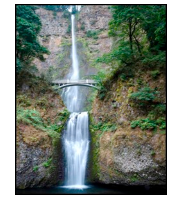
Journal of Environmental Psychology 64 (2019) 12–20

Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.elsevier.com/locate/jep



GPS use negatively affects environmental learning through spatial transformation abilities

Ian T. Ruginski[a,b,*], Sarah H. Creem-Regehr[a], Jeanine K. Stefanucci[a], Elizabeth Cashdan[b]

[a] *University of Utah, Department of Psychology, United States*
[b] *University of Utah, Department of Anthropology, United States*

ARTICLE INFO

Handling editor: Leila Scannell

Keywords:
Spatial cognition
Navigation
GPS use
Spatial abilities
Geospatial technology
Environmental learning

ABSTRACT

Research has established that GPS use negatively affects environmental learning and navigation in laboratory studies. Furthermore, the ability to mentally rotate objects and imagine locations from other perspectives (both known as spatial transformations) is positively related to environmental learning. Using previously validated spatial transformation and environmental learning tasks, the current study assessed a theoretical model where long-term GPS use is associated with worse mental rotation and perspective-taking spatial transformation abilities, which then predicts decreased ability to learn novel environments. We expected this prediction to hold even after controlling for self-reported navigation ability, which is also associated with better spatial transformation and environmental learning capabilities. We found that mental rotation and perspective-taking ability fully account for the effect of GPS use on learning of a virtual environment. This relationship remained after controlling for existing navigation ability. Specifically, GPS use is negatively associated with perspective-taking indirectly through mental rotation; we propose that GPS use affects the transformation ability common to mental rotation and perspective-taking.

1. Introduction

GPS use is an aspect of navigation experience that has recently become common in industrialized societies, yet little is known about the relationship between lifetime variation in GPS use and spatial abilities. Laboratory studies have shown that GPS use reduces navigation efficiency and accuracy (Gardony, Brunyé, & Taylor, 2015; Ishikawa, Fujiwara, Imai, & Okabe, 2008). Similarly, GPS use impairs spatial memory for environments when used to aid navigation (Hejtmánek, Oravcová, Motýl, Horáček, & Fajnerová, 2018; Münzer, Zimmer, Schwalm, Baus, & Aslan, 2006; Parush, Ahuvia, & Erev, 2007; Willis, Holscher, Wilberz, & Li, 2009; c.f. Sönmez & Önder, 2019). Much of this work argues that GPS use disrupts environmental learning via attentional and/or working memory mechanisms. For example, navigators who use GPS may pay more attention to the device than virtual environments (Hejtmánek et al., 2018), have difficulty learning due to divided attention (Gardony et al., 2015), or do not encode environments into spatial working memory (Münzer et al., 2006). This research has established that GPS use negatively affects environmental learning using many different methodologies, such as eye-tracking (e.g. Hejtmánek et al., 2018) and comparison of distracting auditory and visual cues (e.g. Münzer et al., 2006) in both real and virtual environments. However, the cognitive mechanisms by which *everyday* GPS use (as opposed to most of the previous work that manipulated GPS use in a lab setting) adversely affects environmental learning are still unclear. To examine this question, we measured GPS use, visual environmental learning (i.e., navigation without body-based cues) in a virtual landscape, and two spatial abilities that might mediate this relationship: mental rotation and perspective-taking.

Mental rotation (Vandenberg & Kuse, 1978) and perspective-taking (Kozhevnikov & Hegarty, 2001) are two widely studied cognitive processes that involve different types of imagined spatial transformations. Perspective-taking can be defined as one's ability to imagine oneself in another position in the environment (involving an egocentric spatial transformation), while mental rotation can be defined as one's ability to imagine an object in another position in the environment, thereby involving an object-based spatial transformation (Newcombe & Shipley, 2015). These two spatial abilities are of relevance to navigation for a few reasons. First, these abilities are expected to play a role in environmental learning, as environmental learning involves continual updating of one's location in the environment and the spatial relationship of oneself to landmarks in the environment, as well as the spatial relationship between landmarks in the environment (Wolbers & Hegarty, 2010; Wolbers & Wiener, 2014). Similarly, tests of spatial

* Corresponding author. 380 S. 1530 E., Room 502, Department of Psychology, University of Utah, Salt Lake City, UT, 84112, United States.
E-mail address: Ian.Ruginski@gmail.com (I.T. Ruginski).

https://doi.org/10.1016/j.jenvp.2019.05.001
Received 11 December 2018; Received in revised form 2 May 2019; Accepted 2 May 2019
Available online 04 May 2019

memory for learned environments often require imagining oneself in locations previously visited from a different perspective than is currently viewable in the environment (egocentric transformation), or from an object-centered viewpoint such as marking locations on a map. Previous work has shown that both mental rotation and perspective-taking abilities correlate with measures of environmental learning, such as pointing to previously visited landmarks (Fields & Shelton, 2006; Kozhevnikov, Motes, Rasch, & Blajenkova, 2006; Muffato, Toffalini, Meneghetti, Carbone, & De Beni, 2017). Mental rotation also predicts real-world orienteering ability (Malinowski, 2001; Silverman et al., 2000), as well as higher levels of geographic knowledge for the locally traversed environment (Dabbs, Chang, Strong, & Milun, 1998).

Further, these spatial transformation abilities are strongly predictive of environmental learning, even after controlling for self-reported sense of direction and verbal intelligence (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). In a meta-analysis, seven studies with a total of 662 participants reported an unweighted average correlation of 0.26 between small-scale spatial abilities (such as perspective-taking and the embedded figures test) and spatial knowledge acquisition in virtual environments (Hegarty & Waller, 2005). However, there is also contradictory evidence as to the role and relative importance of mental rotation and perspective-taking in environmental learning during navigation. Kozhevnikov et al. (2006) found that perspective-taking uniquely predicted environmental learning above and beyond mental rotation ability, even though the two transformation abilities were highly correlated. The self-to-object spatial updating processes unique to perspective-taking were considered essential for encoding environments effectively. Others have tested mediation models, arguing that the imagined spatial transformation processes in mental rotation support navigation indirectly through better imagined perspective-taking skills. Results have been mixed; Hegarty et al. (2006) found that perspective-taking does not mediate the effect of spatial abilities like mental rotation on environmental learning, whereas Allen, Kirasic, Dobson, Long, and Beck (1996) found that perspective-taking mediates the effect of mental rotation on environmental learning. Including both of these spatial transformation tasks will allow us to address these previously conflicting results (see Fig. 1).

The primary goal of the current study is twofold. First, we sought to answer the question of whether and how everyday GPS use affects different types of spatial transformation and environmental learning abilities, even after accounting for existing navigation ability. Second, we sought to clarify the relations between spatial transformation and environmental learning abilities. To address these questions, we asked individuals to complete two types of imagined transformation tasks and a virtual environmental learning task. GPS use and navigation ability (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002) were each assessed by self-report.

