Three-Dimensional Immersive Diagnostic Tool for Spatial Egocentric Ability

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ABSTRACT

The goal of this study is to design and validate an innovative diagnostic tool to assess egocentric spatial ability, which is the ability to perceive and manipulate objects in space using a self-to-object frame of reference (e.g., imagining a change of perspective). This is important for successful navigation in large-scale 3D space, teleoperation, robotics, dentistry, and surgery. In contrast, allocentric spatial ability is the ability to imagine rotation of objects from a stationary perspective (e.g., mental rotation), and it predicts success in science and engineering. The existing assessments of spatial ability, usually administered in non-immersive environments, where an observer views himself from outside the screen, assess primarily allocentric spatial ability.

We designed an immersive 3D Virtual Reality Perspective-Taking Ability (3D VR-PTA) task, in which participants were shown an array of objects, asked to imagine taking the perspective of an avatar within the scene, and then asked to indicate the direction to a target object from this imagined perspective. In Experiment 1, 13 participants were administered 3D VR-PTA along with the two-dimensional (2D PTA) and 3D non-immersive (3D PTA) versions, and a number of allocentric spatial tasks. The analysis of pointing accuracy pattern suggests reliance on the egocentric system while encoding and manipulating stimuli in 3D VR-PTA vs. 2D PTA. In Experiment 2, 36 participants were administered 3D VR-PTA along with non-immersive spatial tasks (mental rotation, paper folding, 2D PTA) and real-world tasks where they were placed in a new real-world environment and tested on pointing direction tasks, shortcut finding tasks, and path integration tasks. 3D VR-PTA was found to be the best predictor of navigational performance followed by 2D PTA, while all other allocentric spatial ability tasks did not predict real world navigational performance.

ABOUT THE AUTHORS

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INTRODUCTION

Research findings (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001; Kozhevnikov et al., 2006) suggest that spatial ability may be separated into two relatively independent subcomponents, allocentric and egocentric spatial abilities. *Allocentric spatial ability* is the ability to imagine rotation of objects or arrays of objects from a stationary perspective (e.g., mental rotation), and *egocentric* or *perspective-taking ability* is the ability to imagine a reoriented-self (e.g., imagining a change of perspective).

The distinction between egocentric and allocentric spatial abilities is related to the use of different spatial frame of references. Allocentric transformations of an object or arrays of objects involve imaging movements relative to an object-based frame of reference, which specifies the location of one object (or its parts) with respect to other objects. In contrast, imagining a different orientation (perspective) involves movement of the egocentric (body-centered) frame of references, which encodes object locations with respect to the front/back, left/right, and up/down axes of the observer's body (Easton & Sholl, 1995; Klatzky et al., 1998; Wraga, et al., 2000).

The dissociation between allocentric and egocentric spatial abilities is of great importance because research indicates the involvement of different neural and cognitive networks in allocentric and egocentric spatial processing (see Kozhevnikov et al., 2006 for a review), so that a person with high allocentric spatial ability might not be necessarily of high egocentric spatial ability and vice versa. Importantly, allocentric and egocentric spatial abilities are responsible for success in different fields and show different relationships to real-world performance. The encoding of visual-spatial stimuli in relation to egocentric spatial frames of reference has been shown to be critical for successful performance in many real-world tasks as long as one is required to imagine and manipulate objects from their own body-centered perspectives and/or imagine how these objects will look like from a different perspective (Kozhevnikov & Garcia, 2011). Indeed, the ability to perform egocentric spatial transformations has been found to predict performance on a variety of wayfinding and spatial orientation tasks (Allen et al, 1996; Kozhevnikov et al., 2006), teleoperation and robotics (Menchaca-Brandan et al., 2007) as well as medical surgery and dentistry (Kozhevnikov & Garcia, 2011; Kozhevnikov et al., 2013). Furthermore, it is namely egocentric spatial ability was found to be an important predictor of drilling performance of aerospace technicians (Kozhevnikov & Olmedo, in preparation), and is important for firefighters' performance during training operations and on the fireground (Zhong & Kozhevnikov, 2016). In contrast, allocentric manipulation of objects or arrays of objects (e.g., mental rotation of cubes or other geometrical figures) involves imagining movement relative to an object-based frame of reference, which specifies the location of one object (or parts) with respect to other objects. Allocentric spatial ability was found *not to be* a reliable predictor of wayfinding performance in real environment (Hegarty et al., 2002; Hegarty et al., 2004) but an important predictor in achievement in a variety of STEM disciplines, such as mathematics (Uttal, Miller, & Newcombe, 2013), graph and diagram interpretation, chemistry and physics (Höffler, 2010; Kozhevnikov, Motes, & Hegarty, 2007; Wu, & Shah, 2004).

