. Upon the release of the touchpad, the participant was instantly teleported to the new position. The participant's previous orientation was preserved until the participant physically rotated to face the next post in the outbound path.

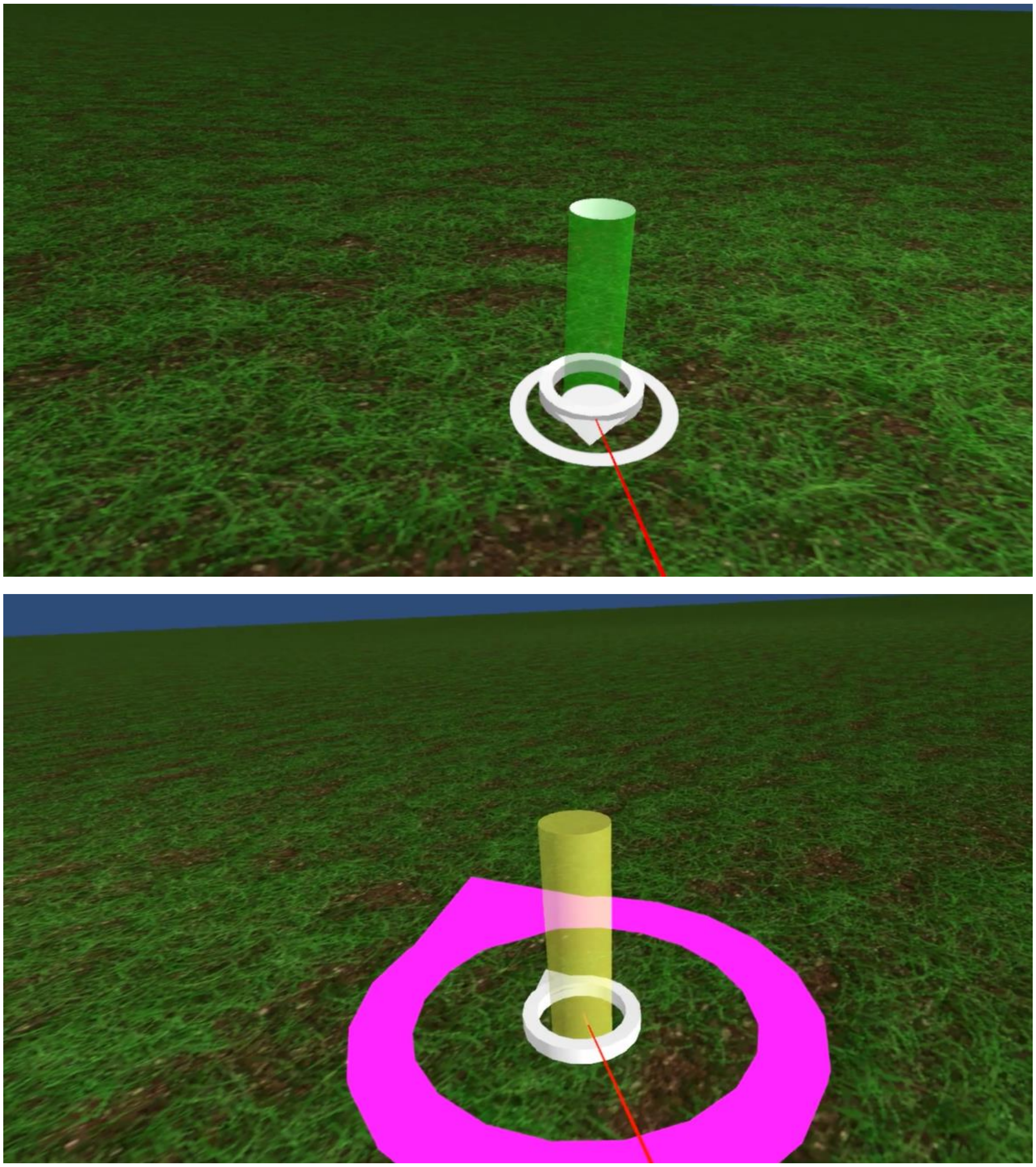

Figure 3. The two teleporting interfaces, shown in the open field VE: partially concordant teleporting (top), in which the user controlled the white ring's location, and discordant teleporting (bottom), in which the user controlled the magenta ring's location and orientation. Also visible in the images is the white arrow at the base of each post, indicating the direction of the next post.

To teleport with the discordant interface, the participant selected a location and orientation on the ground plane by positioning and orienting an arrow affixed to a magenta ring (height = 7.50 cm diameter; outer diameter = 195 cm diameter), which indicated the intended position and orientation (see Figure 3, bottom). To change position and orientation, the participant simultaneously held down the Vive controller touchpad and positioned their thumb on the edge of the touchpad to adjust the orientation of the teleportation arrow. For example, a thumb position directly to the left of the center of the touchpad corresponds to 90° counter-clockwise rotation from the participant's current facing direction while a thumb position directly beneath the center of the touchpad corresponds to a 180° rotation from the participant's current facing direction. Upon the release of the touchpad, the participant was instantly teleported to the new position and orientation.

Upon reaching the end of the path, the participant pointed to the path origin by pressing down on the Vive controller trigger to display a blue disk (39cm diameter) on the ground plane. The blue disk was connected to the controller by a red line, and the participant controlled the position of the disk as if aiming a laser pointer. The response was instantly recorded upon the release of the trigger.

Design

The triangle completion experiment employed a 2 (VE: open field vs. classroom) x 3 (Interface: walking vs. partially concordant teleporting vs. discordant teleporting) repeated-measures design. Participants also completed performance-based and self-report spatial ability measures and surveys of weekly average of video gameplay and previous VR experience. Demographic information was also recorded.