While using GPS may have the immediate benefits of accurately arriving at a given location, we suggest that those who navigate often with GPS perform imagined transformations in navigation to a lesser extent, negatively affecting their long-term spatial transformation abilities (see Fig. 1). In contrast, those who navigate without GPS spend more time honing these spatial skills and benefit from the “desirable difficulties” (Bjork, 1994) of navigating on their own. Based on previous work (e.g., Hegarty et al., 2006; Muffato et al., 2017), we expected that the increased spatial transformation skills across participants would translate to better ability to learn and remember newly encountered environments, as measured by higher performance on validated virtual environmental learning tasks in the laboratory (e.g., Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014). Importantly, the study evaluated the hypothesis that GPS use is associated with virtual environmental learning through mental rotation and perspective-taking even after controlling for navigation ability, which is known to influence spatial abilities and navigation (Hegarty et al., 2006; Pazzaglia & Taylor, 2007; Weisberg et al., 2014).

To our knowledge, only one study has assessed the effects of navigation ability, mental rotation ability, and GPS use in everyday life on the ability to learn environments. Ishikawa (2019) found that navigation ability, mental rotation ability, and experience with GPS contributed independently to wayfinding in a real environment. We view our work as complementary to Ishikawa (2019), with three important distinctions. First, individuals were not assisted with tools for wayfinding (maps or GPS) during the experiment as in Ishikawa's (2019) study. Second, individuals learned a virtual environment, rather than a

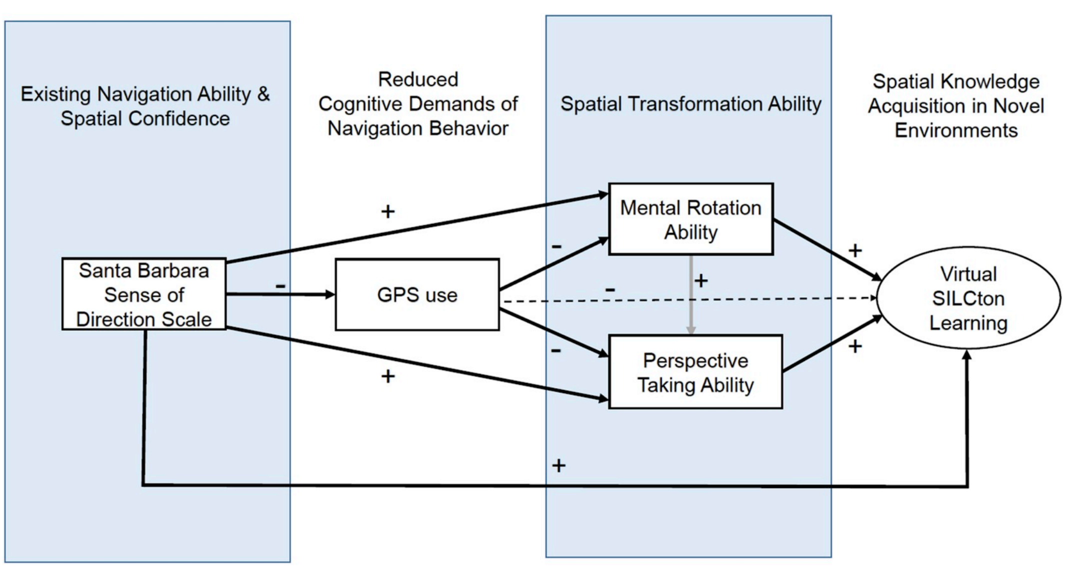


Fig. 1. Conceptual model demonstrating the theory driving the research questions of the current study. Positive (+) and negative (−) signs above each path coefficient indicate the predicted direction of association for each variable pair relationship. GPS use is expected to be associated with lesser spatial transformation skills. It is expected that diminished transformation skills will then be associated with an impaired ability to learn newly encountered virtual environments (environmental learning). The dashed line indicates a direct path that we expect to be accounted for by the spatial transformation abilities mediators. Navigation ability is considered as a potential confounding factor to the effects of GPS usage on spatial abilities. It is unknown whether the relationship between mental rotation and environmental learning is mediated by perspective-taking (grey path), which is assessed in the current study by comparing competing models.

real world environment. Third, we included an additional measure of egocentric spatial transformation ability (perspective-taking, Kozhevnikov & Hegarty, 2001), which is known to be predictive of environmental learning (Kozhevnikov et al., 2006), but dissociable from mental rotation-based spatial transformations (Hegarty et al., 2006; Zacks, Mires, Tversky, & Hazeltine, 2000). To better understand which spatial transformation processes are affected by GPS use, our study also sought to evaluate whether GPS use affects perspective taking only, mental rotation only, or both skills simultaneously. Overall, this work addresses whether the growing use of GPS technologies could affect spatial cognitive abilities above and beyond existing navigation skill, potentially laying the groundwork for future work testing interventions that could affect spatial abilities throughout the lifespan.

2. Material and methods

2.1. Participants & sample size

Participants were 201 students attending the University of Utah aged 18 to 47, with a mean age of 21.3 ($SD = 4.5$). 113 identified as female, 86 as male, and 2 as androgynous. One participant did not follow directions for the perspective-taking task. This participant's perspective taking data were considered missing in analyses (see section 3.1.1 for more on handling of missing data). A sample size of 201 was used to approach Kline's (2015) recommended minimum 10:1 parameter:sample size ratio for adequate power, as there will be 21 free parameters in the most complex model evaluated. In addition, the sample size was sufficiently powered (greater than 0.8, which occurs at a sample size of 148 when using bias-corrected bootstrapping) to detect a modest (mean $\tau' = 0.067$) indirect effect (Fritz & MacKinnon, 2007).

2.2. Experimental design and measures

2.2.1. Virtual SILCton

The virtual SILCton task was adopted from Weisberg et al. (2014) to assess environmental learning. Using a keyboard and mouse to navigate, participants first learned two routes through a virtual college campus environment (see Fig. 2).

Each route featured four landmarks, which were college campus buildings located at Temple University (e.g., Batty House, an admissions building). Participants followed red arrows indicating a route and were not allowed to diverge from the paved roads in the environment. Floating diamonds indicated that an important landmark was nearby and each of these landmarks was labeled with a clearly visible sign. After learning routes with landmarks, participants learned two routes that connected the landmarked routes. Then participants completed pointing, distance estimation, and cognitive map tasks, which were used as dependent measures to compose the latent environmental learning factor (Hegarty et al., 2006).

The pointing task was completed from an egocentric perspective in front of each landmark in the environment. Participants controlled a crosshair appearing in the center of the screen using the mouse and clicked to record their response. 28 trials involved pointing from a landmark to another landmark that was encountered on the other route traversed in the environment and were averaged to create the between-route pointing variable (angular degrees of error). 28 trials involved pointing from a landmark to another landmark that was encountered on the same route and were averaged to create the within-route pointing variable (angular degrees of error).