Yet, most of the existing spatial assessment tools measure allocentric but not egocentric spatial ability. Allocentric spatial ability tests are currently used to predict performance in a variety of domains, including the domains requiring egocentric rather than allocentric processing. For example, PAT (Perceptual Ability Test), which is used for selection of students to dental schools in many countries, comprises mostly items assessing allocentric spatial ability. It is, however, egocentric spatial ability that is required for success in dental performance (Kozhevnikov et al., 2013).

Similarly, while allocentric spatial tests, such as mental rotation, are still used to predict navigational performance, it is egocentric spatial ability which is important the most in navigating in real-world large-scale space. It is not surprising then that allocentric spatial ability tests such as mental rotation or PAT have only weak predictive validity, and thus the development of egocentric spatial ability tests is necessary to improve the process of personnel selection. Similarly, while most spatial ability training procedures are focused on training of allocentric spatial ability, in order for the training to be effective, it is important to identify first the type of spatial ability required in a particular domain and emphasize the training of this particular ability.

Allocentric and egocentric spatial abilities are sometime referred to as "small-scale" and "large-scale" spatial abilities in the literature due to their intertwined relation with small-scale and large-scale environmental spaces or representations (Wang, Cohen, & Carr, 2014). Small-scale spatial ability refers to the ability to mentally represent and transform images in environmental spaces typically smaller than the body that can be apprehend from a single vantage point and is usually measured with pen-and-pencil and computerized psychometric tasks. Large-scale spatial ability refers to the ability to orient oneself in a large-scale environment where the spatial layout cannot be fully apprehended from a single vantage point and is typically measured with real-world wayfinding tasks. Although early studies seem to suggest significant relationship between small-scale spatial ability and large-scale environmental ability (Thorndyke & Goldin, 1983), a review of more recent studies found only weak relations instead (Hegarty & Waller, 2004; Hegarty et al., 2002).

The scale space in which tasks are carried out has a crucial effect on the type of spatial processing recruited to complete such tasks (Wolbers & Wiener, 2014). The reliance on egocentric spatial frame of reference in large-scale real environments versus allocentric spatial frame of reference in small-scale environments would also explain why the results of the training studies show no transfer from training in 2D environments to performance in immersive virtual reality or real world tasks (Pausch et al., 1997). The existing conventional assessments of spatial ability, such as the Mental Rotation Test (Shepard, Metzler, 1973) or Paper Folding Test (Ekstrom et al., 1976) are either paper-and-pencil or computerized tasks that assess only allocentric spatial ability, and are thus are not reliable predictors of egocentric tasks, such as large-scale real-world navigation (Hegarty et al., 2006). Although new paper-and-pencil (Kozhevnikov & Hegarty 2001) and computerized (Kozhevnikov et al., 2006) perspective-taking assessments have been developed recently, and in fact are able to measure egocentric spatial ability to some extent (Kozhevnikov & Hegarty, 2001), they are problematic due to their "small-scale" nature, eliciting the use of allocentric instead of egocentric frame of reference and leading to the situation in which these tests are often solved by mentally rotating the stimulus rather than by reorienting one's perspective (Carroll, 1993).

The main goal of this study is to design and validate an innovative diagnostic tool to assess egocentric spatial ability - 3D Immersive Virtual Reality-based Perspective-Taking Ability test (3D VR-PTA). Our hypothesis for this study is that an immersive virtual reality PTA (3D VR-PTA) task could be a better measure of egocentric spatial ability than currently available 2D PTA, and, as a result, performance on immersive 3D VR-PTA task might be more strongly related to real world navigation as compared to desktop PTA task and traditional spatial ability tasks such as the Mental Rotation or Paper Folding Tests.

We suggest that immersive 3D virtual reality environment might be particular efficient for assessment of large-scale egocentric spatial ability due to its *immersivity* (the user is immersed in the scene "looking inside out". rather than viewing it exocentrically from the outside, and such characteristics as a larger field of view in comparison with a traditional computer screen as well as position and image updating (when the user turns his/her head, the image adjusts correspondingly).

In Experiment 1, we present the design and construct (internal) validation of 3D VR-PTA instrument and compare its psychometric properties with those of 2D non-immersive perspective taking test (2D PTA) presented on a traditional computer display. In Experiment 2, we examine predictive validity of 3D VR-PTA and show that 3D VR-PTA presents a valid tool to uniquely assess such egocentric spatial ability as spatial navigation in a large-scale real-world space.

