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GPS use and navigation ability: A systematic review and meta-analysis

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ABSTRACT

GPS use pervades society; however, its effects on an individuals' navigation ability are not well understood. We reviewed and meta-analyzed the available evidence on the associations between GPS use and navigation ability, in terms of environmental knowledge, sense of direction and wayfinding. Based on the PRISMA guidelines and preregistration in the PROSPERO database (CRD42022378106), we searched the Web of Science, PsycInfo, and Scopus databases. Out of 907 articles, 23 studies met the inclusion criteria and were eligible for our review. We assessed the risk of bias using Joanna Briggs' tools. The narrative synthesis presented negative associations between GPS use and performance in environmental knowledge and self-reported sense of direction measures and a positive association with wayfinding. When considering quantitative data, results revealed a negative effect of GPS use on environmental knowledge ($r = -.18$ [95% CI: $-.28$, $-.08$]) and sense of direction ($r = -.25$ [95% CI: $-.39$, $-.12$]) and a positive yet not significant effect on wayfinding ($r = .07$ [95% CI: $-.28$, $.41$]). Current literature has several strengths but also methodological weaknesses that limit the quality of evidence, with 69% of the studies classified with a moderate to high risk of bias. Although evidence suggests that using GPS tools can have a negative impact on environmental knowledge and sense of direction but a limited effect on wayfinding, future studies should adopt standardized measurements and procedures to further confirm these results and delve more deeply into understanding how GPS could be used as an external aid to support navigation.

1. Introduction

Navigation ability, people's ability to navigate an environment and manage spatial relationships among the objects within it, is a fundamental aspect of our everyday functioning. It is considered a multifaceted construct that combines various cognitive functions (from mental imagery, planning, problem-solving, and decision-making) and comprises various components (Montello, 2005). Among them, wayfinding, the ability to acquire environmental knowledge, and self-reported sense of direction (sense of direction) are particularly relevant (Hegarty et al., 2006; Wiener et al., 2009). Specifically, wayfinding consists of the process of selecting and following routes between an origin and destination and involves decision-making and/or planning processes (Montello, 2001, 2005; Wiener et al., 2009). Wayfinding is based on existing spatial knowledge and contributes to the formation of new spatial knowledge. When navigating in an environment, indeed, people refer to existing spatial knowledge (Wiener et al., 2009; Wolbers & Hegarty, 2010) and simultaneously acquire novel environmental information about landmarks, paths, metrics, and directions (e.g., Ishikawa & Montello, 2006; Montello, 2001). This process can lead to the formation of configural representations of the environment, also called cognitive maps (Tolman, 1948).

Various tasks are typically used to assess wayfinding and environmental knowledge. Wayfinding assessment is based on a person's moves in an environment and the ability to manage environmental information by following a previously learned route or retracing it, determining the shortest route in the environment. Environmental knowledge is tested by recognizing decision points and turning actions in routes (egocentric knowledge, based on person-to-landmark relationships) or by drawing a map that reproduces previously learned landmarks and their locations (allocentric knowledge, based on landmark-to-landmark relationships). Finally, sense of direction is rated using questionnaires to evaluate people's ability to locate and orient themselves in the environment (Hegarty et al., 2002; Pazzaglia et al., 2000) and is also used as a valid

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measure of navigation ability, being positively correlated with actual navigation (Hegarty et al., 2002; Meneghetti et al., 2021).

In recent years, technology and communications have advanced, becoming accessible and widely adopted throughout the world (Wilmer et al., 2017). These innovations also extend to spatial navigation information, allowing us to access a vast amount of geographical, environmental, and spatial data whenever needed (Ishikawa, 2019). Among the technologies used for navigation in one's surroundings, the Global Positioning System (GPS) uses satellite signals and receivers to provide accurate location coordinates and assist with navigation through a variety of apps and tools (Theiss et al., 2005). Prominent examples of navigation assistance systems include Google Maps and many other smartphone apps or in-car systems that offer step-by-step instructions based on turn information (i.e., visual arrows on the display and verbal cues) as well as visual outputs that provide a map as people or vehicles move.

