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RESEARCH ARTICLE

A comparison of virtual locomotion methods in movement experts and non-experts: testing the contributions of body-based and visual translation for spatial updating

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Abstract
Both visual and body-based (vestibular and proprioceptive) information contribute to spatial updating, or the way a navigator keeps track of self-position during movement. Research has tested the relative contributions of these sources of information and found mixed results, with some studies demonstrating the importance of body-based information, especially for translation, and some demonstrating the sufficiency of visual information. Here, we invoke an individual differences approach to test whether some individuals may be more dependent on certain types of information compared to others. Movement experts tend to be dependent on motor processes in small-scale spatial tasks, which can help or hurt performance, but it is unknown if this effect extends into large-scale spatial tasks like spatial updating. In the current study, expert dancers and non-dancers completed a virtual reality point-to-origin task with three locomotion methods that varied the availability of body-based and visual information for translation: walking, joystick, and teleporting. We predicted decrements in performance in both groups as self-motion information was reduced, and that dancers would show a larger cost. Surprisingly, both dancers and non-dancers performed with equal accuracy in walking and joystick and were impaired in teleporting, with no large differences between groups. We found slower response times for both groups with reductions in self-motion information, and minimal evidence for a larger cost for dancers. While we did not see strong dance effects, more participation in spatial activities related to decreased angular error. Together, the results suggest a flexibility in reliance on visual or body-based information for translation in spatial updating that generalizes across dancers and non-dancers, but significant decrements associated with removing both of these sources of information.

Keywords Spatial updating · Virtual locomotion methods · Dance expertise

Introduction

As we walk through an environment, we benefit from multiple sources of self-motion information for keeping track of our location, both from the sensory-motor sources associated with acting (we refer to this as body-based) and the visual-based information from dynamic visual flow of elements in the environment. However, there are many situations in which some sources of information may not be available or in which individuals cannot accurately integrate these cues. For example, being pushed in a wheelchair reduces efferent motor commands and proprioceptive feedback, and walking with complete blindness is inherently performed without visual flow. Virtual environments (VEs) provide a unique circumstance, where cues for self-motion can vary in different ways. For example, navigation using a controller in desktop VEs typically results in only visual flow, in the absence of

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motor, proprioceptive, and vestibular information. However, immersive VEs can provide some or all of body-based cues for self-motion to more closely resemble real world walking. Research using VE paradigms to test the contributions of visual and body-based information for spatial updating of self-location provides mixed conclusions about which sources are necessary or sufficient (Chrastil et al. 2019; Ruddle and Lessels 2006, 2007, 2009; Ruddle et al. 2011; Presson and Montello 1994; Rieser 1989; Chance et al. 1998; Riecke et al. 2002). Our current approach tests whether a focus on individual differences in reliance on motor control and associated sensory feedback can account for and potentially explain these mixed results.

Movement experts (highly trained athletes) are one group of individuals who tend to be more "motor dependent" when completing spatial tasks, at least small-scale spatial tasks that require manipulating objects (Moreau 2012, 2013; Jola and Mast 2005), such as the mental rotation task (MRT; Peters et al. 1995). Movement experts in a variety of domains tend to have at least 10 years or 10,000 h of deliberate practice in their activity (Ericsson et al. 1993; Hodges 1995; Starkes et al. 1996; Helsen et al. 1998; Baker et al. 2003), which results in highly skilled performance in the activity itself, but also some transfer to other cognitive skills. For instance, movement experts show advantages over non-experts on many spatial tasks, the majority of which have tested small-scale spatial abilities such as mental rotation (Voyer and Jansen 2017). Some research suggests that the spatial advantage for movement experts may be a result of a greater reliance on motor processes compared to non-experts. Moreau (2012, 2013) studied expert wrestlers' mental rotation performance as compared to non-expert controls in several interference conditions (no interference, visual interference, and motor interference). Wrestlers outperformed controls in the no interference and visual interference conditions, but were impaired in the motor interference condition, when actual movement conflicted with the direction of mental rotation (now performing at the same level as controls), suggesting that they are more dependent on their motor system. However, a greater dependence on motor processes in movement experts does not always result in improved performance on spatial tasks. Jola and Mast (2005) studied dancers' mental rotation performance and observed slower response times for dancers compared to non-dancers. They argued that dancers may have been trying to "embody" the figures to perform the mental rotation, which slowed the mental transformation process. Thus far this phenomenon of motor dependence for movement experts has only been observed in small-scale spatial tasks, such as tasks that require understanding within-object properties (Uttal et al. 2013). It is unknown if the different effects of motor dependence for movement experts and non-experts persist in larger-scale spatial tasks, or those that require understanding spatial relationships between self and objects (Uttal et al. 2013).

Only a few prior studies have examined individual differences in large-scale path integration abilities (a type of spatial updating that involves traversing segments of a path) related to movement experience. In general, athletes (rugby, handball, and volleyball players) seem to be more accurate at spatial updating when translation is performed at speeds that are relevant to their training (e.g., fast speeds rather than normal or slow speeds; Bredin et al. 2005). The movement experience advantage may depend on the type of athletic training and may be specific to certain response measures of spatial updating tasks (i.e., angular estimates versus distance estimates). For example, Smith et al. (2010) found that rugby players had significantly less heading error, but not distance error, on a triangle completion task compared to martial artists, demonstrating that the "scale" of the space involved in the sport affects spatial updating ability. Other research also suggests that extensive movement training, such as in gymnastics, may improve understanding of heading (rotational information) rather than distances (translational information) in spatial updating (Garcia Popov et al. 2013). These studies in real-world environments suggest that athletic experience may influence estimates of heading more than estimates of distance. In a visual-only virtual environment, Kitson et al. (2015) showed that dancers with more dance and visual movement analysis experience (Laban) are more likely to correctly process visual turn information in spatial updating tasks. Taken together, athletes may possess enhanced spatial updating abilities in both real and virtual environments (at least in terms of processing and estimating heading) that develop as a function of their training and experience with complex rotational body movements. However, to our knowledge there has not been a systematic study of movement experts that has manipulated the body-based information received during the outbound paths. This is a critical step to determining the types of information used by movement experts to spatially update.