For the distance estimation task, individuals adjusted sliders for the distances between each landmark in the environment. Individuals were instructed that “the top slider bar shows the true distance between the

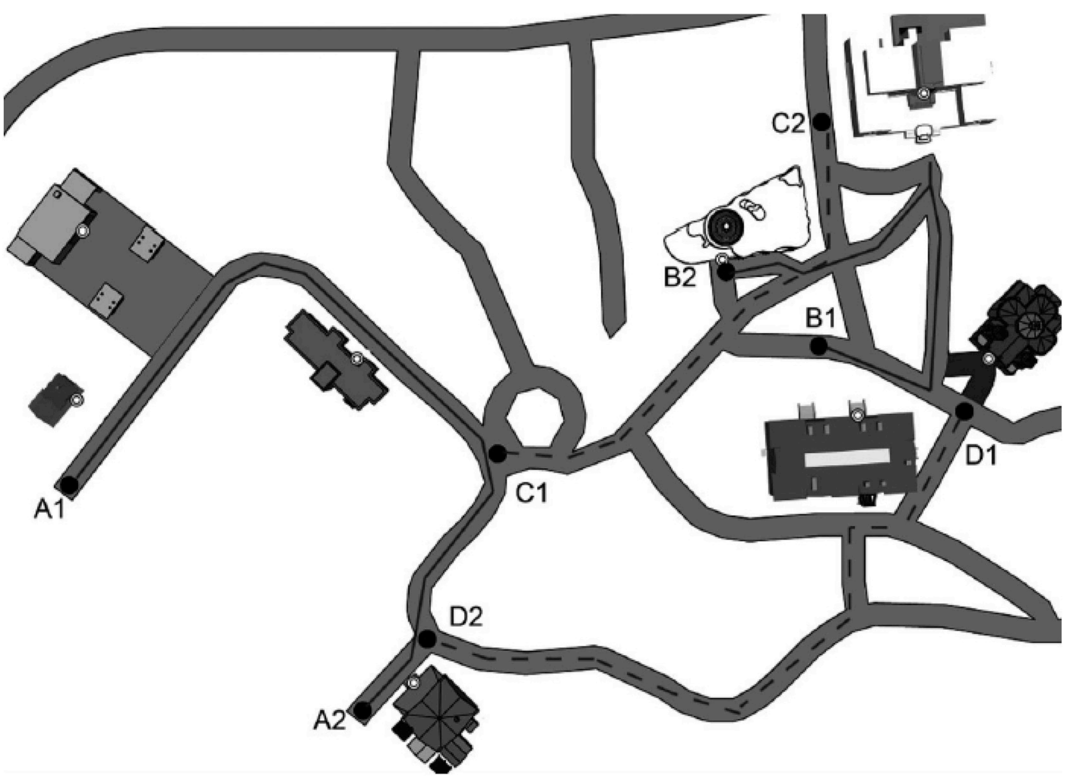


Fig. 2. Overhead view of virtual SILCton environment. Two routes learned in separate parts of the environment are depicted, each featuring four landmarks (A1 to A2 and B1 to B2; solid lines). After learning routes featuring landmarks, participants learned two routes connecting the previously explored portions of the environment (C1 to C2 and D1 to D2; dashed lines). Participants never saw this view of the environment. However, for the cognitive map-building task, participants placed landmarks on a blank canvas (no roads featured) from this perspective. Figure adopted from Weisberg et al. (2014).

two buildings specified. Drag the remaining six slider bars to indicate the distance between the other pairs. The longest distance in each set (page) will fill the entire slider." These instructions provided a relative "measuring stick" to complete distance estimations. In total, participants completed 48 trials (eight landmarks with six estimations per landmark). All trials were averaged prior to analyses and are in the metric of "Unity meters", which approximate one real-world meter.

For the cognitive map task, individuals were shown a blank rectangle "map" and provided with 2-D representations of each landmark encountered in the environment from a birds-eye view perspective. If participants hovered their mouse over the 2-D representation of a landmark, they were provided with an image of that landmark as it was seen in the environment (from an egocentric perspective). Participants placed all eight landmarks on the map for a total of eight trials. Variance captured by individuals' cognitive maps (r^2) was then calculated using bi-dimensional regression (Friedman & Kohler, 2003). Participants were allowed as much time as needed to complete the pointing, distance estimation, and cognitive map tasks.

2.2.2. Vandenberg & Kuse mental rotation task

We utilized a computerized mental rotation task developed by Weisberg et al. (2014). Individuals had 3 min to complete each 10-trial section of the test. For a single trial, individuals were asked to select two of four images that matched a target image by imagining the rotation of the blocks. Scoring used a psychometric framework, such that individuals were rewarded for true positives and true negatives (+2), but penalized for false positives and false negatives (−2). Non-answers were scored a 0. Because two answers were correct on each trial and there were 20 total trials, the maximum possible score was +80 and the minimum was −80.

2.2.3. Kozhevnikov & Hegarty perspective-taking task

To measure perspective-taking, we utilized a paper and pencil version of the spatial orientation task (SOT) as detailed in Kozhevnikov and Hegarty (2001). The test consists of 12 items where individuals are asked to perform imagined pointing to different objects on a two-dimensional map-like array of objects. Individuals were allotted five minutes to answer all 12 questions, and all tests were scored by hand using a protractor. If individuals did not have sufficient time to answer a question, a score of 90 degrees of error was assigned for that question, consistent with chance performance. All errors that exceeded 180° were subtracted from 360 prior to analysis to determine the smallest deviation possible, as the angular deviation between two angles cannot exceed 180°.

2.2.4. GPS & survey questions

The GPS question asked, "About how often do you use a GPS for navigation when traveling?" Individuals responded on a 5-point Likert scale with one indicating never, two indicating rarely, three indicating sometimes, four indicating often, and five indicating always.

Individuals were also asked to answer questions about mobility, or travel frequency. One item assessing daily travel asked, "On days when you work or go to school, about how many different places do you go to, on a typical day? (do not count as "different" other buildings or rooms within the same workplace, school, or marketplace)." This question was scaled from one to seven, with each Likert scale answer corresponding to zero places, one place, two places, three places, four places, five to six places, and seven or more places, respectively. Another item assessing monthly travel frequency asked, "In the month when you traveled the most, about how many different cities, towns, or villages did you spend the night in?" A final question assessing number of places visited in Utah (adopted from Padilla et al., 2017) was asked to measure longer-term, lifetime mobility. These questions were then coded into total distance traveled to places visited in Utah (calculated as the distance from the center of the University of Utah's campus to each place visited). The places visited in Utah question was only completed by a subsample (n = 154) of the study due to procedural errors.

The Santa Barbara Sense of Direction questionnaire (SBSOD; Hegarty et al., 2002) was also given, and data on basic demographic variables were collected.

2.3. Materials

The experiment was run on a Dell computer with four Intel Core i7-4770 3.40 GHz processors, 16 GB of RAM, and Windows 7 as its operating system. The computer was connected to a 1920 × 1200 resolution, 24-inch Dell LCD monitor. The display was updated at a frame rate of 60 Hz.

2.4. Procedure

Prior to conducting research, the University of Utah Institutional Review Board (IRB) reviewed and approved the current study as adhering to ethical guidelines. Upon arriving to the study, participants provided informed consent via an IRB-approved consent form. Participants first completed the Weisberg et al. (2014) virtual SILCton learning and memory task (approximately 25–45 min, described in section 2.2.1). Participants then completed a digital version of the Vandenberg and Kuse (1978) mental rotation task, the Santa Barbara Spatial Orientation perspective-taking task (Kozhevnikov & Hegarty, 2001), and a self-report survey (described in section 2.2.4), in that order.