Interestingly, GPS and other navigational aids are inserted into wayfinding taxonomies (e.g. Wiener et al., 2009) and considered part of so-called social wayfinding (Dalton et al., 2019). GPS provides external self-motion cues that can be used to maintain a sense of position and orientation (path integration) and to keep track of one's location (spatial updating; Wolbers & Hegarty, 2010). In this way, GPS provides and anticipates environmental cues (roads, locations, and landmarks), which are integrated into the encoding process and therefore in the representation of the environment. In other words, GPS can contribute to online processing, resulting in an offline representation of the environment.

The increasing reliance on navigation technology makes it important to understand how GPS affect people's navigation ability (McKinlay, 2016), but the current literature is characterized by mixed results. Several studies, indeed, have shown negative effects of actual GPS use when people learn an environment and of self-reported GPS use on subsequent tasks measuring environmental knowledge, wayfinding performance (e.g., Hejtmánek et al., 2018; Ishikawa, 2019; Ishikawa et al., 2008), and sense of direction (e.g., Dahmani & Bohbot, 2020; He & Hegarty, 2020; Ishikawa, 2019; Miola et al., 2023). Other studies have, in contrast, shown that actual GPS use during environmental learning increases accuracy in subsequent map drawing tasks (such as considering the number of paths reported; Sönmez & Önder, 2019) or when GPS was used during ongoing wayfinding tasks (e.g., Cochran & Dickerson, 2019).

Ultimately, our point is that the literature shows discordant results probably because the studies adopt various methods and procedures and rely on different measures of navigation ability. In fact, some studies require tasks that reveal acquired knowledge about the environment whereas others measure performance in wayfinding tasks, and still others rely on the participant's reported navigation ability. Because these tasks refer to different functions (Hegarty et al., 2002; Wiener et al., 2009), which in turn rely on distinct neural substrates (Arnold, Protzner, Bray, Levy, & Iaria, 2014), we hypothesized that distinguishing among environmental knowledge, wayfinding, and sense of direction would help further clarify the relationship between GPS use and navigation ability, even disambiguating among the apparent discordances in the literature.

For each of these components, an attempt was also made to distinguish between studies with different procedures and methodologies (e.g., correlational vs. experimental studies and, in the latter, the specific conditions adopted in the control group) to verify a possible incidence of these variables in the results.

Therefore, in this paper, we propose a systematic review and meta-analysis summarizing the effects of GPS use on navigation abilities. A systematic review is also important to identify reliable measures to assess the impact of GPS use on navigation abilities. To our knowledge, there is currently no systematic review and meta-analysis of the evidence concerning the relationship between GPS use and navigation ability.

To address this literature gap, we aimed to examine the evidence of the impact of GPS use on individuals' navigational abilities. In particular, we summarized the evidence from studies examining GPS use and its impact on navigation ability, synthesizing and categorizing the findings, objectively measured in experimental settings or self-reported, as (a) environmental knowledge, (b) wayfinding, and (c) sense of direction. For a quantitative synthesis of the effects of GPS use on navigation abilities, our meta-analytic models focused on the effect size estimates deriving from comparisons between the experimental conditions of GPS use and comparison control groups (e.g., groups with no aids, a map, or directions) or from correlations between measurements of GPS use and navigation ability. Moreover, we assessed the quality of the studies (risk of bias) and evidence to identify any methodological weaknesses that could potentially lead to misleading results regarding the effects of GPS use.

2. Method

The present study was conducted according to the preferred reporting items for systematic reviews and meta-analyses criteria (PRISMA; Page et al., 2021). The review procedure protocol was preregistered and available in the PROSPERO International Prospective Register of Systematic Reviews (CRD42022378106; Booth et al., 2012). The literature search was based on the PICOS framework (Schardt et al., 2007), which identified studies assessing the effects of GPS use on navigation abilities, distinct in environmental knowledge, wayfinding, and sense of direction. Inclusion and exclusion criteria comprised the following.