Dancers as a group of movement experts have received relatively little attention in the spatial cognition literature. However, some compelling research argues that dance is a unique movement activity that draws on many types of spatial and cognitive skills, with dancers demonstrating superior motor control, control of complex movements, timing and synchrony, learning and memory, visuomotor imagery, action observation, and aesthetics/expression (Bläsing et al. 2012). Dancers have consistently exhibited high levels of motor imagery (Overby 1990), as imagery is part of dance training and practice (Nordin and Cumming 2005, 2006a, b; Hanrahan and Vergeer 2001) and improves with experience (Nordin and Cumming 2006a, b) and skill (Fish et al. 2004). Additionally, dancers possess superior equilibrium (balance ability) (Golomer et al. 1997, 1999), postural control (Rein et al. 2011; Crotts et al. 1996; Chatfield et al. 2007), and control of movements compared to non-dancers. Some evidence suggests a causal, rather than correlational, relationship between balance ability and dance experience (Bruyneel et al. 2010; Ricotti and Ravaschio 2011; McKee and Hackney 2013; Federici, Bellagamba, and Rocchi 2005), demonstrating that dance experience may improve postural control. Golomer and Dupui (2000) argue that the focus on motor control and proprioception in dance training may instigate a shift in sensorimotor dominance from vision to proprioception, an account corroborated by several studies. Dancers seem to rely more on proprioceptive than visual information, sometimes at a cost to performance on certain tasks that may benefit more from vision (Golomer et al. 1999; Jola et al. 2011). For example, dancers perform better than controls on a hand position-matching task when blindfolded (i.e., proprioception condition), whereas controls perform better than dancers on the same task when only visual information is provided (Jola et al. 2011; Ramsay and Riddoch 2001). Overall, these studies suggest that dancers are less visually dependent (Golomer et al. 1999), but more motor dependent (Jola et al. 2011; Ramsay and Riddoch 2001) than non-dancers on spatial tasks. In the current study, we extended the study of sensorimotor dependence in movement experts from small-scale spatial tasks to large-scale tasks, expecting to observe greater motor dependence in dancers compared to non-dancers in spatial updating.

One method to assess dependence on different sources of sensorimotor information is to compare performance within-subjects on the same task in different conditions that include or exclude the information source of interest. In the case of spatial updating, this has classically been done by varying the locomotion method (e.g., Chance et al. 1998; see Chrastil and Warren 2012 for a review). Virtual reality provides the opportune setting for conducting this type of comparison, as it is feasible to perform manipulations that are not possible in the real world while maintaining high levels of experimental control. Prior research has manipulated both translation and rotation components of spatial updating tasks with inconclusive results. While there is a pretty large consensus for the importance of real rotations in spatial updating (Presson and Montello 1994; Rieser 1989; Chance et al. 1998), evidence is mixed regarding the importance of real translations, with some arguing for the necessity of body-based information (Ruddle and Lessels 2006, 2009; Ruddle et al. 2011) and others arguing for the sufficiency of visual information (Chance et al. 1998; Riecke et al. 2002, 2007). We postulate that individual differences may be one reason for lack of consistency in results regarding translation method. While it is clear that all individuals seem to benefit from and depend on real movement for rotations, some individuals may also be more dependent on body-based processes for acquiring translation information. For this reason, we chose to manipulate translation in our task using three locomotion methods, including real rotations in all conditions.

In addition to walking in a head-mounted display or using a joystick to move around in a desktop or immersive virtual environment, teleporting has become a common way of traversing vast virtual spaces (Moghadam et al. 2018; Coomer et al. 2018; Bozgeyikli et al. 2016; for a review, see Boletsis 2017). Teleporting involves pointing a controller to a certain location in an environment and instantaneously arriving at that location, without receiving either visual or body-based information for self-motion. While useful as a method for traversing large distances and reducing motion sickness, it has been shown to impair spatial updating, specifically over large-scale environments with limited visual landmarks (Cherep et al. 2020). Teleporting serves as an empirical method of eliminating both visual and body-based cues for translation.

The current study

In the current study, expert dancers and non-dancers completed a path integration task in virtual reality using three different locomotion methods to vary the types of information available for the translation component of the task, but always including physical rotation: walking, joystick, and teleporting. In addition to accuracy in heading estimates upon completing the outbound path we measured response time (RT), expecting that slower RTs would serve as an indicator of the processing time needed to compute a heading estimate, which serves as an indicator of difficulty. We expected that all participants would perform with the greatest heading accuracy and fastest RT in the walking condition, because real body-based and visual information were provided for both translation and rotation. In the joystick condition, participants stood and physically turned in place but translated with a joystick, removing body-based information for translation. In the teleporting condition, participants pointed the controller to locations in the environment and locomoted there instantaneously without receiving visual or body-based information for translation. We predicted a decrement in performance in the joystick condition relative to walking, revealed in both higher errors and slower RT. We also predicted that teleporting would lead to a significant decrement (Cherep et al. 2020) in both accuracy and RT, as both body-based and visual information were eliminated for translation. A direct comparison between joystick and teleporting conditions would reveal the importance of visual information for self-motion, beyond the removal of body-based feedback. We also had several predictions regarding movement expertise. First, we expected that dancers would show lower errors and faster RT compared to non-dancers in the walking condition, similar to prior work on spatial updating tasks (Garcia Popov et al. 2013) and small-scale spatial tasks (Voyer and Jansen 2017). Second, we expected that dancers would be more impaired than non-dancers (i.e., have higher errors and slower RT) in the joystick condition relative to the walking condition, given prior evidence for motor-dependence (Jola et al. 2011; Ramsay and Riddoch 2001). While we expected the teleporting condition to be difficult for all, we also expected a greater deficit for dancers, given that their motor experience may have made them more dependent on self-motion information in spatial updating more generally.