3. Results

3.1. Data analysis

Prior to analyses, linear regressions were conducted to determine multicollinearity between the perspective-taking and mental rotation spatial transformation variables for the environmental learning outcomes. Although correlation was high between mental rotation and perspective-taking ($r = -0.56, p < .001$), the variance inflation factor between mental rotation and perspective-taking did not exceed 5 ($VIF = 1.39$), and thus was considered non-problematic for further analyses (Cohen, Cohen, West, & Aiken, 2013).

Because the GPS use variable was ordinal, robust maximum likelihood (MLR) was used for structural equation model estimation given the appropriateness of MLR for ordinal data with five or more categories (Rhemtulla, Brosseau-Liard, & Savalei, 2012). All indirect effects reported, however, require bootstrapping to account for non-normality of indirect effect distributions, which uses maximum likelihood estimation (Preacher & Hayes, 2008). Missing data was relatively sparse,[1] and one individual's perspective-taking data was not scored due to a

[1] Multiple steps were taken to assess and handle missing data. First, coverage (proportion of univariate pairwise missingness; Newsom, 2015) was inspected, and we found that data was mostly non-missing, with many coverage levels between variables around 0.99 and the lowest coverage 0.955. We attempted to assess correlations between observed data and missingness, but did not find any significant associations between observed variables (mental rotation, perspective-taking, environmental learning measures) and missingness. This was likely due to a lack of variability, as there were mostly one to two missing values per variable, with seven at most. Due to this, we made the assumption that the data were missing at random (without statistical evidence of associations between observed values and missingness), and given limited missing data, full information maximum likelihood (FIML) was implemented to handle missing data in all structural equation models that did not implement bootstrapping (Newsom, 2015). Bootstrapped models utilized list-wise deletion due to limitations of the lavaan version 0.6–3 program (Oberski, 2014), but did not appear to significantly deviate from the models that implemented FIML, likely due to limited, nonsystematic missingness.

Table 1
Univariate correlations between study measures.

	1	2	3	4	5	6	7	8	9	10
1. Navigation Ability	–									
2. GPS Use	-.36**	–								
3. Mental Rotation	.21**	-.32**	–							
4. Perspective Taking	.27**	-.26**	.53**	–						
5. Within Pointing	.34**	-.20**	.23**	.26**	–					
6. Between Pointing	.25**	-.08	.12	.14*	.55**	–				
7. Distance	.26**	-.21**	.24**	.29**	.58**	.47**	–			
8. Cog Map r^2	.20*	-.16*	.20*	.23**	.56**	.50**	.59**	–		
9. Daily Travel	.10	-.08	-.03	-.04	-.14*	-.03	-.01	-.10	–	
10. Monthly Travel	.15*	.00	.02	.08	.03	.02	-.03	-.04	.05	–
11. Utah Distance	.12	- .05	.14	.05	.07	-.03	-.01	-.05	.09	.17*

Note. All variables have been transformed so that higher scores indicate more ability, use, or travel. * indicates $p < .05$. ** indicates $p < .01$.

Table 2
Descriptive statistics for all study measures.

Measure	Mean	SD	Skewness	Kurtosis
Navigation Ability	3.8	1.0	−0.3	2.8
GPS Use	3.4	0.9	−0.2	2.7
Mental Rotation	30.5	21.8	0.03	2.6
Perspective Taking	−35.0	23.0	0.9	2.9
Within Pointing	−27.8	12.2	0.4	2.8
Between Pointing	−45.9	12.8	−0.6	2.7
Distance	−134.4	52.5	1.3	5.6
Cog Map r^2	0.49	0.26	0.1	1.9
Daily Travel	3.5	1.5	0.4	2.8
Monthly Travel	3.5	1.7	1.3	4.2
Utah Distance	1576	956	0.3	2.2

failure to follow instructions. Prior to analyses, all error score variables (pointing angular error, distance estimation error, perspective-taking angular error) were reverse coded to make higher values correspond to better ability in our models.

3.2. Preliminary analyses & descriptive statistics

Prior to running structural equation models, we determined if mediation was viable and if GPS use uniquely predicted spatial abilities scores above and beyond the daily travel, monthly travel, and distance to places visited in Utah questions (see Tables 1 and 2 for complete zero-order correlations and descriptive statistics, respectively). Controlling for all travel frequency measures, preliminary analyses revealed a direct effect of GPS use on environmental learning ability ($B = -0.22$, $\beta = -0.19$, $SE = 0.09$, $p = .01$), mental rotation ability ($B = -7.32$, $\beta = -0.30$, $SE = 1.85$, $p < .001$), and perspective-taking ($B = -6.01$, $\beta = -0.24$, $SE = 1.86$, $p < .001$). Further, neither daily travel ($B = 0.02$, $\beta = 0.02$, $SE = 0.05$, $p = .78$), monthly travel ($B = -0.001$, $\beta = -0.001$, $SE = 0.04$, $p = .98$), or total distance to places visited in Utah ($B = -0.001$, $\beta = -0.05$, $SE = 0.0001$, $p = .52$) questions predicted GPS use. These results suggest that GPS use was not strongly influenced by travel frequency, and that GPS use was uniquely important to spatial transformation abilities and environmental learning regardless of travel frequency.

3.3. Theoretical models of GPS use and spatial abilities

3.3.1. Environmental learning latent factor measurement model

A structural equation model was first fit to the measurement portion of the model that was expected based on past research: a latent visual environmental learning factor (Hegarty et al., 2006). This factor was composed of four measures, including between- and within-route pointing errors (Weisberg et al., 2014), a cognitive mapping measure (r^2 measured by bi-dimensional regression; Friedman & Kohler, 2003), and a distance estimation measure. Maximum likelihood estimation was used for this model as these outcomes were roughly normally distributed. As measures varied in terms of scale, a factor variance identification approach was used to identify the model, where the variance of the latent visual environmental learning factor was fixed to 1 (Newsom, 2015).

Model fit was relatively good across multiple indices ($RMSEA = 0.058$, $CFI = 0.995$, $TLI = 0.985$, $SRMR = 0.016$, $\chi^2 = 3.34(2)$, $p = .19$). Between-route pointing error ($B = 8.83$, $\beta = 0.69$, $SE = 0.87$, $p < .001$), within-route pointing error ($B = 9.24$, $\beta = 0.76$, $SE = 0.81$, $p < .001$), r^2 variance captured by cognitive maps ($B = -0.21$, $\beta = -0.78$, $SE = 0.02$, $p < .001$), and distance estimation error ($B = 37.17$, $\beta = 0.71$, $SE = 3.54$, $p < .001$) all loaded onto the latent factor. Given that all observed variables loaded onto the latent environmental learning factor and model fit was good, this factor was retained as an outcome for the full theoretical models tested in sections 3.3.2 and 3.3.3.

3.3.2. Mediation model with no relationship between mental rotation and perspective-taking

We found that model fit was below adequate according to multiple indices (Robust $RMSEA = 0.133$, Robust $CFI = 0.875$, robust $TLI = 0.767$, $SRMR = 0.074$, $\chi^2 = 72.03$ (15), $p < .001$). Given good fit from the measurement portion of the model reported in section 3.3.1, poor fit suggests that the majority of misfit originates from the structural (regression) portion of this model. Results of the model are presented in Fig. 3.