(a) *Population:* healthy and autonomous adults ages 16 years and older. We chose 16 years as a representative age of young adults that marks the initiation of independence in terms of navigating and exploring environments (the lowest age in the United States to obtain a license and start driving). We excluded studies involving children or people with pathological or atypical conditions or diseases.
(b) *Exposure/Interventions:* i) experimental conditions in which participants used GPS, such as using a GPS navigation tool while navigating and learning the environment, or ii) cross-sectional studies with participants referring their use of GPS through self-reported measures of GPS use. All studies in which GPS was used for purposes other than spatial orientation, such as tracking vehicles and people, algorithm computation, sensor refinement, and other technical features of GPS systems, were excluded.
(c) *Comparison:* The group that used GPS during learning or navigating an environment was compared with conditions in which participants did not use a GPS tool or were involved in alternative forms of navigation methods, such as using maps, asking for directions, or having no aids, while navigating and learning an environment.
(d) *Outcomes:* Spatial tasks and self-reported measures of navigation abilities, that is, environmental learning and its subsequent recall (environmental knowledge), wayfinding (planning, finding and retracing routes, or wayfinding performance), or self-reported measure of navigation ability. We excluded studies that analyzed sea and air navigation or nonhuman navigation.
(e) *Studies*: Cross-sectional, longitudinal, correlational, quasi-experimental, or randomized controlled trials published in regular papers, conference abstracts, and official reports published in peer-reviewed journals at any time, in English. We excluded studies with animals, single-case studies, qualitative studies, books, commentaries, meta-analyses, or reviews.

2.1. Strategy for study identification

We conducted electronic searches for this review in December 2022 using PsycINFO, Web of Science, and Scopus. To ensure inclusiveness, no publication time limit was imposed to capture as many relevant records as possible. The search strategy was developed by three authors (first, second and third author), then refined by all the authors. The choice of search terms was based on evaluating the effects of GPS (the exposure of interest) on navigation abilities (the outcomes of interest). The following terms was used: "GPS" OR "Global positioning system" OR "GPS use" AND "navigation ability" OR "spatial ability" OR "spatial navigation" OR "spatial learning" OR "environment learning" OR "navigation learning" OR "environment knowledge" OR "spatial knowledge" OR "wayfinding" OR "navigation task" OR "spatial task" OR "spatial recall task" OR "environment performance" OR "environment recall" OR "sense of direction" OR "spatial orientation".

The literature search in the databases was conducted by the first author. Then, the first and the second authors independently screened the titles and abstracts of the retrieved articles for eligibility. If they disagreed, the fourth author was consulted to reach a final decision. The entire systematic procedure was supervised in accordance with all the authors.

2.2. *Data collection and synthesis of the findings*

We created an ad hoc extraction form to gather information related to the study characteristics (authors, year, country, and study design), participants characteristics (age, gender, and sample size), type of GPS use measurements (objective GPS tools or self-reported measures), type of navigation outcomes (environmental knowledge, wayfinding, and sense of direction), measurement methods employed (objective or self-reported measures), and key findings from each study (see Supplemental Materials, Tables S2, S3, and S6). Data extracted from the included studies were recorded by the first author and revised by the second and the third author, to ensure precision. In addition, we categorized the included and reviewed studies into three main navigation outcomes of interest (environmental knowledge, wayfinding, and sense of direction) and summarized the methodological quality and certainty of evidence for each study (Table 1).

For the quantitative synthesis of findings, we extracted all the effect sizes pertaining to the relationship between GPS use and navigation ability. The coding procedure was employed to ensure accurate extraction of relevant statistical information. To mitigate a publication bias, if any information was missing from the published papers, we reached out to the corresponding author to request the required effect estimates or other necessary variables, such as means and standard deviations. This approach was adopted to ensure comprehensive data collection and minimize potential bias in the analysis.

2.3. *Quality assessment (risk of bias) of the reviewed studies*

The methodological quality of each eligible study was assessed using the Joanna Briggs Institute (JBI) critical appraisal checklist (Munn et al., 2020). As the included studies were either experimental or cross-sectional in nature, the checklists for randomized controlled trials (RCTs) and cross-sectional studies were used for assessment. Using these checklists, we systematically evaluated the methodological quality of each study, taking into account the aspects relevant to the study design. For experimental studies, the checklist focused on identifying potential sources of bias including the presence of randomization of group participants, blindness, bias in outcome measurement, appropriateness of statistical analyses, and overall methodological bias. For cross-sectional studies, the checklist assessed the setting and sample description, identification and measurement of the exposure, validity and reliability of measures, consideration of confounding factors, and appropriateness of statistical analyses. Studies with a low risk of bias were categorized as high quality, whereas those with moderate and high risks of bias were categorized as moderate and low quality, respectively. Two authors (first author, second author) independently evaluated each included study. If they disagreed, a third reviewer (third author) was involved to reach a final decision (see details in the Supplemental Materials, Part 3).