While our primary aim was to test performance related specifically to dance training, we anticipated that the skills and strategies that may distinguish performance in the dancers from the non-dancers could also be present in individuals with experience in other activities. To address this, we assessed all participants' performance on a battery of individual differences tests that we reasoned could be related to spatial updating. We measured postural stability (with and without visual input), expecting that better postural stability should increase accuracy especially in the walking condition. We included two measures of mental imagery—mental rotation and movement imagery—expecting that they may be related to accuracy and response time performance, especially in the teleporting condition, where self-motion is not directly experienced. In addition to our dance experience questionnaire, we included questionnaires about experience with videogames and spatial activities, expecting that experience in other spatially-demanding activities may increase spatial updating accuracy and decrease response time.

Method

Participants

Prior research observing significant expertise*condition interaction effects in spatial tasks included sample sizes with 44 (Moreau 2012), 41 (Bredin et al. 2005) or 32 (Garcia Popov et al. 2013) participants (with 16, 21, and 16 movement experts in each sample, respectively). As such, we aimed for a conservative sample of at least 50 participants (about half in each group). Fifty-three participants completed the experiment (27 expert dancers and 26 non-experts). All participants were female with an average age of 20.0 (range 18 to 29). All participants were current students at the University of Utah and were recruited through the psychology department participant pool or the University of Utah dance department. Participants were classified as expert dancers if they reported at least 10 years of experience in dance. Participants had self-reported normal or corrected-to-normal vision and could walk without impairment. For those who wore glasses to the lab, they wore their glasses while in the headset. As compensation, participants from the participant pool received partial course credit and participants from the Dance Department were paid \$10. All participants signed written informed consent with procedures approved by the University of Utah Institutional Review Board.

Materials

The virtual space for the virtual point-to-origin task was a model of a large indoor lab space built in the Unity gaming engine (version 2018.2.12f1) with similar geometry (7 m × 12 m and 3.5 m tall), coloring and texturing on the walls and floors as the real lab. The environment included four walls, six mounted cameras, and a door, as in the real lab space. Because the task included varying starting locations, sometimes with the participant standing close to the physical walls, we elongated the horizontal dimensions of the virtual room so that it appeared larger than the physical room from within the headset. We did this to minimize participants' concerns about approaching the walls and to make them feel secure perceiving and acting in the space. Participants did not view the real room before seeing the virtual room. We used the cordless HTC Vive Pro head-mounted display, which has a field-of-view of 110 degrees and a resolution of 1440 × 1600 pixels per eye (www.vive.com/us/product/vive-pro/). We used four Lighthouse motion trackers that were positioned in an approximate 4 × 4 m square. Head position was tracked, but we disabled lateral joystick movement (strafing) during visual translating to reduce motion sickness. Interpupillary distance (IPD) was set to about 64 degrees and was not adjusted to each participant. Participants held one Vive controller in each hand in all conditions.

To assess postural stability, participants completed two one-legged balance tasks, one with vision and one without. Participants stood on one leg on a balance pad as long as possible while being timed by the experimenter with a stopwatch (Frick and Mohring 2016). Participants chose which foot to stand on and stepped onto a ProSource Exercise Balance Pad (15.5″ L × 13″ W × 2.5″ H). If participants lost balance within approximately one second, they tried again. For the no vision balance task, participants wore a Mindfold blindfold.

To assess imagery ability, participants completed the short Mental Rotation task developed by Beni et al. (2014), a shorter adaptation of the standard task adapted by Peters et al. (1995) that includes 10 trials completed in 3 min. We used an English translation of the task approved by the authors. Participants first completed three practice trials with a time limit of 5 min and were given the chance to ask any and all questions. Responses were scored using a strict criterion, where a point was only given when both correct answers were selected. Participants also completed the Vividness of Movement Imagery Questionnaire (VMIQ; Roberts et al. 2008). In this scale, participants are asked to rate the vividness of the image that comes to mind when they think of various actions (e.g., kicking a ball, running). Participants rate the vividness for each action from three different perspectives to create three subscales: watching the self, seeing through one's own eyes, and feeling the movement. Scores ranged from 1 (Perfectly clear and as vivid (as normal vision or feel of movement)) to 5 (No image at all, you only "know" that you are thinking of the skill) and an average rating is calculated for each participant for each subscale.

To assess individual differences in spatial activities, including dance, participants completed a general demographics survey, a dance experience questionnaire, spatial activities survey, and a video game questionnaire. The general demographics survey included questions about age, gender, education, and area of study. We modeled the dance experience questionnaire after the Domain Experience Questionnaire-Geoscience (DEQ-G; Hambrick et al. 2012) and we similarly created a summed measure of "experience" for each individual using a weighted points system. We included questions about years of experience, current amount of practice, self-perceived skill level, and experience with different dance genres. The spatial activities survey was modeled after the questionnaire developed by Newcombe et al. (1983) and asked about frequency of participation in 81 different spatial activities, including sports (e.g., soccer, gymnastics), arts (e.g., painting, sculpting), and crafts (e.g., weaving, crocheting). Participants rated their frequency of participation for each activity from 1 (never participated) to 6 (participate more than once a week). We calculated a sum of experience score for each participant, where a higher number indicates more frequent participation in more activities. The video game questionnaire included questions about years of experience, frequency of playing, type of console, and type of game (e.g., first person shooter, puzzle). See the Supplementary Materials for all questionnaires.