3.3.3. Alternative mediation model with a direct relationship between mental rotation and perspective-taking

The previous model was compared with a model that allowed mental rotation to predict perspective-taking. The following results are for the model estimated using robust maximum likelihood estimation (see Fig. 4). Model fit was good overall according to multiple indices (Robust $RMSEA = 0.038$, Robust $CFI = 0.991$, Robust $TLI = 0.981$, $SRMR = 0.032$, $\chi^2 = 18.20(14)$, $p = .19$).

We compared the model reported in section 3.3.2 and the current model using a Satorra-Bentler adjusted chi-square difference test for models estimated using robust maximum likelihood estimation (Satorra & Bentler, 2001). We found that the more saturated model estimating a regression path between mental rotation and perspective-taking fit the data better than the less saturated model with this parameter fixed to 0 (χ^2 difference = 61.96(1), $p < .001$). This suggests that the more saturated model where perspective-taking mediates the direct effect of mental rotation on environmental learning more accurately captures the relationship between GPS use, spatial transformation skills, and environmental learning ability.

To evaluate evidence of mediation, indirect effects were computed using bootstrapped bias corrected 95% confidence intervals in R using lavaan version 0.6–3. This method was selected to account for non-normality and subsequent bias in bootstrapped indirect effects (see

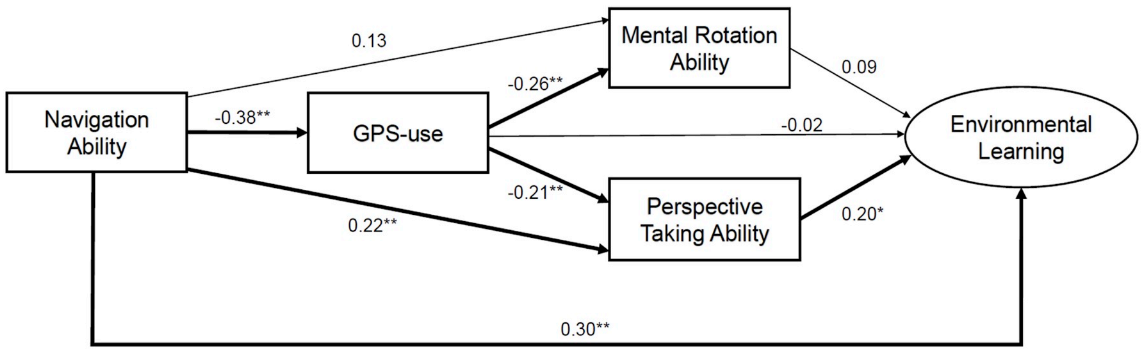


Fig. 3. Model 1, in which no relationship was allowed to exist between mental rotation and perspective-taking (this regression path was constrained to zero during model estimation). Standardized betas are presented for each regression path. **indicates $p < .01$, * indicates $p < .05$. Significant paths ($p < .05$) are bolded for emphasis.

MacKinnon, Lockwood, & Williams, 2004). In addition, we included the potential confounding variable of navigation ability as measured by SBSOD in our structural equation model. Accounting for this confound fulfills assumptions in mediation analysis and reduces bias in estimated direct and indirect effects (see VanderWeele, 2016, for more on assumptions of mediation). In total, five indirect effects were bootstrapped (see Table 3).

The first effect tested whether mental rotation ability alone mediated the direct effect of GPS use on environmental learning ability. The second tested whether perspective-taking alone mediated the direct effect of GPS use on environmental learning. We found that neither perspective-taking nor mental mediated the direct effect of GPS use on environmental learning ability alone.

However, we found evidence of two-mediator mediation, where mental rotation and perspective-taking spatial transformation abilities together mediate the effect of GPS use on environmental learning ability, even after controlling for the confound of navigation ability. This two-mediator mediation was consistent with two single-mediator indirect effects also present in the model. Mental rotation ability fully mediated the direct effect of GPS use on perspective-taking, and perspective-taking fully mediated the effect of mental rotation on environmental learning.

Second, in order to further determine how GPS use and navigation ability differed in their effects on spatial transformation and environmental learning abilities, we explicitly compared effects in the model using bootstrapped difference tests (see Table 4). Navigation ability accounted for more variance in perspective-taking ability than GPS use did as assessed both indirectly through mental rotation ability and directly. Further, navigation ability was more strongly associated with environmental learning than GPS use was, as assessed indirectly through mental rotation and perspective taking ability. However, GPS use contributed more to mental rotation ability than navigation ability did.

Table 3
Estimates of bootstrapped indirect effects testing for mediation.

Indirect Effect	*B*	*β*	*SE*	*Lower CI*	*Upper CI*
GPS → MRT → EL	−0.03	−0.03	0.03	−0.12	0.02
GPS → PT → EL	−0.02	−0.02	0.02	−0.09	0.01
GPS → MRT → PT	−2.91	−0.12	0.99	−4.99	−1.08
MRT → PT → EL	0.01	0.09	0.002	0.001	0.010
GPS → MRT → PT → EL	−0.03	−0.02	0.02	−0.08	−0.01

Note. Bootstrapped bias-corrected 95% confidence intervals were used to determine if an indirect effect was present. If the 95% confidence interval does not include zero, this suggests evidence of an indirect effect. If the indirect effect column is bolded, the direct effect of the first predictor was completely accounted for, consistent with full mediation. Indirect effects with plain text indicate no evidence of mediation (abbreviations: PT, perspective-taking; MRT, mental rotation; EL, environmental learning). B refers to unstandardized effect coefficients, while β refers to standardized effect coefficients.

Table 4
Differences between pathways tested using bootstrapping.

Effects of navigation ability	Effects of GPS use	*B*	*β*	*SE*	*p-value*
SBSOD → PT	GPS → MRT → PT	6.83	0.29	1.61	< .001
SBSOD → PT	GPS → PT	5.57	0.24	1.99	0.005
SBSOD → MRT	**GPS → MRT**	−8.76	−0.29	1.89	< .001
SBSOD → EL	GPS → MRT → PT → EL	0.39	0.34	0.1	< .001

Note. The effects of navigation ability and GPS use columns explicitly show the paths being compared. A bolded column indicates that effect on the named outcome was greater than the opposing column. Both direct and indirect effects were compared (abbreviations: PT, perspective-taking; MRT, mental rotation; EL, environmental learning). *B* refers to unstandardized effect coefficients, while *β* refers to standardized effect coefficients.

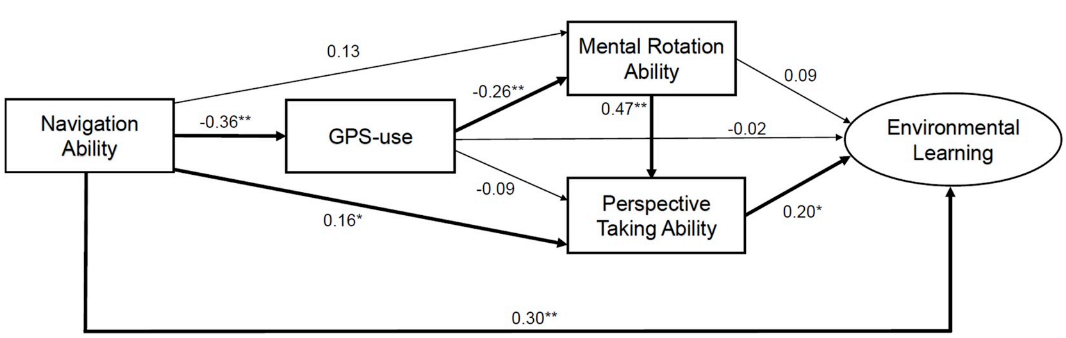


Fig. 4. Model 2, in which mental rotation ability was allowed to predict perspective-taking ability. All other paths in Model 1 were also included in this model. **indicates $p < .01$, * indicates $p < .05$. Significant paths ($p < .05$) are bolded for emphasis.