EXPERIMENT 1

Method and Participants

The goal of this experiment was to provide construct (internal) validation of a VR 3DI PTA tool to measure egocentric spatial ability more reliably than the existing 2D PTA. Thirteen undergraduate students (8 males and 5 females, average age = 21) participated in the study. They received either course credit or monetary compensation. Participants completed the tasks via two different display mediums (i.e. within-subjects design), with order of 2D and 3D VR PTA tasks counterbalanced. Before beginning the PTA trials, participants listened to verbal instructions while viewing the computerized scene in each environment. Two practice trials in each environment were given to ensure participants understood the instructions, if either trial was incorrect, the participants were asked to explain how they solved the task and then repeated the practice trials.

Description of Tasks

Desktop Perspective-Taking Ability Test (2D PTA)
In the 2D PTA (Kozhevnikov & Hegarty, 2001; Kozhevnikov et al., 2006), which consisted of 72 trials, scenes and objects were presented to the participant on a standard computer screen (see Figure 1 (left)). On each trial, a red figure representing a character's head indicated the starting location where participants were to imagine themselves standing. After a short delay, a flashing red dot in the place of the black dot indicated which landmark was to be pointed to. Participants were to indicate the direction to a target location by clicking one of eight directional arrows, which indicated directions in increments of 45° from 0° to 315°. Both accuracy and response time were recorded. To perform the test well, participants were to imagine transforming their actual perspective (i.e. an aerial perspective of the character and the town) to that of the character's perspective, and then the participants were to imagine pointing to the target from the character's perspective. The imagined orientations in the perspective-taking version varied from 100° to 260° (relative to upright direction) in increments of 20°. Angles less than 100° and more than 260° were not used for imagined headings because previous research (Kozhevnikov & Hegarty, 2001) has shown that observers usually used strategies other than perspective-taking strategies for those angles (e.g. analytical strategies or tilting the head to 'see' the angle).

Immersive Virtual Reality-based Perspective-Taking Ability Test (3D VR-PTA)
Based on previously designed 2D PTA test, we created a new version of the task in 3D immersive virtual reality – 3D VR-PTA. In the 3D VR-PTA, which consisted of 52 trials, the participant was placed in a location inside the scene in 3D immersive virtual environment (virtual city depicting many everyday items, such as a car, a mailbox, etc.), as shown in Figure 1 (right). The array of the objects as well as the objects in the array were changed for every trial. The participants were explicitly instructed to imagine taking the perspective of an avatar located within the array of objects, and then to point to a specific target from the new imagined perspective, using a pointing device. Both accuracy and response time were recorded.

The Vizard Virtual Reality Toolkit v. 3.0 (WorldViz, 2007) was used to create the entire VR environment, and to record reaction time and accuracy. Scenes were presented to the participant through an nVisor SX60 (by Nvis Inc) Head Mounted Display (HMD). The HMD has a 44" horizontal by 34" vertical field of view with a display resolution of 1280 x 1024 and under 15% geometric distortion. The participant's head position was tracked by 4 cameras located in each corner of the experimental room that are sensitive to an infrared light mounted on the top of the HMD. The rotation of the participant's head was captured by a digital compass mounted on the back of the HMD.
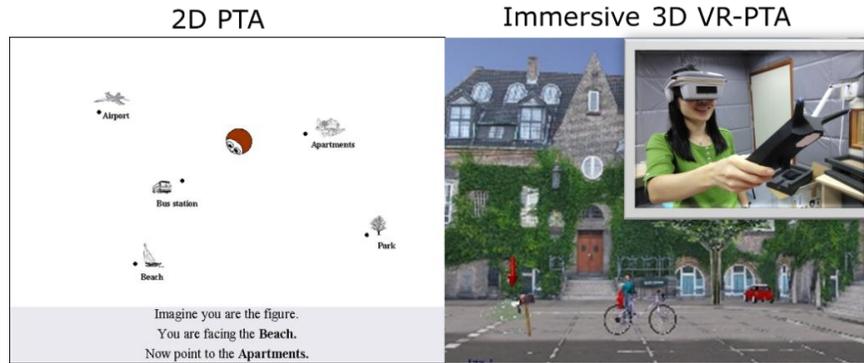
**Figure 1. Screenshots of non-immersive 2D PTA (left) and immersive 3D VR-PTA (right) trials**

On each 3D VR-PTA trial, the HMD portrayed a scene with an avatar surrounded by an array of several objects. Similar to the 2D PTA, the task required participants to take the perspective of the avatar. During the trial, participants then used the pointing tracker to point to the direction of the target object taking the perspective of the avatar. Relative to the avatar, the target objects were arranged in 13 orientations. The four response directions were front-left (270°-0°), front-right (0° - 90°), back-left (90° - 180°), and back-right (180° - 270°).