For each combination of VE and interface, participants completed a block of 12 triangle completion trials corresponding to 12 turn angles (left and right turns of 22.50, 45, 67.50, 90, 112.50, and 135°). Trial order was randomized within blocks. Path leg length was randomly selected on each trial from three possible options (first path leg: 1.52, 1.68, or 1.83 m; second path leg: 1.22, 1.37, or 1.52 m). The path origin was selected from eight possible locations evenly distributed around the VE to ensure that participants would not be required to navigate outside the tracked space when walking. Path origin positions were pseudo-randomized with the constraint that the same path origin was not repeated twice in a row (to ensure that participants did not receive feedback about their responses).

The VE variable was blocked, such that participants completed all three interfaces in one VE and then completed all three interfaces in the other VE, and VE order was counterbalanced. Interface order was counterbalanced and repeated across the two VE blocks.

The primary dependent variable in the triangle completion task was absolute pointing error, calculated as the absolute distance (in meters) between the path origin and the participant's response. Response latency, the time between arrival at the red post and response, was also recorded. Only absolute distance errors are presented, but supplemental analyses with response latency can be found on the Open Science Framework (doi:10.17605/OSF.IO/XC8V5).

Procedure

After signing the informed consent, the participant was given verbal instructions on the triangle completion task. The participant then donned the head-mounted display and was trained on the triangle completion task in the training VE with each of the locomotion interfaces. The participant was required to complete three practice trials with each locomotion interface and could request additional practice. Experimental trials began after training completion. Performance-based feedback was not provided.

On each triangle completion trial, the participant traveled the outbound path by moving to the green post (the path origin), then the yellow post, then the red post. Posts were presented sequentially and disappeared upon arrival. Once all six triangle completion blocks were complete, the participant sat in front of a lab computer and completed the spatial ability measures and demographic information. After completing the experiment, the participant was debriefed and given course credit. The study typically lasted around 90 minutes.

Results

Possible multivariate outliers were examined and analyzed for the six triangle completion conditions (open field: walking, partially concordant teleporting, and discordant teleporting; classroom: walking, partially concordant teleporting, discordant teleporting) using Mahalanobis distance. Possible outliers were compared against the allotted distance from the determined group center statistic ($\chi^2 = 22.46$ for df = 6, $p < .001$). There were two extreme cases (89.10 and 60.91), and these participants were removed from the data set (1 man and 1 woman). Finally, one participant (1 man) was removed for reporting weekly video game hours greater than three standard deviations from the group mean.

Spatial Measure Reliabilities and Correlations

Internal consistency was good for the MRT (Kuder-Richardson 20 = .81), the SBSOD (Coefficient α = .87), the SOT (Coefficient α = .87), and the PSAS (Coefficient α = .81). Bivariate correlations, means, and standard deviations are presented in Table 1. Relationships between the spatial measures were similar to those reported in previous studies (e.g., Hegarty & Waller, 2004; Hegarty et al., 2010). The negative associations with SOT are expected due to the fact that performance on that measure was coded in degrees of error. The MRT was significantly associated with the SBSOD (*r* = .32, $p < .01$), the SOT (*r* = -.65, $p < .01$), the PSAS (*r* = .26, $p < .01$), and weekly video gameplay (*r* = .26, $p < .01$). The SBSOD was significantly associated with the SOT (*r* = -.34, $p < .01$), and the PSAS (*r* = .40, $p < .01$), but was not significantly related to weekly video gameplay (in hours, *r* = .10). The SOT was significantly associated with the PSAS (*r* = -.30, $p < .01$) and hours of video gameplay per week (*r* = -.27. $p < .01$). Gender was positively associated with triangle completion errors, such that women (coded as 1 and men as 0) tended to produce higher errors during partially concordant teleporting (open field: r = .26, $p < .01$; classroom: r = .39, $p < .01$) and discordant teleporting (open field: r = .36, $p < .01$; classroom: r = .30, $p < .01$) in both VEs compared to men. Gender was also associated with the spatial ability measures as women tended to perform worse on the MRT (*r* = -.44, $p < .01$), the SBSOD (*r* = -.25, $p < .01$), the SOT (*r* = .43, $p < .01$), and the PSAS (*r* = -.19, $p < .01$). Women also reported fewer video game hours per week (*r* = -.35, $p < .01$). Triangle completion error across the six conditions was also significantly intercorrelated and had significant associations with spatial ability measures and participant characteristics. These relationships are explored more fully in the LPA.

Table 1. Means, standard deviations, and correlations between study variables

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	*M*	*SD*
1. Gender	---											---	---
2. Field – Walking	-.05	---										.71	.25
3. Field – Partially Concordant	.26**	.32**	---									1.38	.46
4. Field – Discordant	.36**	.19**	.55**	---								2.33	.78
5. Classroom – Walking	-.02	.36**	.25**	.13	---							.64	.20
6. Classroom – Partially Concordant	.39**	.16*	.38**	.39**	.23**	---						.94	.37
7. Classroom – Discordant	.30**	.22**	.37**	.38**	.20**	.74**	---					1.33	.70
8. MRT	-.44**	-.12	-.35**	-.36**	-.10	-.44**	-.44**	---				9.69	4.69
9. SBSOD	-.25**	-.07	-.09	-.17*	-.08	-.20**	-.17*	.32**	---			4.15	1.02
10. SOT	.43**	.13	.32**	.32**	.02	.56**	.46**	-.65**	-.34**	---		36.90	27.00
11. PSAS	-.19**	-.10	-.17*	-.07	.05	-.23*	-.17*	.26*	.40**	-.30**	---	4.54	.80
12. Weekly video gameplay (hours)	-.35**	.08	-.09	-.15*	.11	-.25**	-.22**	.26**	.10	-.27**	-.10	13.58	13.17

Note. Gender was coded 0 = men and 1 = women.