Procedure

Participants arrived and filled out written informed consent forms. They then completed the eyes closed balance task, mental rotation task, and the eyes open balance task. The experimenter next demonstrated the point-to-origin task in the real world, using three cones to indicate the starting location, first target, and second target. The participant practiced moving between each and then turning to face back to the start. Then the experimenter warned the participant about motion sickness and encouraged the participant to voice concerns and take breaks as needed. Participants put on the blindfold and were led into the testing room. The experimenter placed the headset on the participant's head and adjusted it to her comfort. Then, the participant completed a series of practice trials that involved turning the entire body (including the toes, upper body, and head) to face toward various objects in the environment. They turned to face five objects one at a time before facing back to a starting object. A blue feedback line was projected out of the front of the head-mounted display to aid with aiming. Participants then completed the same practice trials with the screen turning black during the turn, to practice making responses with no visual information.

After completing the practice pointing trials, participants began the point-to-origin task. Participants traveled to and memorized the starting location (a green pole), then traveled to two red poles (see Fig. 1). Each trial included two path segments with targets positioned in the shape of a triangle with different angles and leg lengths. Participants heard a beep through the headphones once they arrived at each pole, and the poles disappeared once the participant reached them. As such, participants could never view more than one pole at a time. Upon reaching the second red pole, the screen turned black and participants turned to face back to the remembered location of the green pole and the experimenter recorded heading direction on the computer. This response was made without visual information, so was based on the remembered path between poles. Then, participants took one step forward toward the remembered target location and the experimenter again recorded the location on the computer. We included the step to encourage participants to make their response as if they were going to walk back to the start, forcing them to commit to the chosen heading angle. Angular response was calculated as the degree of difference between the participant's heading direction at the final red circle and their heading direction after making the response turn and before the step. We chose to use the heading estimate before the step as our primary measure of angular estimate, because we were most interested in the immediate response before the added potential noise of the step.[1]

We recorded the response time from when participants reached the second red pole to when they completed their turn back to the start, which was verbally indicated by the participant. We had participants say "ready" when they were ready for us to record their response. As such, this response time measure includes both the time taken to turn and the time taken for the participant to feel confident enough to commit to a direction estimate. The experimenter manually recorded the time by pressing a key after participants said "ready." Then the screen reappeared and participants located the next green pole. The green pole location varied trial-to-trial in the joystick and teleporting conditions. The

[1] For sake of exploration, we looked at the difference in computed angles before and after the step. The average difference between pre- and post-step angle was 5.49° (SD = 6.38), reflecting minimal change in heading estimate.

Table 1 Practice and experimental triangles in the virtual point-to-origin task

Triangle type	Triangle number	Leg 1 length	Turning angle between Legs 1 and 2	Leg 2 length	Correct response angle
Practice	Practice 1	2 m	90° Right	2 m	–
Practice	Practice 2	2 m	90° Left	2 m	–
Practice	Practice 3	1.5 m	45° Right	2.5 m	–
Experimental	1	1.5 m	50° Right	1.5 m	155° Right
Experimental	2	1.5 m	50° Left	2.5 m	161.65° Left
Experimental	3	2.5 m	80° Right	1.5 m	128.15° Right
Experimental	4	2.5 m	80° Left	2.5 m	140° Left
Experimental	5	1.5 m	120° Left	1.5 m	120° Left
Experimental	6	2.5 m	120° Right	1.5 m	96.59° Right
Experimental	7	2.5 m	150° Left	2.5 m	105° Left
Experimental	8	1.5 m	150° Right	2.5 m	148.02° Right

All participants completed all trials in each condition and the order of the experimental trials was randomized in each condition for each participant. Reproduced from Barhorst-Cates et al. (2020)

real-world location of the green pole was always the same in the walking condition (in a location in the room, where participants could still safely walk all leg lengths of the triangle without running into the walls). To minimize the ability for participants to predict the location of the green pole, we rotated the virtual room between every trial so that the green pole was not consistently associated with any specific visual landmarks. These visual room rotations occurred on every trial in all three conditions. After the completion of each trial, the experimenter walked the participant to a new location in a circuitous route which, when combined with the change in orientation of the virtual room, masked that the starting pole was in the same location in the physical room. We also anticipated that participants may be sensitive to external environmental cues (such as sounds) that could allow them to predict the location of the green pole. To mitigate this, we incorporated white noise through the attached headphones on the headset in all trials and conditions.

Locomotion condition order was randomized and counterbalanced between participants. We encouraged participants to keep their head and body continually facing the same direction (not to turn their head without turning their body). We included a virtual blue line projecting straight forward from the face position in the head-mounted display to help with aiming, which was present for the first 0.5 m of movement. Participants completed three practice and eight experimental trials in each of the following conditions: walking, joystick, and teleporting. See Table 1 for the specific trial information. The walking condition served as the full cue condition, where both visual and body-based self-motion translation information was present. Participants walked between targets just as they would in the real world. In the joystick condition, continual optic flow information was still present, but translation was performed with the Vive controller of the dominant hand by pulling the trigger on the back of the controller with the index finger. Movement progressed at 0.5 m/s and was isolated so that no movement was allowed unless the participant was heading toward the next target. Speed jumped to 0.5 m/s and did not have a smooth acceleration/deceleration. In the teleport condition, participants used the controller to point to a location, viewed an arc that designated the trajectory, adjusted the trajectory by moving the controller closer to or farther from the body, and released the thumbpad to be transported there. Participants could only teleport to the next target location. This condition removed both visual and body-based information for translation, although we included a quick fade to black while teleporting to reduce motion sickness. In all conditions, participants were standing and rotating (turning) using real movement rotations in the environment. As such, the only difference between conditions was the method of translation (or getting from one point to the next). Between each condition, participants were given the opportunity to remove the headset and take a short break before beginning the next condition. Several precautionary measures were taken to ensure the safety of participants. When possible, one experimenter remained at the computer, while the other stood next to the participant. He or she ensured the participant did not approach any walls. Experimenters asked participants continually how they were feeling and encouraged them to take breaks as needed.

After completing all three locomotion conditions, participants returned to the anteroom of the lab and completed the demographics survey, the VMIQ, dance experience questionnaire, spatial activities survey, and video game survey on a laptop. They were then debriefed, thanked, and dismissed.