Results

Pointing Accuracy and Response Time (RT) as Functions of the Imagined Heading
We examined pointing accuracy (i.e. absolute angular error) and response time as a function of imagined heading (i.e. the angle between the participant's actual perspective and the avatar's perspective: and as a function of version of the PTA test (3D VR-PTA or 2D PTA). We used only four angles for imagined heading (100°, 120°, 140°, and 160°), which that were presented both in 3D VR-PTA and 2D PTA tasks. Absolute angular error represented the absolute degrees between the subject's pointing direction and the correct pointing direction (i.e. the actual direction of the target from the imagined heading. The imagined heading of 180° was omitted from the analysis because subjects often use analytical strategies to perform the task (Kozhevnikov & Hegarty, 2001).

For accuracy, neither test version [$F(1,12) = 0.02$, $p = 0.9$] nor imagined heading [$F(3,36) = 0.87$, $p = 0.4$] were significant, or their interaction, possibly due to the overall high accuracy on both versions of the tasks (M=27.64, SD = 11,16]. However, there was a significant main effects for response time (see Figure 2): the effect of test version: $F(1,12) = 9.08$, $p = 0.01$, 95% CIs [3,03, 4.78] and [3.55, 5.72] for 2DPTA and 3D PTA, respectively). as well as imagined heading: $F(3,36) = 4.03$, $p < 0.05$, 95% CI [3.09, 4.51, [3.34,5.39], [3.42, 5.40], and [3.31, 6.70] for imagined headings 100, 120, 140, and 160 degrees, respectively) were significant, but not interaction [$F(3,36) = 0.66$, $p = .64$].
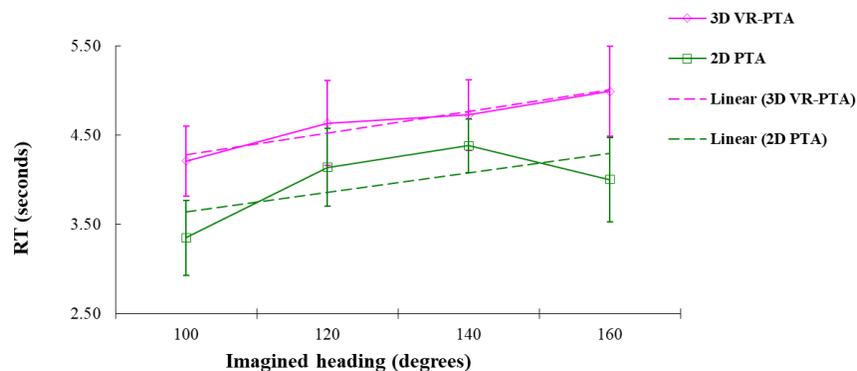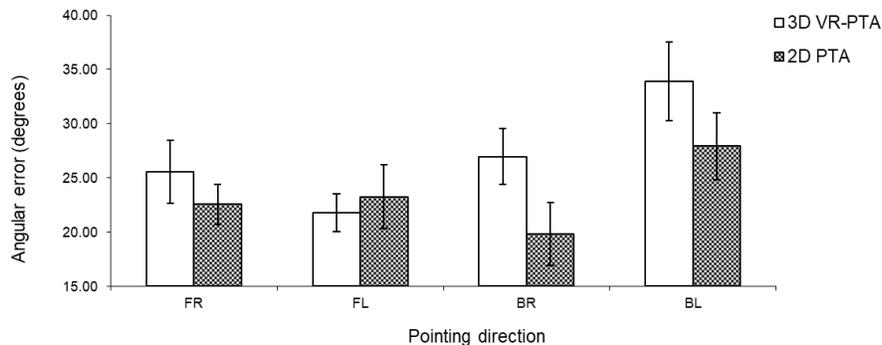

Figure 2. Response Times as a function of viewing environment and imagined heading. Linear regressions on the data are also shown.

Pointing Accuracy and RT as Functions of Pointing Direction
Pointing accuracy (i.e. angular error) and response time were examined as functions of pointing direction (front right, front left, back right, and back left) according to the direction of the target from the participant's imagined heading (4 sections of 90°) and test environment with a 4 (pointing directions) X 2 (tests) repeated measures ANOVA.

For pointing accuracy (see Figure 3), there was a significant effect of pointing direction: $F(3,36) = 6.86$, p =.001, 95% CI [18.30, 27.75], [19,37, 28.05], [20.78, 30.47], and [25,87, 36.75] for FR, FL, BT, and BL responses respectively. but the effect of test version was not significant [$F(1,12) = 1.2$, p =.29], as well as interaction [$F(3,36) = 1.94$, $p =.14$]. Front right and front left pointing directions were more accurate than back left (*p's* = .001 and .005, respectively), and back right pointing was more accurate than back left (*p*=.02).