**p* <.05. ***p* <.01

Effects of Environment and Interface on Triangle Completion

There was no evidence of a speed-accuracy trade-off on the triangle completion task as the within-participant correlation between absolute pointing error and latency was significantly positive (M = .31, SE = .04), $t(181) = 8.34$, $p < .001$. Absolute errors (Figure 4) were analyzed in a repeated-measures ANOVA with terms for interface and environment. Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated for interface, $\chi^2(2)$ = 103.85, $p < .001$, and the interaction term, $\chi^2(2) = 63.74$, $p < .001$. Therefore, a Huynh-Feldt correction and a Greenhouse-Geisser correction was used for interface and the interaction term, respectively. Significant main effects for interface, $F(1.40, 253) = 563.80$, $p < .001$, $\eta^2_p = .63$, and environment, $F(1, 181) = 304.04$, $p < .001$, $\eta^2_p = .76$, were qualified by a significant interaction between interface and environment, $F(1.54, 278.85) = 150.22$, $p < .001$, $\eta^2_p = .45$.

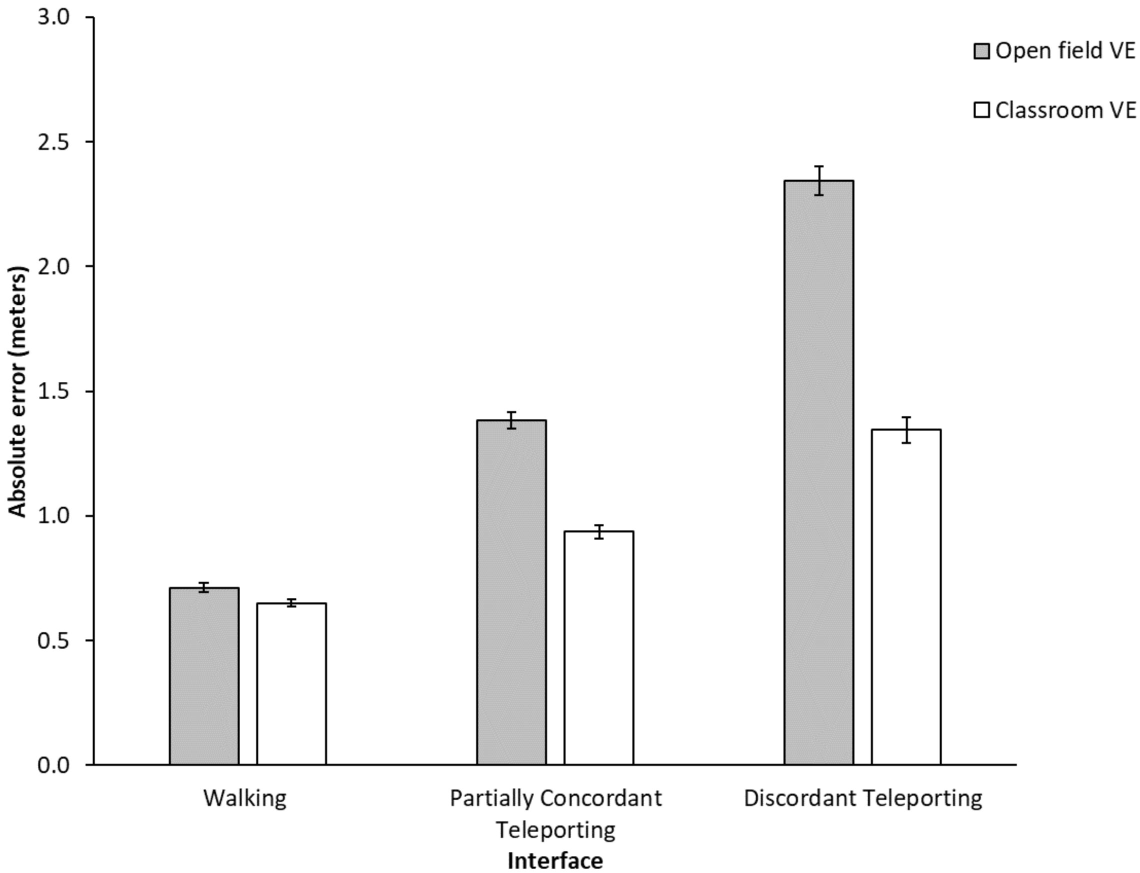

Figure 4. Average absolute error when performing the triangle completion task. Error bars represent ± 1 *SEM*.

Across both environments, the discordant teleporting interface produced larger errors than the partially concordant interface; classroom: $t(181) = 11.10$, $p < .001$, $d = .81$; open field: $t(181) = 19.55$, $p < .001$, $d = 1.45$ (Figure 4). The partially concordant interface produced larger errors than the walking interface; classroom: $t(181) = 9.98$, $p < .001$, $d = .76$; open field: $t(181) = 20.22$, $p < .001$, $d = 1.50$. Additionally, the classroom VE produced lower errors compared to the open field when using the discordant teleporting interface, $t(181) = 16.10$, $p < .001$, $d = 1.20$, the partially concordant teleporting interface, $t(181) = 12.86$, $p < .001$, $d = .94$, and the walking interface, $t(181) = 3.12$, $p = .002$, $d = .23$.