2.4. *Effect coding and meta-analytic strategy*

Pearson's correlation or standardized regression coefficients between measures of GPS use and navigation ability (both objective and self-reported) were coded for each study. In cases in which correlations were unavailable, especially in studies comparing different groups, we derived effect sizes (such as Cohen's *d*) from standardized differences between groups using GPS and comparison groups. Before computing the meta-analysis, these effect sizes were converted into Pearson's correlation and Fisher's Z scale. Each effect was coded as a separate row in the data set. The type of navigation ability measure (objective or self-reported with further specification on the outcome) and measures of GPS use (objective or self-reported) were reported. For effect sizes derived from group comparisons, we also coded the criteria used to define the groups (i.e., "GPS group vs. map group" or "GPS group vs. no aids group"), along with the number of participants in each group, means, and standard deviations. The data extraction and coding process for the meta-analytic procedure were conducted by two raters: the first rater (first author) collected the necessary data from the included studies, then the second rater (second author) reviewed and confirmed the accuracy of the extracted data.

We performed all statistical analyses using R software. Specifically, the meta-analysis was conducted using the "metafor" package (Viechtbauer, 2010). We chose a random-effects model due to the expected significant heterogeneity among the included studies. Studies were treated as random effects, following an approach Borenstein (2009) outlined. Since various tasks were used to assess navigation ability in the included studies, multiple effect sizes were often reported for the same participant sample. To account for this dependency structure between effect sizes, we employed multilevel modeling using the "rma.mv" function of the "metafor" package. The observed effect sizes were treated as observations clustered within studies. To estimate the covariance structure between effect sizes, we utilized the "clubSandwich" package (Pustejovsky & Tipton, 2022), assuming a correlation of .50 between effects within the same research and study. The correlation of .50 was chosen on the basis of the authors' results in which correlations between different measures of navigation ability range between .14 and .45 (Muffato et al., 2023).

We assessed heterogeneity using Sigma squared (σ^2).

3. Results

We identified a total of 907 records through the literature search and two additional records from other sources: one through research on the reference list of the included papers (as recommended by Horsley et al., 2011) and the second through a paper by the authors that was accepted during the literature search. After removing deduplicates, we screened 598 records for relevance based on their titles and abstracts. From this screening process, 82 studies were considered potentially eligible for inclusion. The agreement between the two reviewers in the screening process yielded a Cohen's *k* of .92, indicating almost perfect agreement. Subsequently, of the full-text articles of potentially eligible studies, 23 met the inclusion/exclusion criteria and were included in the systematic review. After contacting the authors, we included quantitative data in the meta-analysis from 18 studies (see Fig. 1). The agreement between the two reviewers in the full-text screening phase yielded a Cohen's *k* value of .90, indicating once again very high agreement.

3.1. *Participants and study design*

Table 1 provides details of the 23 studies included in the review (see also Table S2 in Supplemental Materials). The sample sizes of the included studies ranged from 13 to 636 participants, and the age of the

Table 1
Summary of findings divided by outcomes.