Table 5
Gender differences in study measures.

Variable	Men (n = 86)	Women (n = 113)	Mean Difference	Mean Difference *95% CI*	Cohen's d
	Mean (*SD*)	Mean (*SD*)			
Navigation Ability	4.1 (0.9)	3.6 (1.0)	−0.54**	−0.81, −0.27	0.56
GPS Use	3.2 (0.9)	3.5 (0.9)	0.36*	0.11, 0.63	0.39
Mental Rotation	39.5 (21.4)	23.5 (19.6)	−16.0**	−21.9, −10.2	0.79
Perspective Taking	−26.4 (17.9)	−41.4 (21.4)	−14.9**	−8.9, −20.9	0.68
Within Pointing	−24.9 (10.4)	−30.3 (13.0)	−5.4**	−2.1, −8.6	0.45
Between Pointing	−45.3 (13.2)	−46.7 (12.6)	−1.4	−5.1, 2.3	0.11
Distance	−120.0 (42.4)	−146.0 (57.0)	−26.0**	−39.9, −12.1	0.22
Cog Map r^2	0.52 (0.26)	0.47 (0.27)	−0.05	−0.13, 0.03	0.19
Daily Travel	3.6 (1.4)	(3.4 (1.6)	-.13	−0.55, 0.30	0.09
Monthly Travel	3.5 (1.7)	3.3 (1.7)	.21	−0.27, 0.68	0.12
Utah Distance	1697 (1029)	1484 (902)	−212.9	−525.1, 99.2	0.22

Note. All tests were independent samples t-tests (two-tailed) assuming unequal variances amongst groups. ** indicates $p < .001$. * indicates $p < .01$. All variables have been transformed so that higher scores indicate more ability, use, or travel. All differences are women's mean minus men's mean. Two individuals self-identifying as androgynous were not included in these analyses.

3.4. Gender differences

Though not a focus of our study, we also tested for gender differences across study measures in the case that these would be of interest to other spatial abilities researchers considering past gender differences in spatial abilities (e.g. Voyer, Voyer, & Bryden, 1995). Results are reported in Table 5, along with a measure of effect size (Cohen's d, Cohen, 1988). We observed gender differences showing a male advantage in navigation ability, mental rotation, perspective-taking, within-route pointing, and distance estimation, with the largest gender difference being in mental rotation ($p < .001$, $d = 0.79$). Men also reported using GPS devices less than women ($p = .004$, $d = 0.39$).

4. Discussion

Broadly, the current study sought to determine whether and how an emerging and pervasive navigational aid — GPS — affects spatial abilities. Prior work has established that GPS use in the laboratory adversely affects environmental learning and wayfinding outcomes (Gardony et al., 2015; Hejtmánek et al., 2018; Ishikawa et al., 2008). However, it was unclear whether long-term GPS use in everyday life would affect virtual environmental learning in the absence of a direct manipulation. We hypothesized that long-term GPS use would indirectly and negatively affect environmental learning ability through decreased object-based (mental rotation) and egocentric (perspective-taking) spatial transformation abilities, which are known to be associated with environmental learning outcomes (Fields & Shelton, 2006; Kozhevnikov et al., 2006; Muffato et al., 2017).

We found evidence of two-mediator mediation consistent with our hypotheses, where mental rotation and perspective-taking fully mediated the effect of GPS use on environmental learning of a virtual environment. Critically, this relationship remained even while controlling for self-reported navigation ability, suggesting that the effect of GPS use on environmental learning cannot be fully explained by navigation ability (consistent with Ishikawa, 2018). Overall, we view the primary contribution of the work as establishing that GPS use in everyday life affects environmental learning indirectly via differences in spatial transformation processes such as mental rotation and perspective-taking. Our results can only be generalized to visual environmental learning without the proprioceptive and vestibular cues provided through walking and head movements (Chrastil & Warren, 2012), though visual environmental learning is substantially related to real-world environmental learning (Hegarty et al., 2006).

One important limitation of our study is that GPS use was assessed using a single, self-reported question. Although there are likely advantages to using a finer grained measure of GPS use (such as a measure that accounts for hours of use, e.g. Ishikawa, 2019), we did our best to account for potential confounding factors. In preliminary analyses (section 3.2), the effect of GPS use on spatial transformation and environmental learning outcomes remained regardless of individuals' travel frequency, suggesting that GPS use is uniquely associated with spatial outcomes. Nonetheless, the GPS use question may indirectly measure another construct, such as spatial ability or confidence. We anticipated this, and found that the effect of GPS use remained even after accounting for self-reported sense of direction across all study variables. Despite taking these steps, we still view the use of a single, self-reported GPS use measure as a limitation. Future work would benefit from implementing a more thorough GPS use measure that 1) disentangles reason for GPS use and 2) implements multiple measurements of GPS use. In addition, it is important to note that we cannot make causal claims as to the nature of the relationship between GPS use, spatial transformation abilities, and environmental learning, because GPS use was not manipulated over time. Note that a model which switches the ordering of GPS use and spatial abilities (where mental rotation and perspective taking predict GPS-use, which in turn predicts environmental learning ability) has the exact same fit indices as model 2 *(Robust RMSEA* = 0.038*, Robust CFI* = 0.991*, Robust TLI* = 0.981*, SRMR* = 0.032*,* $\chi2 = 18.20(14)$*,* $p = .19$*)*. This alternative model can be viewed in OSF supplementary materials and is demonstrative as to why we did not test models with different orderings, as well as why we cannot claim causality in our study. It could be that more GPS use decreases spatial transformation abilities or that decreases in spatial transformation abilities lead to increased GPS use. GPS use may also decrease environmental learning indirectly through alternative paths not measured in the current study, such as navigational style (Richter, Dara-Abrams, & Raubal, 2010) or human gaze behavior (Brügger, Richter, & Fabrikant, 2019). However, the current results are an informative first step in broadly establishing a negative association between everyday GPS use and environmental learning while also identifying spatial transformation abilities as a potential mediating factor in this relationship.

In past work that manipulated GPS use in the laboratory, researchers have proposed a few alternative explanations as to why GPS use negatively affects environmental learning. These accounts most often claim that GPS use affects environmental learning through changes in spatial attention and/or working memory. For example, navigators pay more attention to the GPS device than the environment (Hejtmánek et al., 2018) or divide their attention between device and environment (Gardony et al., 2015; Willis, Hölscher, Wilbertz, & Li, 2009), impairing learning. Others have argued that using GPS replaces the need for navigators to actively encode the environment into spatial working memory (Münzer et al., 2006; Parush et al., 2007). We view our results as complementary to these accounts, but also providing a different level of explanation. We suggest that when individuals reduce their attention or reliance on environmental features during navigation, the need for imagined spatial transformations also is reduced. Continuous use of GPS may decrease the spatial transformation abilities that would have supported environmental learning without the technology. Spatial transformation abilities may also share other spatial cognitive processes that relate to environmental learning (e.g., spatial working memory; Muffato et al., 2017), suggesting directions for future work that combine examination of effects of GPS use, working memory, and spatial transformations on environmental learning.