Latent Profile Analysis

The purpose of an LPA is to find hidden typologies within the population. Ideally, these classes are discrete, exhaustive, and non-overlapping. Fit indices produced alongside classes can assist researchers in deciding upon the final class solution. The most common fit indices are the log-likelihood (LL), Akaike information criteria (AIC), the Bayesian information criteria (BIC), the sample-size adjusted BIC, the Lo-Mendell-Rubin adjusted likelihood ratio (LMRT), the bootstrap likelihood ratio (BLRT), and associated *p*-values. When examining fit statistics, there is a trend that lower values yield a better model fit, although only certain fit indices, such as LMRT and BLRT, provide a *p*-value to test for significantly better model fit. The way to interpret the model fit is to compare *K*-1, where *K* is the number of classes. Although fit indices are the first step in finding true latent profiles, they do not always indicate the same ideal profile count, and some class solutions are more useful for understanding human behavior than others. As fit indices within the data suggested different profile counts, interpretability and utility were considered when deciding on the final profile count (see Table 2).

Table 2. Fit statistics for the latent profile analysis of triangle completion performance

Model	Fit Statistics										
Number of Groups	LL	AIC	BIC	SSA BIC	Entropy	LMRT (*p*)	BLRT (*p*)	1	2	3	4	5
1	-586.080	1196.160	1234.608	1196.603	1.000	---	---	182 (100%)				
2	-479.681	997.361	1058.237	998.062	0.793	207.113 0.0004	212.799 < 0.001	95 (52%)	87 (48%)			
3	-420.385	892.769	976.073	893.728	0.835	115.424 0.0900	118.592 < 0.001	76 (42%)	72 (40%)	34 (18%)		
4	-386.107	838.215	943.947	839.432	0.885	66.723 0.5908	68.555 < 0.001	82 (45%)	66 (35%)	26 (15%)	8 (5%)	

Note. LL = log-likelihood; AIC = Akaike Information Criteria; BIC = Bayesian Information Criteria; SSA-BIC = Sample Size Adjusted BIC; LMRT = Lo-Mendell-Rubin Adjusted Likelihood Ratio Test; BLRT = Bootstrap Likelihood Ratio Test; *p* = *p* value.

Triangle completion data were used to identify any latent classes using Mplus version 7 (Muthén & Muthén, 1998-2012). Although, the four-class model produced better fit, one class was too small to be useful (*n* = 8) and ease of interpretability and parsimony suggested a three-class solution which was consistent with similar cluster analyses used to group performance on a navigation task (Weisberg & Newcombe, 2016; Weisberg et al., 2014). All three classes contained a reasonable proportion of the sample and varied in a distinct, identifiable pattern across the different variables manipulated in our study. One class, termed “Accurate Integrators,” had excellent triangle completion performance across all conditions and performed better in the classroom VE than the open field VE (42%, *n* = 76), which suggests that they integrated path-based cues with landmarks when available. Another class, termed “Inaccurate Integrators,” also performed better in the classroom VE than the open field VE but had lower overall accuracy (40%, *n* = 72). The final class, termed “Inaccurate Non-Integrators,” had low accuracy and improved the least when landmarks were available (18%, *n* = 34). Triangle completion error is shown separately for each class in Figure 5 (for a bar graph version with error bars, see Supplemental Figure S1). Based on previous research, parsimony, model fit, and class size, a three-class model appeared to represent the best solution. For three-class models, entropy values around .76 and above are related to an accuracy of 90% in correctly assigning class membership to participants (Wang et al 2017). In the current study, the three-class model had an entropy value of .84 which suggests that individuals were classified with a high degree of accuracy.