Figure 3. Angular error as a function of viewing environment and imagined heading

For response time, there was a significant main effect of pointing direction: $F(3,36) = 8.49$, p < .001, 95% CI [3.03, 5.72], [3.12, 4.83, [3.33, 5.27], and [3.39, 5.78] for FR, FL, BR, B responses respectively, and test version [$F(1,12) = 12.43$, p < .01, 95% CI [2.94, 4,74], and [3.54, 5.557] for 2D PTA and 3D PTA respectively), and marginally significant interaction [$F(3,36)=2.80$, p = .052]. Latencies for front right pointing directions were significantly faster than back left and right pointing directions (p's = .01), and front left was faster than back left (p = .01). Pointing was significantly slower in 3D VR than in 2D (*p* = .01).

Reflection vs. Adjacent Errors
In order to test the hypothesis that an egocentric frame of reference was used more in 3D VR-PTA task than in 2D PTA, the number of reflection errors in each condition was compared. A 2 (front vs back) X 2 (test version) repeated measures ANOVA revealed a significant main effect of test version: $F(1,12) = 6.94$; $p < 0.05$, with significantly more reflection error committed in a 3D VR-PTA (M = 2.35, 95% CI [1.49, 3.19]). than in 2D PTA (M = 1,61, 95% 95% CI [0.62, 2,60]).

The effect of back/front pointing direction was not significant (*F*<1), as well as interaction (F<1).

To illustrate that participants specifically commit more back reflection errors in 3D VR but not more adjacent errors, we examined the number of adjacent errors committed in each test environment using a 2 (front vs back) X 2 (test version) repeated measures ANOVA. There was a marginally significant main effect of test environment $F(1,12) = 3.47$; $p =.08$, but no significant effects of pointing direction (F<1) or interaction (*F's* < 1). Thus, participants in 2D PTA tended to make more back adjacent errors than in 3D-PTA condition.

Discussion of Experiment 1

PTA tasks involve mental transformations over two angles: (1*) imaging heading*, i.e., the angle between the orientation of the array and the perspective to be imagined and (2) *pointing direction*, i.e., the angle between the imagined perspective and the direction to the target object. Both of these transformations contribute to task difficulty. During similar perspective taking real world tasks, when individuals asked to point to different objects in a room or landmarks in a large-scale space from an imagined perspective, angular errors and RTs increase with the degree of angular

deviation between the imagined perspective and the orientation of the object array (Hintzman et al., 1981; Rieser, 1989; Shelton & McNamara, 1997)).

As we expected, the findings of Experiment 1 indicate that both 3D VR-PTA and 2D PTA tests show similar pattern of responses to real-world perspective-taking tasks (increase in angular error and RT with imagined heading, and increased difficulty in pointing to the targets in the back than in front), suggesting reliance on the egocentric system while encoding and manipulating stimuli in both PTA tests.

At the same time, comparative analysis of subjects' responses in 3D VR-PTA vs. 2D PTA suggests that the 3D VR-PTA requires the most involvement of egocentric spatial encoding. In particular, while the participants were as accurate on performing 3D VR-PTA as on performing 2D PTA, their errors were qualitatively different. For 3D VR-PTA performed in 3D immersive environment, most errors were systematically due to confusion between "right-left" and "back-front" coding in respect to the body, indicating that they indeed were relying more on body-centered frame of reference. In contrast, in 2D PTA environment, participants made more "allocentric" errors characterized by over-rotating or under-rotating the scene. We conclude that that 3D VR-PTA (immersive version of 3D PTA task) is the only version which reliably access egocentric spatial ability, and that immersive environment is necessary to provide adequate information for building a spatial reference frame crucial for egocentric processing.

EXPERIMENT 2

Method and Participants

The goal of Experiment 2 was to provide predictive (external) validation of a VR 3DI PTA tool by showing that it can reliably predict real-world large-scale spatial navigation performance. Thirty-six undergraduate participants were recruited to participate in this study. In addition, a subgroup of trained navigators was selected and consisted of 14 males who had undergone navigation training during mandatory national service in Singapore. While they have different ranks, all of them had gone through basic navigation training, in which they were familiarized with topographical map reading and compass skills. At the end of this training, they had to traverse dense rainforests with rolling terrains to locate multiple check-points. All participants in this subgroup had passed this training.

The assessments included a computer desktop version of the Mental Rotation Test (MRT), the Paper Folding task (PFT), 2D PTA and 3D VR-PTA. Participants also were brought to a novel environment and tested on their real world large-scale navigational performance: pointing direction tasks and shortcut finding, which are measures of navigational performance.