Outcome of Interest	Study	Study Design	Risk of bias	GPS Measurements	Effect Direction	Type of Environment	Results	Summary of Findings
ENVIRONMENTAL KNOWLEDGE	Ishikawa et al. (2008)	Experimental	Moderate	GPS group vs. control (map and no aids)	⇓	Real	GPS group performed worse in estimating direction and drawing a map compared to the group with no aids	The evidence on environmental knowledge with actual GPS use showed mixed findings: Two studies reported better performance, two lower performance, and two studies found no difference. The evidence on environmental knowledge with self-reported GPS use is more coherent as all the studies (n = 5) report negative relations
	Fajnerová et al. (2018)	Experimental	High	GPS group (3 m) vs. control (no aids)	⇔	Real	No effect of use of GPS in estimating directions	
	* Johansson et al. (2013)	Experimental	Moderate	GPS condition vs. control (no aids)	⇑	Real	GPS group performed better in estimating directions	
	Sönmez and Önder (2019)	Experimental	High	GPS group vs. control (asking for direction)	⇑⇔	Real	GPS group performed better in map drawing (number of paths); No differences in landmarks, nodes, number of items	
	Münzer et al. (2012)	Experimental	Moderate	GPS group vs. control (compass vs. route mode)	⇓	Real	GPS group showed worse configural learning than map and compass group	
	Ishikawa (2019)	Experimental	Moderate	GPS group vs. control (paper map)	⇔	Real	No differences between groups in direction estimation	
	Ruginski et al. (2019)	Cross-sectional	Moderate	Self-reported	⇓	Virtual	Negative relation between GPS use and pointing performance, distance estimation, and map drawing task	
	Dahmani and Bohbot (2020)	Cross-sectional	Low	Self-reported (GPS experience, dependence, reliance)	⇓	Virtual	Negative relation between use of GPS and performance in map task	
	Hejtmánek et al. (2018)	Cross-sectional	Low	How long participants spend looking at the aid during their navigation	⇓	Virtual	Negative relation between GPS use and estimating direction and map task	
	Yan et al. (2022)	Cross-sectional	Low	Self-reported (questionnaires on GPS dependence)	⇓	Virtual	GPS dependency was negatively associated with efficiency of detecting spatial target	
	Steele (2016)	Cross-sectional	Moderate	Self-reported	⇓	Virtual	Negative relation between GPS use and direction estimation task*	
WAYFINDING PERFORMANCE	Ishikawa et al. (2008)	Experimental	Moderate	GPS group vs. control (map and no aids)	⇓	Real	GPS group performed worse (stopped more and traveled longer distances) compared to map and no aids group. No differences in wayfinding performance (reaching goals)	The evidence on wayfinding performance and actual GPS use showed mixed findings: Six studies reported better performance, two studies lower performance, and one study no differences. The evidence on wayfinding performance and self-reported GPS use report negative relations (n = 1) and a positive relation (n = 1)
	Vaez et al., 2020	Experimental	High	GPS group vs. control (no aids and map)	⇑	Real	GPS group performed better on average distance traveled compared to signage-only group	
	Ishikawa (2019)	Experimental	Moderate	GPS group vs. control (paper map)	⇓	Real	GPS group performed worse in terms of travel time, the number of stops, the number of deviations, and traveled distance compared to map group	
	Fajnerová et al. (2018)	Experimental	High	GPS group vs. control (no aids)	⇔	Real	No effect of GPS use in wayfinding performance (path efficiency)	

(continued on next page)

Table 1 (*continued*)

Outcome of Interest	Study	Study Design	Risk of bias	GPS Measurements	Effect Direction	Type of Environment	Results	Summary of Findings
	Cochran and Dickerson (2019)	Experimental	Moderate	GPS group vs. control (printed direction)	⇑	Virtual	GPS group performed better on driving (driving errors)	
	Young et al. (2008)	Experimental	Moderate	GPS group vs. control (compass)	⇑	Virtual	GPS group performed better than compass group (evaluating waypoint)	
	Wang et al. (2020)	Experimental	Moderate	GPS group vs. control (no aids, map, color map)	⇑	Virtual	GPS condition showed better performance in terms of path length and time of walking	
	Münzer et al. (2012)	Experimental	Moderate	GPS group (route mode) vs. control (compass, map)	⇑	Virtual	GPS group performed better (less wayfinding errors) compared to map and compass group	
	Li et al. (2019)	Experimental	High	GPS group vs. control (friends and strangers)	⇑	Virtual	GPS group performed better in route retracing than group asking strangers (without feedback and correct guidance)	
	Dickerson (2020)	Cross-sectional	High	Questions on GPS	⇑	Real	Navigation technology is perceived by older adults as helpful for wayfinding, with minimal distractions	
	Hejtmánek et al. (2018)	Cross-sectional	Low	How long participants spend looking at the aid during their navigation	⇓	Virtual	Negative relation between GPS use and wayfinding (path redundancy)	
SENSE OF DIRECTION	Ishikawa (2019)	Experimental	Moderate	Self-reported	⇓	NA	GPS use negatively correlated with sense of direction (SBSOD)	The evidence on self-reported sense of direction is consistent, and nine studies found negative relations between using GPS and self-reported sense of direction. Three studies found no association, and one study found a positive relation
	He and Hegarty (2020)	Cross-sectional	Moderate	Self-reported	⇓	NA	GPS use negatively correlated with sense of direction (SBSOD)	
	Dahmani and Bohbot (2020)	Cross-sectional and longitudinal	Low	Self-reported	⇓⇔	NA	GPS dependence negatively correlated with sense of direction (SBSOD); No significant relationship emerged with GPS reliance and GPS experience	
	Meneghetti et al. (2019)	Cross-sectional	Moderate	Self-reported	⇓⇔	NA	GPS use negatively correlated weakly with sense of direction and use of cardinal points; No relations emerged with preference for survey mode and preference for landmark and route modes	
	Steele (2016)	Cross-sectional	Moderate	Self-reported	⇓	NA	GPS use negatively correlated with sense of direction (SBSOD)	
	Miola et al. (2023)	Cross-sectional	Low	Self-reported	⇓	NA	GPS use negatively correlated with sense of direction (SDSR)	
	Hejtmánek et al. (2018)	Cross-sectional	Low	How long looking at the aid during navigation	⇓	NA	GPS and map use negatively correlated with self-reported navigation skill	
	Ruginski et al. (2019)	Cross-sectional	Moderate	Self-reported	⇓	NA	GPS use negatively correlated with sense of direction (SBSOD)	
	Muffato et al. (2022)	Cross-sectional	Low	Self-reported	⇔	NA	No relations emerged between sense of direction and GPS use	
	Zeng et al. (2022)	Cross-sectional	Low	Self-reported	⇓	NA	GPS use negatively predicted self-reported sense of direction	