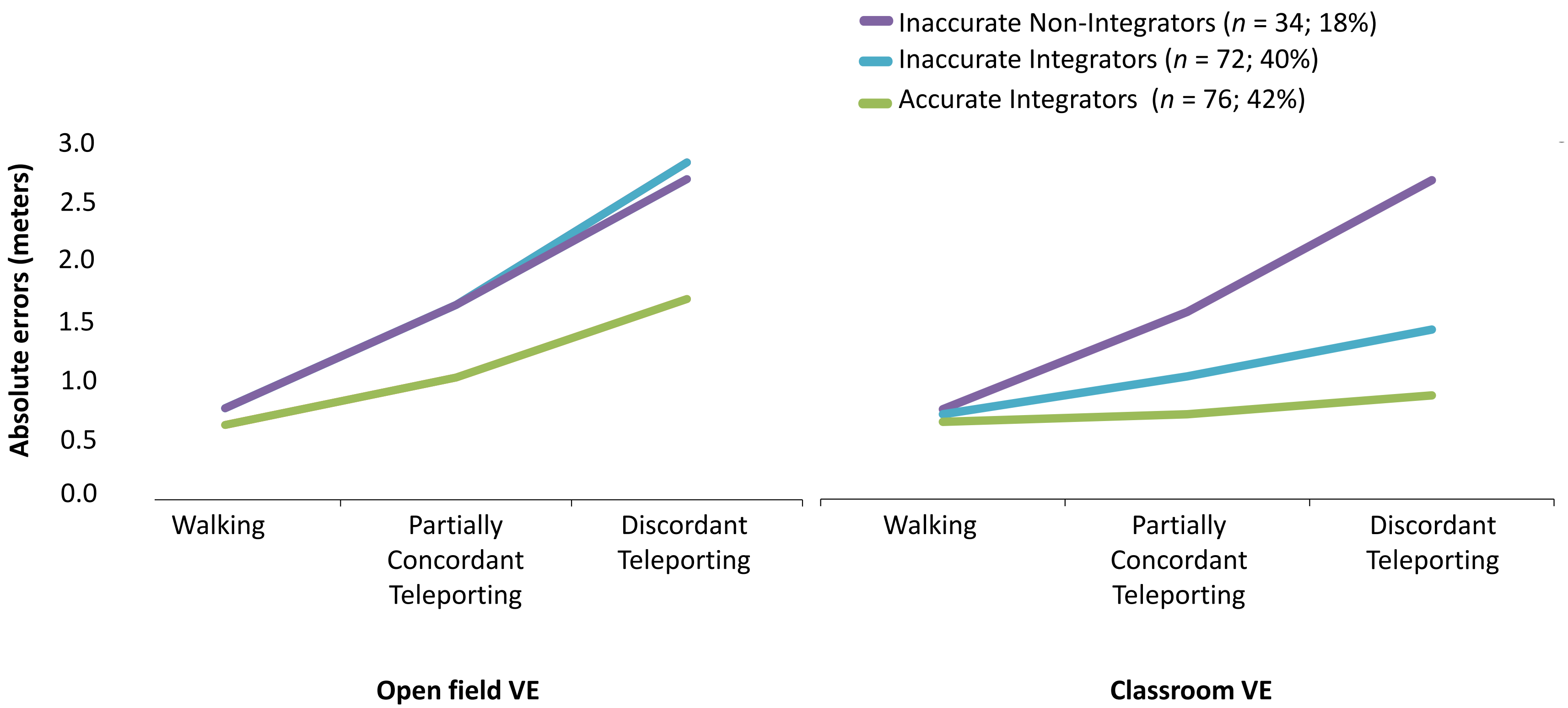

Figure 5. Three-class model of triangle completion performance.

Triangle Completion Performance Differences

Following the LPA, the three classes were examined using one-way ANOVAs to identify any significant differences in triangle completion errors across the six VR conditions. Levene's test showed that the variances for all of the classroom conditions and the partially concordant and discordant open field conditions were not equal (*p's* < .01). Therefore, the Brown-Forsythe statistic was reported for all of the classroom conditions and the partially concordant field conditions since the data were positively skewed. The Welch statistic was used for the discordant field conditions since the data were not skewed. The Games-Howell post-hoc correction was applied to all conditions to account for unequal variances and sample size, except for the walking interface in the open field VE which used Hochberg's GT2.

In the open field VE, Accurate Integrators performed better than Inaccurate Integrators and Inaccurate Non-Integrators on all three interfaces, and Inaccurate Integrators and Inaccurate Non-Integrators did not significantly differ on any interface. When using the walking interface, Accurate Integrators (M = .63, SD = .22) had significantly lower errors compared to Inaccurate Integrators (M = .77, SD = .23) and Inaccurate Non-Integrators (M = .77, SD = .31), $F(2, 179)$ = 7.34, p = .001, η^2_p = .08. When using the partially concordant teleporting interface, Accurate Integrators (M = 1.03, SD = .27) had lower errors compared to Inaccurate Integrators (M = 1.64, SD = .45) and Inaccurate Non-Integrators (M = 1.64, SD = .24), $F(2, 149.41)$ = 77.12, p < .001, η^2_p = .51. When using the discordant teleporting interface, Accurate Integrators (M = 1.69, SD = .53) had significantly lower errors compared to Inaccurate Integrators (M = 2.84, SD = .67) and Inaccurate Non-Integrators (M = 2.70, SD = .37), $F(2, 179)$ = 7.34, p < .001, η^2_p = .08.

Analysis of the errors in the classroom VE showed that the three classes were indistinguishable when walking, but that partially concordant and discordant teleporting led to lower errors for Accurate Integrators compared to Inaccurate Integrators, and lower errors for Inaccurate Integrators compared to Inaccurate Non-Integrators. Accurate Integrators (*M* = .67, *SD* = .17) had significantly better performance using partially concordant teleporting compared to Inaccurate Integrators (*M* = .97, *SD* = .22) and Inaccurate Non-Integrators (*M* = 1.48, *SD* = .34), and Inaccurate Integrators had significantly better performance compared to Inaccurate Non-Integrators, $F(2, 68.95) = 109.15$, $p < .001$, $\eta^2_p = .76$. For discordant teleporting in the classroom VE, Accurate Integrators (*M* = .82, *SD* = .24) had significantly better performance compared to Inaccurate Integrators (*M* = 1.34, *SD* = .38) and Inaccurate Non-Integrators (*M* = 2.52, *SD* = .46), and Inaccurate Integrators had significantly better performance compared to Inaccurate Non-Integrators, $F(2, 84.24) = 232.22$, $p < .001$, $\eta^2_p = .85$. There were no significant class differences across Accurate Integrators (*M* = .61, *SD* = .18), Inaccurate Integrators (*M* = .67, *SD* = .18), or Inaccurate Non-Integrators (*M* = .71, *SD* = .31) for walking in the classroom VE, $F(2, 70.35) = 2.63$, $p = .079$, $\eta^2_p = .07$.

Collapsing across interface, there were significant differences for the three classes across VEs. Accurate Integrators showed significant improvement in triangle completion errors in the classroom (*M* = .74, *SD* = .17) compared to the open field (*M* = 1.36, *SD* = .33), $t(75) = 15.10$, $p < .001$, $d = 1.74$. Inaccurate Integrators also showed significant improvement in the classroom (*M* = 1.16, *SD* = .25) compared to the open field (*M* = 2.25, *SD* = .43), $t(71) = 16.46$, $p < .001$, $d = 2.60$, as did the Inaccurate Non-Integrators; classroom (*M* = 2.00, *SD* = .28), open field (*M* = 2.18, *SD* = .22) $t(33) = 3.22$, $p = .003$, $d = 0.54$. Notably, although the Inaccurate Non-Integrators showed improvement in the classroom VE this difference was much smaller ($d = .54$) compared to the other two classes; Accurate Integrators ($d = 1.74$) and Inaccurate Integrators ($d = 2.60$).

To summarize, Accurate Integrators had significantly lower absolute distance errors compared to the Inaccurate and Inaccurate Non-Integrators across all conditions except the classroom walking condition. Inaccurate Integrators and Inaccurate Non-Integrators performed similarly in the open field VE, but Inaccurate Integrators performed better than Inaccurate Non-Integrators in the classroom VE when using the partially concordant and discordant teleporting interfaces.