Participants were tested individually over two sessions that took place not more than a week apart. In Session 1, which took approximately one hour, participants completed four visual-spatial tests in a counterbalanced sequence. The three non-immersive tests were PFT, MRT and 2D PTA tests. Finally, they were given an immersive 3D VR-PTA, during which they had to complete egocentric trans-formation tasks in an immersive environment. In Session 2, which took approximately one hour, participants completed a set of navigational performance tasks. First, participants were guided along a route inside the university campus and were asked to take note of landmarks. The route was approximately 600 meters long and participants took approximately 10 minutes to complete it. At the end of the route, participants completed the route pointing direction test (PDT), in which they were required to point as accurately as possible to unseen landmarks. After this, participants were asked to find shortcuts to three landmarks that were previously pointed out by the experimenter. Finally, participants returned to the lab to complete the test of landmark recognition and the Imaginal Pointing Direction task (IPDT). In this task, participants had to imagine themselves at the specific landmark looking at a second landmark, after which they had to point to a third landmark.

Description of Tasks

3D VR-PTA
The description of the 3D VR-PTA is given in Experiment 1.

Non-immersive Small-scale Spatial Tests
Paper Folding Test (PFT). The PFT consisted of 10 test trials and measures spatial visualization ability, which is the ability to apprehend, encode and mentally manipulate abstract spatial forms (Ekstrom et al., 1976).

Mental Rotation Test (MRT). The test administered consisted of 36 test trials and is a computerized version of Shepard and Metzler's mental rotation test (Shepard, Metzler, 1973).

Desktop Perspective-Taking Ability Test (2D PTA). The description of the 2D PTA is given in Experiment 1.

Navigation Performance Tasks
Guided Navigation (followed by PDT task). The route spanned two floors and approximately 600 meters. Along the route, 15 landmarks were chosen and named. These landmarks were used during the following tasks: PDT, IPDT, and Shortcut-Finding task. In order to have the right level of difficulty for the Shortcut-Finding task, the route spanned three interconnected buildings and two floors. Before starting, participants were instructed to remember the route and the landmarks that would be pointed out to them.

Pointing Direction Task (PDT). The PDT test consisted 15 test trials and measured the ability to judge the direction of surrounding unseen objects with respect to oneself. Performance on this task reflects spatial updating ability and is based on the self-to-object-representational system. Both accuracy and reaction time in milliseconds were recorded.

Imaginal-Pointing direction test (IPDT). The IPDT consisted of 30 test trials (accuracy and response time were measured in ms) and measured the ability to perform spatial transformation on landmarks, which were shown to participants during guided navigation. The participants received written instructions which gave them sequential instructions to imagine themselves standing at a landmark (from the guided navigation) looking at a second landmark, after which they had to point to a third landmark.

Shortcut-Finding Task. This task was designed to measure participant's ability to navigate within a novel environment. Participants were instructed to find several landmarks in succession one after the other. Care was taken to choose landmarks that were out of the view of the participant from the beginning of each leg and to place them far apart with respect to the guided navigation. The experimenter followed behind each participant and recorded time and distance travelled. Prior to the test, all participants had only been exposed to the route only once during the Guided Navigation task.

Results

Data Processing: Correlations
Correlations between the PFT, MRT, PTA, 3D VR-PTA and the three navigational tasks are shown in Table 1. As expected, all measures of navigation performance (PDT, IPDT and Shortcut finding) were correlated (all $r > .30$, $p \leq .005$). PFT and MRT were correlated with each other ($r = .44$, $p \leq .001$), while 2D PTA and 3D VR-PTA, were also correlated ($r = .50$, $p \leq .001$). These correlations suggest that correlated measures tap into shared spatial abilities. Interestingly, PFT was also correlated with 2D PTA ($r = .58$, $p \leq .001$) and 3D VR-PTA ($r = .38$, $p \leq .005$), which suggests that they also require the use of some shared spatial abilities. Furthermore, while PFT and MRT were not correlated to any of the navigational performance measures, 2D PTA and 3D VR-PTA were correlated with some of them. It suggests that PTA and 3D VR-PTA engage some spatial ability that is also being used in the navigation tasks.

Table 1. Correlations between measures

		1	2	3	4	5	6	7
1.	PFT	-	0.44**	0.58**	0.38*	0.23+	0.24+	0.17
2.	MRT		-	0.23+	0.24+	0.04	0.07	-0.09
3.	PTA			-	0.50**	0.37*	0.21+	0.23+
4.	3D VR-PTA				-	0.50**	0.34*	0.22+
5.	PDT					-	0.31*	0.34*
6.	IPDT						-	0.43*
7.	Reversed Distance Score							-

**. Correlation is significant at the 0.01 level (1-tailed)
*. Correlation is significant at the 0.05 level (1-tailed)

+. Correlation is approaching significance at .1 level (1-tailed)

Data Processing: Principle Component Analysis
To further analyze this pattern of correlations, Principle Component Analysis (PCA) was conducted to reduce the number of dimensions of the data set. It was expected that PFT and MRT would load an allocentric factor, while 2D PTA and 3D VR-PTA would load on an egocentric factor, since these tasks were designed to measure each ability respectively.