(*continued on next page*)

Table 1 (*continued*)

Outcome of Interest	Study	Study Design	Risk of bias	GPS Measurements	Effect Direction	Type of Environment	Results	Summary of Findings
	Nori et al. (2022)	Cross-sectional	Low	Self-reported	⇑	NA	GPS use positively predicted SOD (regression); No relations emerged between SOD and GPS use (correlation)	

Note. *Steel et al. (2016) called the direction estimation task as a wayfinding task.
Direction of effect: ⇑= positive association between GPS use and navigation ability; ⇓ = negative association between GPS use and navigation ability; ⇔ = no association between GPS use and navigation ability; NA = Not applicable.

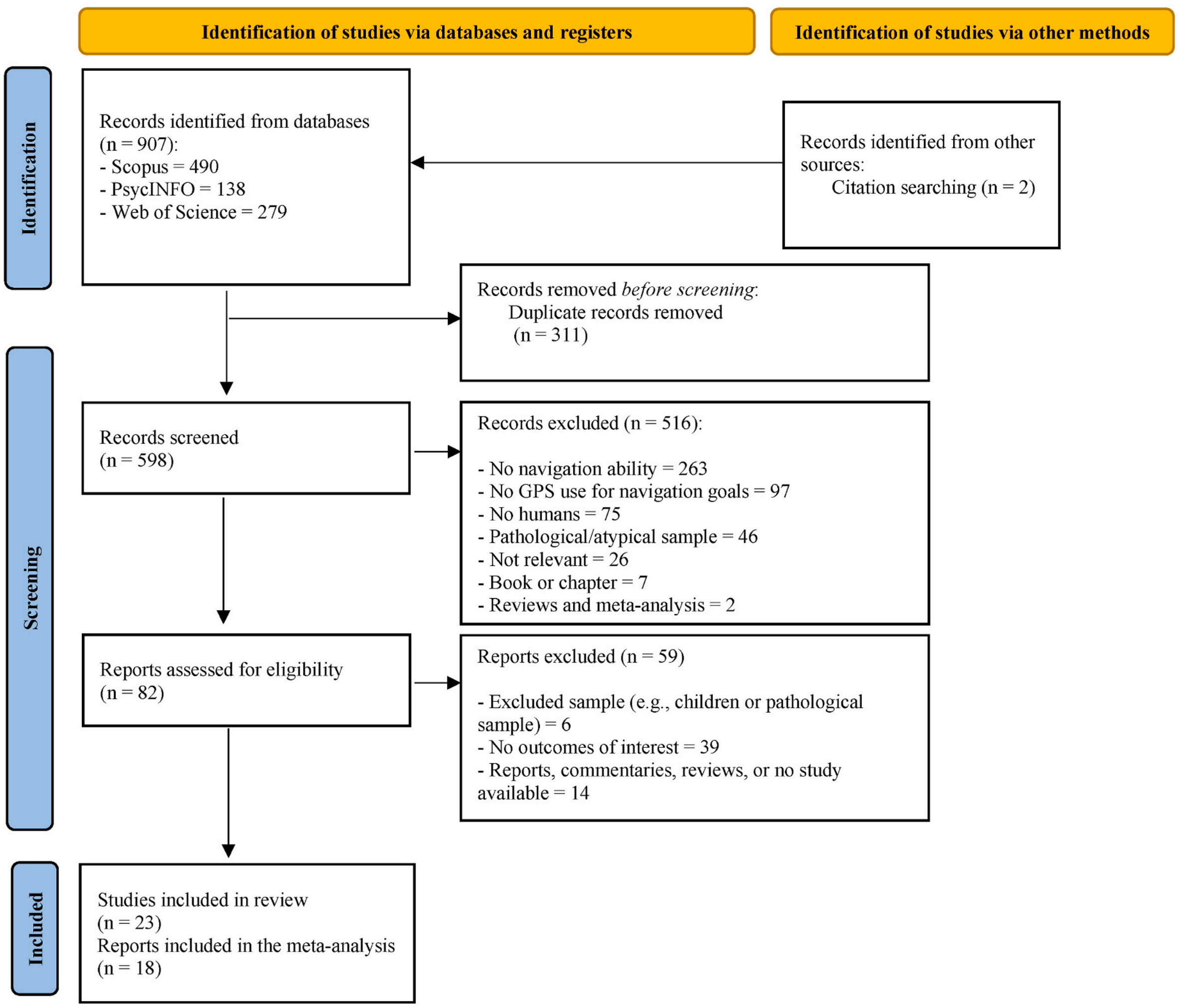

Fig. 1. Prisma diagram of the study selection process.

participants ranged from 16 to 84 years. Regarding the study design, all the studies included quantitative data. The majority of them collected data at a single point in time, whereas only one study measured variables after 3 months and one after 3 years. Among the included studies, 11 were classified as experimental studies because they compared the performance of groups using a GPS tool during navigation (GPS group) with groups that used other aids or no aids during the learning phase. Specifically, five studies included a control group with no aids (Fajnerová et al., 2018; Ishikawa et al., 2008; * Johansson et al., 2013; Vaez, Burke, & Yu, 2020; Wang et al., 2020), and 12 studies included one or more control groups using other navigation aids (i.e., six studies used maps or printed directions [Cochran & Dickerson, 2019; Ishikawa, 2019; Ishikawa et al., 2008; Münzer et al., 2012; Vaez et al., 2020; Wang et al., 2020]; two studies used a compass [Münzer et al., 2012; Young et al., 2008]; and two studies included asking other people for directions [Li et al., 2019; Sönmez & Önder, 2019]). The 12 studies were classified as cross-sectional and correlational studies. In terms of the types of environments used for testing navigation ability, 10 studies employed a virtual environment (e.g., on desktop simulations), and nine studies used real environments (such as city, neighborhood, or campuses).