Demographic Differences

The three classes were also examined to determine whether there were significant differences in gender, weekly video game hours, and VR experience. For gender, significant differences emerged, $\chi^2(2) = 27.63$, $p < .001$, such that there were more women (65.3%, $n = 47$) than men (34.7%, $n = 25$) in the Inaccurate Integrators class and more women (76.5%, $n = 26$) than (23.5%, $n = 8$) men in the Inaccurate Non-Integrators class. For the Accurate Integrator class, there were more men (69.7%, $n = 56$) than women (30.3%, $n = 23$). Classes also significantly differed on weekly video game hours (Supplemental Figure S2), $F(2, 146.04) = 5.58$, $p = .005$, $\eta^2_p = .07$. Accurate Integrators reported significantly more video game hours ($M = 17.24$, $SD = 13.77$) than Inaccurate Integrators ($M = 11.31$, $SD = 12.26$, $p = .17$) and Inaccurate Non-Integrators ($M = 10.21$, $SD = 11.99$, $p = .026$). Inaccurate Integrators and Inaccurate Non-Integrators did not significantly differ on video game hours ($p = .97$). Classes also significantly differed in VR experience, $\chi^2(2) = 8.39$, $p = .02$, as eleven participants in the Accurate Integrators class (73.33%) reported having used VR previously, compared to one participant in the Inaccurate Integrators class (6.67%) and three participants in the Inaccurate Non-Integrators class (20%).

Spatial Measure Differences

One-way ANOVAs were conducted to examine whether performance-based measures of spatial ability (MRT and SOT) and self-report measures of spatial ability (SBSOD and PSAS) significantly differed among the three classes. Levene's test showed that the variances for the SBSOD, $F(2, 179) = 3.10$, $p = .048$, and the SOT, $F(2, 179) = 26.13$, $p < .001$ were not equal. Therefore, the Brown-Forsythe statistic was reported for the SOT since the data were positively skewed. Since the data were not skewed for the SBSOD, the Welch statistic was used. The Games-Howell post-hoc correction was applied to the SBSOD and the SOT to account for unequal variances and sample size, and Hochberg's GT2 post-hoc correction was used for the MRT and the PSAS.

For the performance-based spatial ability measures (see Supplemental Figures S3 and S4), Accurate Integrators ($M = 22.45$, $SD = 13.38$) performed significantly better (i.e., lower error) on the SOT compared to Inaccurate Integrators ($M = 41.57$, $SD = 28.15$) and Inaccurate Non-Integrators ($M = 59.31$, $SD = 29.00$). Inaccurate Integrators performed significantly better than Inaccurate Non-Integrators, $F(2, 91.51) = 27.23$, $p < .001$, $\eta^2_p = .37$. Accurate Integrators ($M = 12.11$, $SD = 4.18$) performed significantly better on the MRT compared to Inaccurate Integrators ($M = 8.64$, $SD = 4.13$) and Inaccurate Non-Integrators ($M = 6.53$, $SD = 4.29$), $F(2, 179) = 24.71$, $p < .001$, $\eta^2_p = .22$. There was a marginally significant difference between Inaccurate Integrators and Inaccurate Non-Integrators ($p = .048$).

For the subjective (i.e., self-report) spatial ability measures (see Supplemental Figures S5 and S6), Accurate Integrators ($M = 4.40$, $SD = 1.11$) reported significantly better perceived sense of direction on the SBSOD compared to Inaccurate Non-Integrators ($M = 3.72$, $SD = 1.08$), $F(2, 84.68) = 4.84$, $p = .010$, $\eta^2_p = .10$. Inaccurate Integrators ($M = 4.08$, $SD = .80$) did not significantly differ on the SBSOD from Accurate Integrators or Inaccurate Non-Integrators.

Accurate Integrators (*M* = 4.69, *SD* = .84) also reported greater perceived small-scale spatial ability on the PSAS compared to Inaccurate Non-Integrators (*M* = 4.54, *SD* = .80), *F*(2, 179) = 3.52, *p* = .032, η^2_p = .04. Inaccurate Integrators (*M* = 4.51, *SD* = .80) were not significantly different from Accurate Integrators or Inaccurate Non-Integrators.

Gender Differences

The three classes differed significantly in gender proportion. Specifically, there were more men than women in the Accurate Integrators class, but more women than men in the Inaccurate Integrators and Inaccurate Non-Integrators class. Furthermore, gender has long been a variable of interest in spatial cognitive research. Therefore, independent sample t-tests were conducted to investigate differences between men and women for triangle completion errors across the six conditions (see Supplemental Figure S7). Men, compared to women, had significantly lower absolute distance error while using partially concordant teleportation in the open field VE, *t*(180) = 3.53, *p* = .001, *d* = .52, men: *M* = 1.26, *SD* = .50, women: *M* = 1.49, *SD* = .39, and in the classroom VE, *t*(168.40) = 5.82, *p* < .001, *d* = .84, men: *M* = .78, *SD* = .27, women: *M* = 1.07, *SD* = .40. Men also had significantly lower errors while using discordant teleporting in the open field VE, *t*(155.20) = 5.09, *p* < .001, *d* = .77, men: *M* = 2.04, *SD* = .85, women: *M* = 2.61, *SD* = .63, and in the classroom VE, *t*(179.64) = 4.32, *p* = .001, *d* = .64, men: *M* = 1.12, *SD* = .62, women: *M* = 1.55, *SD* = .72. There were no significant differences between men and women for walking in the open field VE, *t*(180) = .65, *p* = .52, *d* = .08, men: *M* = .72, *SD* = .27, women: *M* = .70, *SD* = .23, or for the classroom VE, *t*(180) = .26, *p* = .79, *d* = .05, men: *M* = .66, *SD* = .22, women: *M* = .65, *SD* = .21. In summary, men tended to have lower absolute distance errors across both teleportation interfaces in each VE, but men and women performed similarly when walking.