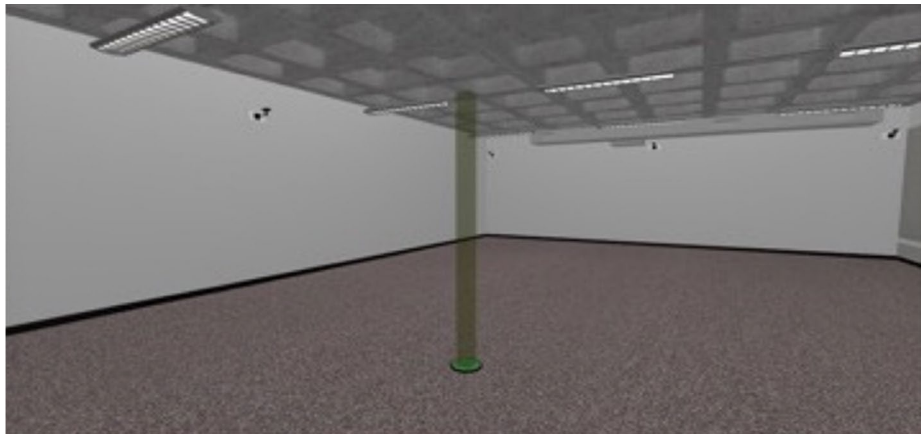

Fig. 1 Virtual environment with target pole. Participants traveled to and remembered the location of the green pole, then traveled to two red poles before turning to face back to the green pole, while the screen was black. Poles disappeared upon arrival, so participants could never see more than one pole at a time

Design and data analysis

This experiment used a 2×3 mixed factorial design with both between-subjects individual differences factors and a within-subjects repeated measures manipulated factor. Dance expertise was considered a between-subjects factor with half of participants in the expert dancer group and the other half of participants in the non-expert group. Locomotion method was manipulated within-subjects, such that every participant completed three conditions in the experiment. Due to experimenter or technical error, we are missing 15 trials (1.2%) of the data. We used mixed effects modeling to include random effects of both Participant and Trial and to account for imbalances in number of trials per participant in the case of missing data. Mixed effects modeling analyses were performed using the *lme4* package in R (Bates et al. 2015) with maximum likelihood estimation. We used likelihood ratio tests to test significance of each factor in the model by comparing goodness of model fit between the model with and without the factor. We report the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) values as indices of model fit, where a lower number is better. There is no current consensus for effect size reporting in mixed effects models (Peugh 2010). We used the Proportion Reduction in Variance (PRV; Raudenbush and Bryk 2002; Singer et al. 2003), which provides an index of effect size but the values are not comparable in the same sense as standard effect size estimates. We performed post hoc pairwise contrasts using the emmeans package in R (Lenth 2019) with Tukey adjustments for multiple comparisons.

Results

Pointing error

Error was calculated as the smallest absolute (unsigned) angular difference between the participant's response and the correct response. The data were positively skewed (skewness = 2.6) but resembled a normal distribution with a square root transformation (skewness = 0.92). We square root transformed the error in our linear mixed effects model. The full model with condition, expertise, and condition*expertise revealed a significant improvement in model fit with the effect of condition ($\chi^2(4) = 25.32$, $p < 0.001$, AIC = 5485.9, BIC = 5516.7, $PRV = 0.021$). Neither expertise ($\chi^2(3) = 0.46$, $p = 0.9$, AIC = 5508.7, BIC = 5534.4) nor the expertise*condition interaction significantly improved model fit ($\chi^2(2) = 0.43$, $p = 0.8$, AIC = 5491.4, BIC = 5537.6). To compare angular error between the three locomotion conditions, we performed post hoc pairwise contrasts with a Tukey adjustment for multiple comparisons. Across both dancers and

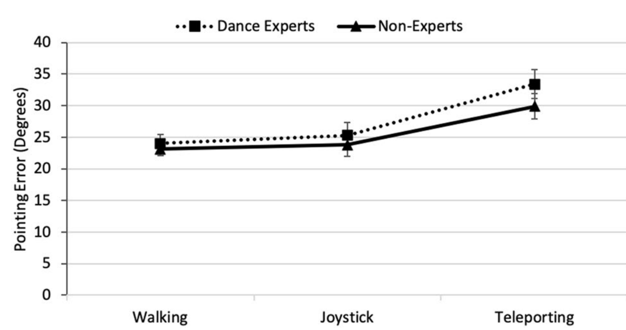

Fig. 2 Average angular error between conditions and groups. Error bars represent ± 1 standard error of the mean

Table 2 Average scores on individual differences measures for dancers and non-dancers

	Range	Dancers *M* (SD)	Non-dancers *M* (SD)	Regression coefficient	Overall *M* (SD)	χ^2
MRT	0–7	3.04 (1.60)	3.27 (2.11)	$B = -.23$ (n.s.)	3.2 (1.9)	.53 (n.s.)
VMIQ—watching self	1–5	3.54 (1.21)	3.37 (1.09)	$B = .18$ (n.s.)	3.46 (1.14)	.03 (n.s.)
VMIQ—own eyes	1–5	3.85 (1.19)	3.71 (1.24)	$B = .13$ (n.s.)	3.78 (1.21)	.10 (n.s.)
VMIQ—feeling self	1–5	3.91 (1.18)	3.54 (1.28)	$B = .37$ (n.s.)	3.73 (1.23)	.40 (n.s.)
Balance—eyes open (s)	4–900	175 (131)	121 (181)	$B = 54.02$ (n.s.)	148.1 (158.4)	.4 (n.s.)
Balance—eyes closed (s)	1–15	4.67 (2.84)	3.38 (2.16)	$B = 1.28$ (n.s.)	4.04 (2.6)	.04 (n.s.)
Spatial activities	108–208	157 (25)	149 (24.7)	$B = 8.26$ (n.s.)	153.3 (24.71)	3.93*

Standard deviation is in parentheses following the mean for each group and overall. We report the coefficients from the linear regressions testing differences between groups in the regression coefficient column. We report the specific χ^2 value and significance of the addition of each factor to the mixed effects model predicting pointing error in the final column. *$p < .05$

non-dancers, walking error ($M = 20.4$, SE = 1.69) did not differ from Joystick ($M = 19.5$, SE = 1.66, $t = -0.70$, $p = 0.7$). Teleporting error ($M = 25.7$, SE = 1.91) was higher than both walking ($t = 3.95$, $p < 0.001$) and joystick ($t = 4.62$, $p < 0.001$). This suggests that participants were impaired in Teleporting compared to both Walking and Joystick, which did not differ from each other.