3.2. *Synthesis of characteristics of reviewed studies grouped by outcomes of interest*

Most of the studies reviewed reported significant effects of GPS use on navigation ability outcomes. However, there was considerable heterogeneity in assessing GPS use, as well as examining the measurements and outcomes. To address the latter source of variability, and according to theoretical models (Dalton et al., 2019; Hegarty et al., 2006; Wiener et al., 2009), we grouped the study results based on three main types of navigation ability outcomes: (a) environmental knowledge, (b) wayfinding performance, and (c) sense of direction. Table 1 provides detailed information on each category of study, including their specific characteristics and key findings.

3.2.1. Environmental knowledge

In total, eleven studies (see Table 1) assessed environmental knowledge and incorporated a learning phase in which participants familiarized themselves with a specific environment, either real or virtual. Following the learning phase, a testing phase evaluated participants' knowledge of the environment and its metrical and configural features in a subsequent session with various spatial recall tasks measuring participants' ability to recall a learned environment, such as direction estimation tasks (pointing; eight studies) assessing egocentric knowledge and map tasks (eight studies) or distance estimation tasks (one study) assessing allocentric knowledge.

The majority of the studies used a GPS tool or GPS with augmented reality during the learning phase in real and virtual environment and then tested the knowledge of the environment (see Supplemental Materials Tables S2 and S3 for details on the procedure).

One study used eye tracking to investigate GPS use (how long participants spent looking at a GPS-like map) to correlate with the performance on environmental knowledge (Hejtmánek et al., 2018).

Finally, four studies used self-reported measures of GPS use correlated with environmental knowledge tasks (Dahmani & Bohbot, 2020; Ruginski et al., 2019; Steele, 2016; Yan et al., 2022).