Independent sample t-tests also showed that men compared to women had significantly better performance on the MRT (Supplemental Figure S8), *t*(180) = 6.63, *p* < .001, *d* = .98, men: *M* = 11.88, *SD* = .4.12, women: *M* = 7.73, *SD* = 4.31, and the SOT (Supplemental Figure S9), *t*(158.02) = 6.50, *p* < .001, *d* = .94, men: *M* = 24.75, *SD* = 17.57, women: *M* = 47.78, *SD* = 29.32, reported a greater sense of direction on the SBSOD (Supplemental Figure S10), *t*(180) = 3.39, *p* = .001, *d* = .51, men: *M* = 4.41, *SD* = .89, women: *M* = 3.91, *SD* = 1.01, reported greater small-scale spatial ability on the PSAS (Supplemental Figure S11), *t*(180) = 2.63, *p* = .39, men: *M* = 4.70, *SD* = .84, women: *M* = 4.39, *SD* = .74, and reported a greater number of video game hours per week (Supplemental Figure S12), *t*(180) = 4.99, *p* < .001, *d* = .74, men: *M* = 18.42, *SD* = 13.12, women: *M* = 9.24, *SD* = 11.68. In summary, men tended to perform better on performance-based measures of spatial ability and reported a greater sense of direction and small-scale spatial ability, as well as more video game hours.

Discussion

The present study investigated individual differences in a triangle completion task in VR using three locomotion interfaces and two VEs. The locomotion interfaces differed in available self-motion cues, and the VEs differed in available piloting cues. As predicted, absolute distance errors when pointing to the path origin were greatest for discordant teleporting, followed by partially concordant teleporting, followed by walking. Additionally, errors were consistently lower in the classroom VE compared to the open field VE. Contrary to predictions, errors were also significantly lower for walking in the classroom VE compared to walking in the open field

VE. This is likely due to the larger sample size in this study (*N* = 182) compared to the sample size in Cherep, Lim, Kelly, Acharya, et al. (2020) (*N* = 24).[1]

Correlations among the spatial ability measures were consistent with previous literature, as the MRT, the SBSOD, the SOT, and the PSAS were all significantly associated in the expected directions. Weekly video game hours were significantly associated with the MRT and SOT, but not the SBSOD or the PSAS. This relationship follows from other work that has shown that computer experience (which includes video gameplay) has a positive relationship with MRT (Terlecki & Newcombe, 2005) and SOT performance (Ventura et al., 2013).

On average, men and women performed similarly when walking, but men outperformed women with the two teleporting interfaces. This suggests that women may be more reliant on self-motion cues compared to men, who were better able to compensate for limited access to self-motion cues. These finding parallels other work on spatial updating showing that men and women perform similarly with ample piloting cues but that men outperform women when piloting cues are reduced or degraded (Kelly et al., 2009). Additionally, women performed worse than men on the MRT and the SOT, reported lower spatial ability on the SBSOD and the PSAS, and reported fewer video game hours per week. It is, therefore, possible that the male advantage when teleporting occurred because men, when faced with the challenge of reduced-cue locomotion, were better able to draw on the spatial cognitive resources that underlie processes such as mental rotation and perspective-taking to compensate for the lack of sensory cues.

An exploratory LPA using triangle completion errors from six conditions identified three classes: Accurate Integrators, Inaccurate Integrators, and Inaccurate Non-Integrators. Accurate

[1] The magnitude of this difference (Cohen's d) was similar in both studies (*d* = .23 for the current study and *d* = .20 for Cherep et al., 2020).

Integrators were characterized by overall accurate triangle completion performance and superior performance in the classroom VE compared to the open field VE, reflecting the fact that they integrated path-based cues and piloting cues when available. They also exhibited good performance on the MRT and SOT, and self-reported high spatial ability on the SBSOD and PSAS. Furthermore, Accurate Integrators played more hours of video games and were predominantly male.

Triangle completion performance by Inaccurate Integrators and Inaccurate Non-Integrators was indistinguishable in the open field VE, but their performance diverged in the classroom VE, where Inaccurate Integrators outperformed Inaccurate Non-Integrators when using the two teleporting interfaces. This divergence indicates that Inaccurate Integrators were better able to integrate path-based cues with piloting cues in the classroom VE compared to Inaccurate Non-Integrators. It is worth noting that Inaccurate Non-Integrators did benefit from the piloting cues available in the classroom VE, suggesting that they did integrate path-based cues with piloting cues, but they did so only modestly compared to the other two classes. Beyond these differences in triangle completion performance, Inaccurate Integrators and Inaccurate Non-Integrators differed on the SOT and differed marginally on the MRT, with Inaccurate Integrators outperforming Inaccurate Non-Integrators on both tasks. Both groups were predominantly female.

The three-class description of triangle completion performance echoes previous work on individual differences in a route integration task (Weisberg & Newcombe, 2016; Weisberg et al., 2014). For example, participants in one study (Weisberg at al., 2014) learned landmark locations along two routes through a VE and later pointed between pairs of landmarks located on the same route (within-route judgments) or on different routes (between-route judgments). A cluster analysis based on pointing accuracy identified three clusters of participants: a good between/good within cluster, a bad between/bad within cluster, and a bad between/good within cluster. These clusters suggest that individuals vary in their ability to integrate routes to represent a cognitive map, with some individuals demonstrating functional integration and others having difficulty integrating routes. The three clusters were also compared on a battery of performance-based and self-report spatial measures. Significant differences were found between all three groups on a self-report of sense-of-direction and significant differences were found between the best and worst-performing groups on mental rotation. Better performance on mental rotation and higher perceived sense-of-direction was associated with better route integration (Weisberg et al., 2014). Their results provide support for the three-category description based on triangle completion performance in the present study.