Dance expertise effects We planned a priori to analyze the strength of the difference between conditions for dancers and non-dancers, expecting that the effect would be larger for dancers (indicating motor dependency). We took a subset of the data that included the dancers only and tested the effect of Condition, which significantly improved model fit compared to an intercept-only model ($\chi^2(2) = 15.03$, $p < 0.001$, AIC = 2866.9, BIC = 2893.7, PRV = 0.024).[2] We conducted the same analysis within the non-dancer subsample and observed again that Condition significantly improved model fit ($\chi^2(2) = 9.68$, $p = 0.008$, AIC = 2632.8, BIC = 2659.3, PRV = 0.018).[3] These results suggest highly similar performance between dancers and non-dancers, although the effect size was larger for dancers. See Fig. 2 for a graph of the estimated marginal means.

Individual differences

We first assessed scores on the individual differences measures for dancers and non-dancers. We performed separate linear regressions with Group predicting performance in each task. None of the measures differed between the dancer and non-dancer groups. See descriptives in Table 2.

We next assessed the relationship between each individual differences measure and performance on the spatial updating task. We used the same mixed effects modeling approach described above. Because neither expertise nor the condition*expertise interaction terms were significant, we dropped these terms from the model. We tested each of the following individual differences factors in the model with condition as a fixed effect in addition to participant and trial as random effects. We tested imagery using the mental rotation task (MRT) and the vividness of movement imagery scale (VMIQ), which provides a separate score for "watching self", "looking through one's own eyes", and "feeling the movement". Neither MRT nor any of the VMIQ subscales significantly improved model fit (χ^2s < 0.5, ps > 0.5). See Table 2 for specific effects. We tested postural stability using two one legged timed balance tasks. Neither balance time (eyes open) nor balance time (eyes closed) significantly improved model fit (χ^2s < 0.4, ps > 0.5). Thirteen participants reported current play of video games. We tested whether these individuals differed in spatial updating accuracy from the non-gamers by including gaming status as an additional factor in our model. Gaming did not significantly improve the model ($\chi^2(1) = 0.007$, $p = 0.9$). However, we did observe a significant effect of spatial activities. Adding spatial activities to the model with condition, participant, and trial significantly improved model fit ($\chi^2(1) = 3.93$, $p = 0.047$, AIC = 5483.9, BIC = 5519.9). As spatial activities increased, pointing error decreased across all conditions ($B = -1.02$, $p = 0.048$).

Taken together, participants, across dancers and non-dancers, perform equally well when walking and using the

[2] Post hoc pairwise contrasts revealed no significant difference ($t = -.31$, $p = .95$) between Walking ($M = 20.2$, $SE = 2.30$) and Joystick ($M = 19.6$, $SE = 2.27$) for the dancers. Teleporting errors ($M = 26.5$, $SE = 2.63$) were higher than both Walking ($t = 3.21$, $p = .004$) and Joystick ($t = 3.52$, $p = .001$).

[3] Post hoc pairwise contrasts revealed no difference ($t = -.65$, $p = .8$) between Walking ($M = 20.5$, $SE = 1.96$) and Joystick ($M = 19.4$, $SE = 1.92$) for the non-dancers. Teleporting error ($M = 25.0$, $SE = 2.17$) was higher than Walking ($t = 2.35$, $p = .051$) and significantly higher than Joystick ($t = 2.96$, $p = .009$).

joystick to translate. Translating with teleporting impairs accuracy for everyone. Additionally, angular error was not impacted by dance expertise, imagery, postural stability, or videogaming. However, greater self-reported involvement in spatial activities was related to decreased angular error across conditions.

Response time

As is common with response time data, our data were positively skewed (skewness = 2.23) and resembled a log distribution. We log-transformed the response time data, which resulted in a closer to normal distribution (skewness = 0.80). We then conducted a linear mixed effects model with likelihood ratio tests to compare goodness of model fit with and without the factor of interest. Our full model with condition, expertise, and condition*expertise revealed that condition significantly improved model fit ($\chi^2(4) = 187.44$, $p < 0.001$, AIC = − 874.2, BIC = − 843.4, PRV = 0.141). Neither expertise ($\chi^2(3) = 5.29$, $p = 0.2$, AIC = − 694.1, BIC = − 668.4) nor the condition*expertise interaction ($\chi^2(2) = 5.16$, $p = 0.076$, AIC = − 873.5, BIC = − 827.3) significantly improved the model. To examine the differences between locomotion conditions we performed post hoc pairwise contrasts with a Tukey adjustment for multiple comparisons. Across both dancers and non-dancers, Walking RT ($M = 6.92$, SE = 0.15) was significantly quicker than Joystick ($M = 7.61$, SE = 0.17; $t = -8.63$, $p < 0.001$) and significantly quicker than Teleporting ($M = 8.06$, SE = 0.18; $t = -13.87$, $p < 0.001$). Joystick RT was also significantly quicker than Teleporting ($t = -5.19$, $p < 0.001$). These data suggest that time to compute and perform a heading response was quickest in walking, followed by joystick, followed by teleporting.