PCA on efficiency measures revealed seven factors, two of which had Eigen values greater than 1, explaining 59.5% of the variance of efficiency measures. The first factor had an Eigen value of 2.80 and accounted for 39.9% of the variance of accuracy measures. The second factor had an Eigen value of 1.37 and accounted for 19.6% of the variance. Summarized factor loadings (for two factors with Eigen values greater than 1) are shown in Table 2 (where numbers indicate loading from Rotated Varimax Solution). The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was .73 and that showed the total sample size of 35 participants to be adequate (CITE).

All measures of navigational performance, namely PDT, IPDT and Shortcut Finding, loaded positively on factor 1. PFT and MRT loaded positively on factor 2. 2D PTA and 3D VR-PTA both loaded on factors 1 and 2.

Table 2. Principle component analysis

Task	Factor	
	1	2
Distance (Reversed)	**0.78**	-0.08
IPDT	**0.70**	0.11
PDT	**0.70**	0.23
PFT	0.19	**0.81**
MRT	-0.22	**0.77**
2D PTA	**0.39**	**0.68**
3D VR-PTA	**0.53**	**0.55**

PCA on both accuracy and efficiency measures revealed two factors with Eigen values greater than 1. Measures of navigation performance loaded on factor 1, measures of allocentric ability (PFT and MRT) loaded on factor 2, while 2D PTA and 3D VR-PTA loaded on both factors 1 and 2. These two factors accounted for about 60% of the variance.

Discussion of Experiment 2

The first factor was identified as the egocentric perspective-taking factor, since both tests of egocentric perspective taking (2D PTA and 3D VR-PTA) loaded on this factor. The second factor was identified as the allocentric transformation factor, since both measures of allocentric transformation ability (PFT and MRT) loaded on the second factor. All three measures of navigational performance loaded on the perspective taking factor but not the allocentric factor. It means that our measures of navigational ability are related to egocentric perspective taking but not allocentric transformation ability. This is consistent with present literature that informs us that real world navigation requires a different set of abilities apart from those measured by PFT and MRT (Kozhevnikov et al., 2006). Interestingly, 2D PTA and 3D VR-PTA tasks loaded on both factors, which suggests that while they were designed to measure egocentric transformation ability, some participants might still be using allocentric strategies to perform the tasks. However, as predicted, only tests of perspective taking (2D PTA and 3D VR-PTA), and not tests measuring allocentric ability (PFT and MRT), loaded on the same factor as navigational performance.

CONCLUSIONS

An immersive 3D VR-PTA task was successfully designed as a novel diagnostic tool to assess egocentric spatial ability, and its construct (internal) and predictive (external) validities were examined. The results of the experiments revealed that immersive environment itself is a crucial factor to measure accurately egocentric spatial ability.

Furthermore, our findings suggest that this novel immersive 3D VR- PTA task could be the best measure of egocentric spatial ability among currently available instruments. The results also indicate that immersive 3D VR-PTA is the best predictor of large-scale navigational performance within a 3D space followed by 2D PTA, while all allocentric spatial ability tasks do not predict real world navigational performance.

This research has significant theoretical and practical applications such as developing models of transfer of spatial information embedded in egocentric and allocentric processing frames, the further development of unique measures of egocentric and allocentric spatial ability tests suitable for personnel selection in different professional fields.

One of the limitations of this research is its relatively small sample size. However, our results provide strong evidence that 3D PTA is a reliable and valid measure of egocentric spatial ability. Utilizing this diagnostic tool could ultimately provide the capability to profile/screen individuals for professional aptitude in advance of training successful navigation in large- and medium-scale (vista) 3D space for the professions that require high navigational abilities, such as astronautics, air piloting, UAV and other teleoperation, robotics, dentistry, surgery, etc. In addition to its use as an assessment tool, since it engages egocentric representational system and provides constant feedback in 3D space, it is very promising for training purposes as well via this tool's potential to improve navigation task performance by effective use of immersive virtual environment to organize a navigable 3D tasks and transfer of training to real-world tasks.

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REFERENCES

Allen, G. L., Kirasic, K. C., Dobson, S. H, Long, R. G., & Beck, S. (1996). Predicting environmental learning from spatial abilities: an indirect route. *Intelligence*, 22, 327–355.