These results from the LPA and subsequent analyses are consistent with the notion that better performance on spatial measures would be related to triangle completion performance; however, self-report measures of spatial ability were less diagnostic of spatial updating performance when teleporting except in extreme comparisons (e.g., Accurate Integrators and Inaccurate Non-Integrators). In other words, self-report measures of spatial ability, such as the SBSOD and the PSAS appear to do well at parsing participants who perform well on all the interfaces from participants who perform poorly but do not distinguish the mid-performing class (Inaccurate Integrators).

Compared to the performance-based spatial ability measures (i.e., MRT and SOT), self-report measures of spatial ability (i.e., SBSOD and PSAS) produced weaker correlations with triangle completion performance and only distinguished the highest-performing class (Accurate Integrators) from the lowest-performing class (i.e., Inaccurate Non-Integrators). Only the SOT clearly distinguished between all three classes[2]. Why would the SOT uniquely differentiate performance between the three classes? The SOT involves perspective-taking, which is assumed to involve a process whereby participants reorient themselves to the environment from novel perspectives. Likewise, triangle-completion requires updating of self-orientation along the outbound path.

The three classes identified in the LPA are interpreted as representing differences in overall accuracy as well as differences in the integration of path-based cues and piloting cues. Differences in accuracy are evident directly in the error data, but differences in cue integration are inferred and more work is needed to determine whether those differences are due to suboptimal integration or lower accuracy when using piloting cues. Research on cue integration typically evaluates navigation performance with multiple cues and also with individual cues in isolation. Evidence for integration is found when performance with multiple cues exceeds that of single-cue conditions, and evidence for optimal integration is determined by whether response variability with multiple cues is reduced to optimal levels determined by a mathematical model based on single-cue response variability (Chen et al., 2017; Nardini et al., 2008; Sjolund et al., 2018; Zhang et al., 2019). To evaluate integration in this way, the current study would need to be modified by including a condition in which only piloting cues are available when returning to a learned location.

In one of the very few studies to describe individual differences in spatial updating, Hegarty et al. (2002) reported that SBSOD was significantly correlated with performance on a task in which blindfolded participants pointed to home after walking outbound paths ranging

[2] The MRT also distinguished between all three groups, but due to the exploratory nature of the LPA we are cautious when interpreting the marginally significant performance difference between Inaccurate Integrators and Inaccurate Non-Integrators.

from 2-5 path segments. In the walking conditions reported here, SBSOD did not correlate with pointing performance, nor did any other measure collected outside of the VE. Individual differences in the current study only emerged when self-motion cues were removed (i.e., in the teleporting conditions). It is, therefore, possible that the individual differences in spatial updating only occur under conditions of reduced self-motion cues, such as teleporting or wearing a blindfold.

There is a clear need to reduce disorientation in VEs, especially among those in the Inaccurate Non-Integrators class. The current project likely underestimates the extent of disorientation in a typical VR experience, which involves much more complex exploration paths than the two-legged paths used here. Additionally, self-report data shows that 20% of users who have previously used VR belong to the Inaccurate Non-Integrators class, which suggests that lower spatial ability and a greater propensity for disorientation does not dissuade these users from at least trying VR. Future research should consider whether feedback-based training with teleporting interfaces could reduce disorientation, particularly among those most susceptible. Likewise, investigation of the characteristics of piloting cues (e.g., cue quantity or cue salience) could reveal methods for creating VEs that allow all individuals to integrate path-based and piloting cues. Furthermore, the teleporting interfaces themselves could be modified to reduce their disorienting effects. For example, the presence of another person in a scene can cause spontaneous perspective-taking (Tversky & Hard, 2009), and the inclusion of an avatar at the selected location when teleporting might aid the to-be-taken perspective. Other modifications could include previews of the to-be-taken perspective or overhead (i.e., bird’s eye view) maps showing current and selected locations. Also, adding visual cues corresponding to distance travelled during teleportation could enhance path-based cues, though those visual cues would likely need to be crafted to not induce cybersickness via techniques such as tunneling (foveal optic flow with blurred periphery) (Lin et al., 2020; Norouzi et al., 2018).

This study was not designed to identify whether individual characteristics, such as video game hours or spatial ability, are causally related to triangle completion performance. However, identification of such causal connections could provide training opportunities to reduce disorientation in VR. Spatial abilities are known to be malleable (Uttal et al., 2013), and if spatial abilities such as mental rotation or perspective taking were causally related to navigation in VR, then training those skills could make VR applications more effective and more enjoyable.

The SOT was an objective measure of perspective-taking that distinguished spatial updating performance between all three classes. This result suggests that the SOT could be administered (perhaps in a shortened form) as a predictive measure and used to personalize and adapt the interface and VE to better suit the user. For example, if an individual performs well on the SOT, then the VR application could suggest a variety of partially concordant and discordant teleporting interfaces alongside VEs that vary in visual piloting cues. However, if an individual scores poorly on the SOT, this suggests that the user would benefit from using a partially concordant interface or walking (when feasible) and VEs that include numerous visual piloting cues.

Disorientation will impede the effectiveness of VR for training and education, as well as the popularity of VR for entertainment. The results reported here are consistent with previous research showing that teleporting disrupts spatial updating, leading to disorientation. Additionally, this work demonstrates that individuals vary in the extent to which disorientation will occur. These individual differences reflect differences in overall navigational accuracy as well as differences in cue integration. Furthermore, individual susceptibility to disorientation is related to performance on measures of spatial ability.

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