Dance expertise effects To test our a priori hypothesis about the differences in the strength of the effect of locomotion condition for dancers compared to non-dancers, we tested the effect of condition separately in each group. Within the dancer-only subsample the effect of Condition significantly improved the model ($\chi^2(2) = 121.95$, $p < 0.001$, AIC = − 441.3, BIC = − 414.5, PRV = 0.18).[4] For the non-dancer subsample, condition also significantly improved the model ($\chi^2(2) = 63.21$, $p < 0.001$, AIC = − 419.8, BIC = − 393.3, PRV = 0.10).[5] These results suggest that both dancers and non-dancers were similarly impaired by a reduction in self-motion information. However, there was a larger effect size of condition for the dancers. See Fig. 3 for a graph of the estimated marginal means.

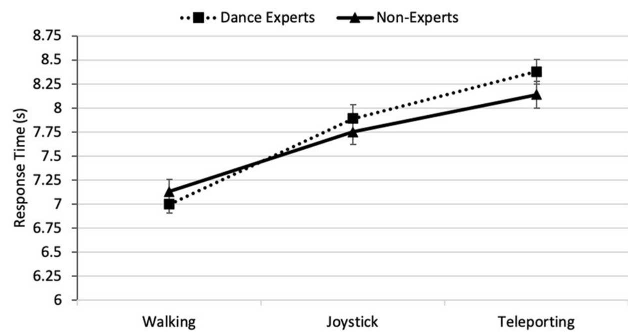

Fig. 3 Average response times in each locomotion condition for each group. Error bars represent ± 1 standard error of the mean

Individual differences

We retained the significant effect of condition and dropped the non-significant effects of expertise and condition*expertise from the model. We separately tested the influence of each of individual differences measures in the model with condition, participant, and trial. None of the individual differences measures improved model fit significantly (all χ^2s < 2.84, all *ps* > 0.09).

Discussion

Expert dancers and non-dancers performed a virtual point-to-origin task with three locomotion methods that varied the availability of self-motion translation information: walking (both visual- and body-based), joystick (visual-only), and teleporting (neither visual- nor body-based). We first predicted that all participants would estimate return-to-home heading with the greatest accuracy and quickest response time in walking, followed by joystick, followed by teleporting, with each subsequent reduction in self-motion information impairing performance. We also expected that dancers would perform better than non-dancers on the walking condition, given that this condition relied on body-based information that should have allowed the movement experts to outperform the non-experts (Moreau 2012, 2013). Finally, we predicted that dancers would show larger decrements in the other two conditions (relative to walking) compared to

[4] Post hoc contrasts revealed that Walking RT ($M = 6.88$, $SE = .20$) was significantly quicker than Joystick RT ($M = 7.67$, $SE = .23$, $t = -7.14$, $p < .001$) and Teleporting RT ($M = 8.21$, $SE = .24$; $t = -11.48$, $p < .001$) for the dancers. Joystick RT was also quicker than Teleporting ($t = -4.36$, $p < .001$).

[5] Post hoc contrasts showed that Walking RT ($M = 6.96$, $SE = .21$) was significantly quicker than Joystick RT ($M = 7.54$, $SE = .23$; $t = -5.04$, $p < .001$) and Teleporting RT ($M = 7.90$, $SE = .24$; $t = -8.06$, $p < .001$). Joystick RT was also quicker than Teleporting ($t = -2.95$, $p = .01$).

non-dancers, supporting a greater reliance on body-based information (joystick) or more generally on combined body and visual information for self-motion (teleport). Comparing teleporting to walking provided an indication of the overall dependence on self-motion information.

Counter to our hypothesis, angular error for both groups did not differ between walking and joystick. However, consistent with our hypothesis, walking elicited the quickest response times. Furthermore, a complete lack of dynamic self-motion information for translation (teleporting) did hurt performance for both groups, as revealed in both accuracy and response time. It is somewhat surprising to find that accuracy in the joystick condition was equivalent to the walking condition for both groups. A number of prior studies have argued for the importance of physical self-movement in spatial updating (Ruddle and Lessels 2006, 2009; Ruddle et al. 2011). However, others suggest that accurate spatial updating can be performed with visual-only translation information (Riecke et al. 2002, 2007) and some of our recent data also demonstrate similar performance between walking and joystick in young adults (Barhorst-Cates et al. 2020). Moreover, vision and proprioception may be weighted equally in path integration (Chrastil et al. 2019). It is possible that the similar performance between walking and joystick could be explained by distance estimation that occurred prior to traversing the segments (i.e., making static visual judgments of distance to each target) rather than during the translation. However, similar static judgments were also possible in the teleporting condition, yet we observed detriments in performance. This suggests that the translation information itself was important. As such, we postulate that these results suggest flexibility in the use of different types of translation self-motion information for spatial updating, as long as some type of information for self-motion is available (visual or body-based). However, slower response times in joystick compared to walking suggest that walking may facilitate ease of computation of a heading estimate. Of note, many have argued that real translation is not necessary as long as real rotations are performed (Presson and Montello 1994; Rieser 1989; Chance et al. 1998). In the current paradigm, removing real rotations would likely have shown stronger differences between conditions.

Errors in the teleporting condition were higher for both dancers and non-dancers, suggesting that removing self-motion translation information is detrimental to spatial updating. This increase in error is consistent with recent research demonstrating the detriments of teleporting locomotion methods (Cherep et al. 2020). Cherep et al. (2020) found worse performance in teleporting conditions compared to walking, especially in virtual environments without sufficient visual cues. Our study adds a vital further comparison between teleporting and joystick, which allows for a direct test of the importance of visual translation information. Paris et al. (2019) recently demonstrated that locomotion methods that provide continuous movement information (like in our walking and joystick conditions) result in more accurate spatial updating than locomotion methods that provide discrete movement information (as in teleporting). This continuous-discrete division could explain the similar performance between joystick and walking in our study, with teleporting being worse. However, our response time results do suggest greater processing time demands in the joystick condition compared to walking (and a further increase in response time with teleporting), suggesting that walking may allow for easier computations of return-to-home heading compared to the conditions without body-based translation information (even though movement information was still continuous in the joystick condition). This may be because walking provides automatic information about self-location (Presson and Montello 1994; Rieser 1989), while in joystick and teleporting the information may not be automatically acquired.