Carroll, J.B. (1993), Human cognitive abilities: A survey of factor-analytical studies. Cambridge University Press.

Easton, R. D., & Sholl, M. J. (1995). Object-array structure, frames of reference, and retrieval of spatial knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*, 483-500.

Ekstrom, R. B., French, J. W., & Harman, H. H. (1976). *Manual for kit of factor-referenced cognitive tests*. Educational Testing Service: Princeton, New Jersey.

Hegarty, M., Richardson, A. E., Montello, D. R., Lovelace, K., & Subbiah, I. (2002). Development of a self-report measure of environmental spatial ability. *Intelligence, 30*, 425–447.

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence*, 32, 175–191.

Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence, 34*, 151–176.

Hintzman, D.L., O'Dell, C.S., & Arndt, D.R. (1981). Orientation in cognitive maps. *Cognitive Psychology, 13*, 149-206.

Höffler, T. N. (2010). Spatial ability: Its influence on learning with visualizations: a Meta- analytic review. *Educational Psychology Review*, 22, (3), 245-269.

Klatzky, R. L. (1998). Allocentric and egocentric spatial representations: definition, distinctions, and interconnections. In spatial Cognition (pp. 1-7). Springer: berlin. Heldelberg.

Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition, 29*(5), 745-756.

Kozhevnikov, M., Motes, M. A., Rasch, B., & Blajenkova, O. (2006). Perspective-Taking vs. Mental Rotation Transformations and How They Predict Spatial Navigation Performance. *Applied Cognitive Psychology, 20*, 397-417.

Kozhevnikov, M., Motes, M. A., & Hegarty, M. (2007). Spatial visualization in physics problem solving. *Cognitive Science: A Multidisciplinary Journal, 31*, 549-579.

Kozhevnikov, M., & Garcia, A. (2011). Visual-Spatial Learning and Training in Collaborative Design in Virtual Environments. In X. Wang, & J. Jen-Hung (Eds.), Collaborative design in virtual environments.

Kozhevnikov, M., Schloerb, D. W., Blazhenkova, O., Koo, S., Karimbux, N., Donoff, R., & Salcedo, J. (2013). Egocentric versus allocentric spatial ability in dentistry and haptic virtual reality training. Applied Cognitive Psychology, 27, 373-383.

Kozhevnikov, M., & Olmedo, E. (In Preparation). The role of egocentric abilities in drilling performance pf aerospace technicians. The manuscript will be submitted to the International Journal of Human- Computer Interaction.

Menchaca-Brandan, M., Liu, A. M., Oman, C. M., & Natapoff, A. (2007). Influence of perspective-taking and mental rotation abilities in space teleoperation. *2nd ACM/IEEE Conference on Human-Robot Interaction* (HRI 07), Washington, DC.

Pausch, R., Proffitt, D., & Williams, G. (1997). Quantifying immersion in virtual reality. In: Proceedings of the 24th annual conference on Computer graphics and interactive techniques (pp. 13-18). ACM Press/Addison Wesley Publishing Co

Rieser, J: 1989, Access to knowledge of spatial structure at novel points of observation, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 1157-1165.

Shelton, A.L., & McNamara, T.P. (1997). Multiple views of spatial memory. *Psychonomic Bulletin & Review*, 4, 102-106.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*(3972), 701-703.

Thorndyke, P W., & Goldin, S E. (1983). Spatial learning and reasoning skills. In spatial orientation (pp. 195-217). Springer, Boston, MA.

Uttal, D. H., Miller, D. I., & Newcombe, N. S. (2013). Exploring and enhancing spatial thinking links to achievement in Science, Technology, Engineering, and Mathematics. Current Directions in Psychological Science, 22, 367-373.

Wang, L., Cohen, A.S., & Carr, (2014). Spatial ability and two scales of representation a meta-analysis. *Learning and individual Differences,* 36, 140-144.

Wolbers, T., & Wierner, J. M. (2014). Challenge for identifying the neural mechanisms that support spatial navigation. The impact of spatial sale. Frontier in Human Neuroscience. 8, https://www.ncbi.nlm.nih.gov/pubmed/25140139.

WorldViz. (2007). Vizard VR Toolkit R3. Available at: http://www.worldviz. com/products/vizard4/index.html

Wraga, M., Creem, S. H., & Profitt, D. R (2000).Updating displays after imagined object and viewer rotations. *Journal of Experimental* Psychology: Learning, Memory& Cognition, 26, 151-168.

Wu, H. K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education*, 88, 465- 492.

Zhong, J. Y., & Kozhevnikov, M. (2016). Relating allocentric and egocentric survey-based representations to the self-reported use of a navigation strategy of egocentric spatial updating. *Journal of Environmental Psychology*, 46, 154–175.