Our research also builds on Hegarty et al.'s (2006) model of the positive relationship between spatial transformation and environmental learning abilities, which is supported by previous experimental work (Fields & Shelton, 2006; Kozhevnikov et al., 2006; Muffato et al., 2017). Specifically, in showing that perspective-taking fully mediates the direct effect of mental rotation-like spatial abilities on environmental learning, our result provides a conceptual replication of Allen et al. (1996), but not Hegarty et al. (2006) .[2] This result suggests that perspective-taking plays a critical mediating role between object-based spatial transformations like mental rotation and acquisition of spatial knowledge from novel environments. Self-reported navigation ability also did not predict mental rotation ability in our model, consistent with past work (Hegarty et al., 2002, 2006). We also replicated previously observed gender differences in spatial transformation abilities (Hegarty et al., 2006; Voyer et al., 1995) and environmental learning (Weisberg et al., 2014).

Furthermore, we found that individuals of lower navigation ability use GPS more often than those of higher ability ($\beta = -0.38$). Navigation ability ($\beta = 0.30$) also contributed significantly to environmental learning, as expected based on past work in both real (Burte & Montello, 2017) and virtual (Pazzaglia & Taylor, 2007; Weisberg et al., 2014; Weisberg & Newcombe, 2016) environments. Despite these two results, however, we still observed that GPS use indirectly affects environmental learning above and beyond the strong effect of navigation ability. So what is it about GPS use that contributes to decreased spatial transformation abilities and, in turn, to worse environmental learning? Interestingly, we found that GPS use was more negatively associated with mental rotation ability ($\beta = -0.26$) than with perspective-taking ability ($\beta = -0.09$), and GPS use only affected perspective-taking indirectly through mental rotation ($\beta = -0.12$). These differences in effects point to a diverging influence of GPS use dependent on *type* (object-based vs. egocentric) of spatial transformation.

GPS use might relate to mental rotation more than perspective-taking due to the different spatial processes involved in each type of ability. Both require imagined transformations, but perspective-taking also requires spatial updating of one's position relative to other spatial reference points. Spatial updating is a process involved in perspective-taking that relates to path integration and ability to effectively learn environments (Wolbers & Hegarty, 2010). It involves maintenance of one's position in relation to landmarks in the environment. Spatial updating dissociates perspective-taking from mental rotation despite sharing an imagined transformation process (Hegarty & Waller, 2004; Kozhevnikov et al., 2006). In our study, we found evidence that mental rotation fully explains the effect of GPS use on perspective taking. This result suggests that GPS use affects the common spatial transformation process underlying both mental rotation and perspective-taking. One possible mechanism is that imagined spatial transformations underlie the formation of allocentric (viewpoint independent) representations. If GPS use eliminates the need for allocentric representations because of the explicit route-based information that it provides, then this transformation process is less likely to be regularly used.

Our study focuses on the general effect of everyday GPS use on spatial transformation and subsequent environmental learning abilities. A useful direction of future work could evaluate which aspects of GPS use contribute to degraded spatial outcomes, as GPS devices can be used in many different ways to support navigation. For instance, the GPS can be used as an allocentric map (without turn-by-turn directions) versus an egocentric directional guide, or for other purposes such as to track traffic trends for route selection. Schwering, Krukar, Li, Anacta, and Fuest (2017) have suggested that GPS devices negatively contribute to environmental learning ability due to their tendency to provide route-specific information. They propose that GPS devices would better support environmental learning by providing information that aids orientation to global space and landmarks, rather than turn-by-turn directions requiring little spatial attention (see also Brunyé, Gardony, Holmes, & Taylor, 2018; Münzer, Fehringer, & Kühl, 2016). Changing the information provided by GPS devices would help answer the question of whether providing different spatial information decreases the likelihood of negative associations of GPS use with environmental learning and transformation abilities. When globally-oriented, individuals may be more likely to actively incorporate spatial transformation processes during spatial learning. On the other hand, GPS devices may contribute to deficits in spatial transformation and/or environmental learning abilities regardless of the information they provide. Future work should test this possibility by manipulating the types of information GPS devices provide over time, as well as frequency of device use.

In sum, our work suggests that GPS exerts its negative influence on spatial cognitive abilities in the long-term, building on work that has shown its negative effects on environmental learning in the short-term. Most noteworthy is that 1) GPS independently relates to spatial transformation and environmental learning abilities even after accounting for the fact that individuals of lower navigation ability use GPS devices more often, 2) GPS use indirectly relates to environmental learning through decreased spatial transformation abilities, and 3) GPS use relates to mental rotation, but not perspective-taking, and only affects perspective-taking indirectly through mental rotation. The latter result suggests that GPS use is associated with the common spatial transformation process underlying both mental rotation and perspective-taking. The relationship between decreased mental transformation abilities and increased use of GPS may be a consequence of reduced attention or encoding of one's environment, consistent with previously shown decrements in navigation tasks when GPS use has been manipulated.

Declarations of interest

None.

Acknowledgments

We thank Taylor Larsen, Miley Nguyen, and Jenn Isenhour for their help collecting data. Thank you to the National Science Foundation, whose funding helped support this work under grant number 1329091.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2019.05.001.

[2] The spatial abilities measured in the current study only conceptually, but not directly, test a replication of Hegarty et al. (2006) and Allen et al.'s (1996) studies. Different constructs were utilized to test their mediation models. In Allen et al.'s study, latency of perspective-taking was used as the mediator. A different spatial abilities latent factor was also used as the focal predictor, comprised of surface development, cube comparison, map planning, hidden figures, and Gestalt completion. In Hegarty et al.'s study, a latent spatial ability factor was used as the focal predictor, which contained mental rotation as one observed variable, but also two other related spatial abilities: embedded figures and the arrow span task.

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*(3), 327–355.

Bjork, R. A. (1994). Memory and metamemory considerations in the training of human beings. In J. Metcalfe, & A. Shimamura (Eds.). *Metacognition: Knowing about knowing* (pp. 185–205). Cambridge, MA: MIT Press.

Brügger, A., Richter, K. F., & Fabrikant, S. I. (2019). How does navigation system behavior influence human behavior? *Cognitive research: Principles and Implications, 4*(1), 5.

Brunyé, T. T., Gardony, A. L., Holmes, A., & Taylor, H. A. (2018). Spatial decision dynamics during wayfinding: Intersections prompt the decision-making process. *Cognitive Research: Principles and Implications, 3*(1), 13.

Burte, H., & Montello, D. R. (2017). How sense-of-direction and learning intentionality relate to spatial knowledge acquisition in the environment. *Cognitive Research: Principles and Implications, 2*(1), 18.