Second, we did not find evidence for the predicted movement expertise advantage, as revealed by indices of model comparisons. Despite prior research showing enhanced proprioception and balance abilities in dancers (Golomer et al. 1997, 1999; Rein et al. 2011; Crotts et al. 1996; Chatfield et al. 2007) as well as advantages in spatial updating in movement experts (Garcia Popov et al. 2013), our results did not support a dancer advantage in spatial updating in the walking condition. The lack of an expertise advantage for dancers, while contrary to our predictions, is consistent with Voyer and Jansen's (2017) meta-analysis of spatial abilities of movement experts. They showed advantages for movement expertise on spatial tasks, but weaker or no effects when analyzing dancers as a specific group of experts. Many of the spatial tasks from the studies included in the meta-analysis tested small-scale spatial abilities. Here, we extend the battery of tested tasks on expert dancer populations to include large-scale spatial abilities, which may be more representative of the spatial abilities used in dance, yet still we did not observe an advantage. We also did not find strong evidence for the predicted larger decrement between conditions for dancers compared to non-dancers, although the proportion reduction in variance was larger for dancers in both angular error and response time measures. We suspect that removal of real rotations would strengthen this effect, a manipulation which should be tested in future research.

Our results from the Spatial Activities survey do show evidence for more spatial activities involvement relating to improved accuracy in spatial updating. As such, it is possible that other movement expert populations would be more likely to reveal expertise differences in spatial updating (such as martial artists, Smith et al. 2010, or gymnasts, Garcia Popov et al. 2013). However, the Spatial Activities survey also includes a number of items in addition to sports participation, such as art, crafts, construction, and mechanics. While outside of the scope of the current study, it would be interesting for future research to identify which activities better predict spatial updating performance in addition to identifying the shared or distinct components across the activities that may improve large-scale spatial thinking. This finding has exciting implications regarding the malleability of spatial skills, which has previously been considered mostly in the context of small-scale spatial tasks (Uttal et al. 2013).

Limitations and future directions

Our methodology has several limitations worth pointing out. The use of virtual reality (VR) as a research technique has clear benefits in that VR provides precise experimental control and allows for manipulations (such as teleporting) that are not possible in the real world. However, with VR there are always relevant questions of artificiality and generalizability to the real world. Several recent papers have argued for similarity between real- and virtual-world navigation (Hejtmanek et al. 2020; Williams et al. 2007), especially with new technology that provides greater visual fidelity. We tried to minimize the artificiality of the virtual world as much as possible by including textured visual landmarks and allowing for real movement with the cordless headset. Nonetheless, it is possible that performance in the task was influenced by the virtual environment, a limitation that should be addressed by comparing performance on the same tasks in both real and virtual environments. In any case, effects of environmental realism should have been equated across our three conditions. Physical lab constraints also prevented us from acquiring estimates of distance back to the start, which could reveal important information about individual or condition differences in spatial updating. For instance, if participants systematically over- or under- estimated the distance of each segment of the outbound path, we might expect intact angular estimates but errors in distance estimates. It would be interesting in future research to assess the effects of locomotion method on the scale of traveled segments in virtual environments. Our data suggest that teleporting may impair perception of distance traveled, leading to more error-prone spatial updating, but this account needs to be further tested.

One aspect of our methodology may contribute to the lack of a difference between walking and joystick. In our walking condition, participants were free to choose their own path to traverse between targets. Although we included a straight blue virtual line projecting from the front of the head mounted display to help with aiming and to encourage straight-line paths, the walking condition likely included greater deviation from the straight-line path, which could have increased error (Lappe et al. 2007). In contrast, in our joystick condition, participants were forced to follow a straight-line path, because movement was only possible if participants were looking directly at the target. The inherent straight-line path could have facilitated performance in this condition. Future research could compare forced straight-line walking paths to joystick conditions that deviate from a straight-line path to measure the influence of path deviation in visual and body-based locomotion methods. Translation in the joystick condition was also necessarily slower than translation in walking, which may have influenced performance. However, we would expect the longer time required to complete the joystick condition to increase working memory demands, which should have resulted in higher angular errors (which was not the case). We included these stipulations to minimize motion sickness, which has often been a concern with joystick locomotion methods.

Finally, the response time method we used was somewhat imprecise, as we asked participants to verbalize when they were ready for us to manually record on the computer. As such, this measure includes the time taken to turn, the time taken for the participant to commit to the response, and the time taken for the experimenter to record, which may have inflated the response time values. Even considering this, our data show interesting processing time effects that are influenced by locomotion method which could be studied more precisely in future research.

Conclusions

In conclusion, we demonstrate that the absence of translational self-motion information inherent to "teleporting" in virtual environments negatively affects spatial updating, with similar effects across movement experts and non-experts. Moreover, locomotion methods that restrict physical translation may require significantly longer processing time for individuals to compute heading estimates. While movement training expertise associated with dancing specifically did not show strong effects on our spatial updating tasks, other individual differences in spatial expertise and abilities should be considered in future work. As virtual reality becomes more ubiquitous in daily life, it is important that researchers and designers carefully consider locomotion methods as well as individual differences in how people understand and interact with virtual worlds.

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Data availability Data are available in the Open Science Framework repository at https://osf.io/wujbs/ under https://doi.org/10.17605/OSF.IO/WUJBS.

Compliance with ethical standards

Conflict of interest The authors declare no conflicts of interest or competing interests.

Ethical approval All procedures were approved by the University of Utah Institutional Review Board and adhere to the 1964 Declaration of Helsinki.

Informed consent All participants gave informed consent via written signed consent forms prior to their participation in the study.

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