Chrastil, E. R., & Warren, W. H. (2012). Active and passive contributions to spatial learning. *Psychonomic Bulletin & Review, 19*(1), 1–23.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences.* Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (2013). *Applied multiple regression/correlation analysis for the behavioral sciences.* Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Dabbs, J. M., Chang, E. L., Strong, R. A., & Milun, R. (1998). Spatial ability, navigation strategy, and geographic knowledge among men and women. *Evolution and Human Behavior, 19*(2), 89–98.

Fields, A. W., & Shelton, A. L. (2006). Individual skill differences and large-scale environmental learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*(3), 506.

Friedman, A., & Kohler, B. (2003). Bidimensional regression: Assessing the configural similarity and accuracy of cognitive maps and other two-dimensional data sets. *Psychological Methods, 8*(4), 468.

Fritz, M. S., & MacKinnon, D. P. (2007). Required sample size to detect the mediated effect. *Psychological Science, 18*(3), 233–239.

Gardony, A. L., Brunyé, T. T., & Taylor, H. A. (2015). Navigational aids and spatial memory impairment: The role of divided attention. *Spatial Cognition and Computation, 15*(4), 246–284.

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*(2), 151–176.

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*(5), 425–447.

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence, 32*(2), 175–191.

Hegarty, M., & Waller, D. (2005). Individual differences in spatial abilities. In P. Shah, & A. Miyake (Eds.). *The cambridge handbook of visuospatial thinking* (pp. 121–169). Cambridge, UK: Cambridge University Press.

Hejtmánek, L., Oravcová, I., Motýl, J., Horáček, J., & Fajnerová, I. (2018). Spatial knowledge impairment after GPS guided navigation: Eye-tracking study in a virtual town. *International Journal of Human-Computer Studies, 116*, 15–24.

Ishikawa, T. (2019). Satellite navigation and geospatial awareness: Long-term effects of using navigation tools on wayfinding and spatial orientation. *The Professional Geographer, 71*(2), 197–209.

Ishikawa, T., Fujiwara, H., Imai, O., & Okabe, A. (2008). Wayfinding with a GPS-based mobile navigation system: A comparison with maps and direct experience. *Journal of Environmental Psychology, 28*(1), 74–82.

Kline, R. B. (2015). *Principles and practice of structural equation modeling.* New York, NY: Guilford Press.

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*(3), 397–417.

MacKinnon, D. P., Lockwood, C. M., & Williams, J. (2004). Confidence limits for the indirect effect: Distribution of the product and resampling methods. *Multivariate Behavioral Research, 39*(1), 99–128.

Malinowski, J. C. (2001). Mental rotation and real-world wayfinding. *Perceptual and Motor Skills, 92*(1), 19–30.

Muffato, V., Toffalini, E., Meneghetti, C., Carbone, E., & De Beni, R. (2017). Individual visuo-spatial factors and familiar environment knowledge: A structural equation modeling analysis. *Personality and Individual Differences, 113*, 96–102.

Münzer, S., Fehringer, B. C., & Kühl, T. (2016). Validation of a 3-factor structure of spatial strategies and relations to possession and usage of navigational aids. *Journal of Environmental Psychology, 47*, 66–78.

Münzer, S., Zimmer, H. D., Schwalm, M., Baus, J., & Aslan, I. (2006). Computer-assisted navigation and the acquisition of route and survey knowledge. *Journal of Environmental Psychology, 26*(4), 300–308.

Newcombe, N. S., & Shipley, T. F. (2015). Thinking about spatial thinking: New typology, new assessments. *Studying visual and spatial reasoning for design creativity* (pp. 179–192). Dordrecht, Germany: Springer Publishing.

Newsom, J. T. (2015). *Longitudinal structural equation modeling: A comprehensive introduction.* New York, NY: Routledge.

Oberski, D. L. (2014). Lavaan. survey: An R package for complex survey analysis of structural equation models. *Journal of Statistical Software, 57*(1), 1–27.

Padilla, L. M., Creem-Regehr, S. H., Stefanucci, J. K., & Cashdan, E. A. (2017). Sex differences in virtual navigation influenced by scale and navigation experience. *Psychonomic Bulletin &; Review, 24*(2), 582–590.

Parush, A., Ahuvia, S., & Erev, I. (2007, September). Degradation in spatial knowledge acquisition when using automatic navigation systems. *International conference on spatial information theory* (pp. 238–254). Berlin, Heidelberg: Springer.

Pazzaglia, F., & Taylor, H. A. (2007). Perspective, instruction, and cognitive style in spatial representation of a virtual environment. *Spatial Cognition and Computation, 7*(4), 349–364.

Preacher, K. J., & Hayes, A. F. (2008). Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behavior Research Methods, 40*(3), 879–891.

Rhemtulla, M., Brosseau-Liard, P.É., & Savalei, V. (2012). When can categorical variables be treated as continuous? A comparison of robust continuous and categorical SEM estimation methods under suboptimal conditions. *Psychological Methods, 17*(3), 354.

Richter, K. F., Dara-Abrams, D., & Raubal, M. (2010, September). Navigating and learning with location based services: A user-centric design. *Proceedings of the 7th international symposium on LBS and telecartography* (pp. 261–276). .

Satorra, A., & Bentler, P. M. (2001). A scaled difference chi-square test statistic for moment structure analysis. *Psychometrika, 66*(4), 507–514.

Schwering, A., Krukar, J., Li, R., Anacta, V. J., & Fuest, S. (2017). Wayfinding through orientation. *Spatial Cognition and Computation, 17*(4), 273–303.

Silverman, I., Choi, J., Mackewn, A., Fisher, M., Moro, J., & Olshansky, E. (2000). Evolved mechanisms underlying wayfinding: Further studies on the hunter-gatherer theory of spatial sex differences. *Evolution and Human Behavior, 21*(3), 201–213.

Sönmez, B. E., & Önder, D. E. (2019). The influence of GPS-based navigation systems on perception and image formation: A case study in urban environments. *Cities, 86*, 102–112.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three- dimensional spatial visualization. *Perceptual & Motor Skills, 47*(2), 599–604.

VanderWeele, T. J. (2016). Mediation analysis: A practitioner's guide. *Annual Review of Public Health, 37*, 17–32.

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin, 117*(2), 250.

Weisberg, S. M., & Newcombe, N. S. (2016). How do (some) people make a cognitive map? Routes, places, and working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42*(5), 768.

Weisberg, S. M., Schinazi, V. R., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2014). Variations in cognitive maps: Understanding individual differences in navigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*(3), 669.

Willis, K. S., Hölscher, C., Wilbertz, G., & Li, C. (2009). A comparison of spatial knowledge acquisition with maps and mobile maps. *Computers, Environment and Urban Systems, 33*(2), 100–110.

Wolbers, T., & Hegarty, M. (2010). What determines our navigational abilities? *Trends in Cognitive Sciences, 14*(3), 138–146.

Wolbers, T., & Wiener, J. M. (2014). Challenges for identifying the neural mechanisms that support spatial navigation: The impact of spatial scale. *Frontiers in Human Neuroscience, 8*, 571.

Zacks, J. M., Mires, J., Tversky, B., & Hazeltine, E. (2000). Mental spatial transformations of objects and perspective. *Spatial Cognition and Computation, 2*(4), 315–332.