Of these eleven studies measuring environmental knowledge, six studies compared a group using a GPS tool (i.e., GPS used during navigation) with control groups using no aids, a map, or asking for directions and then assessing spatial recall tasks (Fajnerová et al., 2018; Ishikawa, 2019; Ishikawa et al., 2008; * Johansson et al., 2013; Münzer et al., 2012; Sönmez & Önder, 2019).

Among the six studies that compared groups, two studies found a lower performance in the GPS group compared to the CG in direction estimation (errors) and map drawing task (accuracy of number of routes that showed all the turns in the correct directions and sequences and configural accuracy; Ishikawa et al., 2008; CG: no aid; Münzer et al., 2012; CG: map and compass groups). Differently, two studies found that the GPS groups performed better than the control groups (CGs) in direction estimation tasks (* Johansson et al., 2013; CG: no aids) and number of paths drawn in the map tasks (Sönmez & Önder, 2019; CG: asking for directions). Finally, two studies reported no differences between the GPS and comparison groups in error of direction estimates (CG: no aids groups, Fajnerová et al., 2018; paper map group: Ishikawa, 2019).

Four studies used self-reported measures to assess GPS use, using a single question: "About how often do you use a GPS for navigation when travelling?" (Ruginski et al., 2019) or a questionnaire (i.e., McGill GPS questionnaire; Dahmani & Bohbot, 2020) measuring the habits and/or frequencies in using GPS during moves (see Table S6 for details). All the studies reported a negative association between GPS use and performance on spatial recall tasks. Ruginski et al. (2019) found a negative association between the reported frequency of GPS use with performance in a pointing task, distance estimation, and map tasks. Dahmani and Bohbot (2020) found a negative relationship between the use of GPS and map drawing (accuracy in locating landmark), both in a cross-sectional study and a longitudinal study. Similarly, Steele (2016) found that GPS use was negatively associated with performance in direction estimation and Yan et al. (2022) showed an association between GPS dependence (GPS dependence questionnaire; Dahmani & Bohbot, 2020) and searching for a spatial target from a map (higher fixation), with high GPS dependency associated with lower efficiency in the spatial target search.

Finally, one study by Hejtmánek et al. (2018) registered how long participants spent looking at the GPS map using eye tracking during the learning phase and recall phase finding that the duration of fixations was negatively associated with performance in a pointing task and a map task (location placement and naming scores).

Overall, seven out of the eleven studies reviewed above found a negative relationship between GPS use and egocentric (direction estimation task and pointing) and allocentric (map task) environmental knowledge (Dahmani & Bohbot, 2020; Hejtmánek et al., 2018; Ishikawa et al., 2008; Münzer et al., 2012; Ruginski et al., 2019; Steele, 2016; Yan et al., 2022), whereas two studies (Fajnerová et al., 2018; Ishikawa, 2019) did not find such relationships, and two studies (* Johansson et al., 2013; Sönmez & Önder, 2019) also reported positive relationships between the use of GPS and performance in direction estimation and map drawing tasks.

3.2.2. Wayfinding performance

A total of eleven studies (see Table 1) assessed wayfinding performance (see also Tables S2 and S3) including route repetition and retracing tasks, shortcut task or navigation performance during the GPS use (driving tasks, find locations, following the device). Of the eleven studies measuring wayfinding, nine experimental studies compared GPS groups with CGs using no aids, a map or asking for directions (Cochran & Dickerson, 2019; Fajnerová et al., 2018; Ishikawa, 2019; Ishikawa et al., 2008; Li et al., 2019; Münzer et al., 2012; Vaez et al., 2020; Wang et al., 2020; Young et al., 2008). Among the nine studies, eight measured the effect of GPS use during the performance of wayfinding, and one study assessed wayfinding before and after using the GPS tool (Fajnerová et al., 2018). Finally, other two studies used either eye tracking or self-reported measures of GPS use (Dickerson, 2020; Hejtmánek et al., 2018).

Six out of eight studies found that the GPS group exhibited better wayfinding performance compared with CGs. Cochran and Dickerson (2019) found fewer driving errors of the GPS condition compared to a condition with printed directions on a driving task (within subject design). Young et al. (2008) found a better performance of the GPS group in planning and navigating compared to a compass group. Wang et al. (2020) found that the GPS condition had better performance in finding the exit of a maze (path length and time of walking) compared to the no aids condition (within subject design). Vaez et al. (2020) found better performance in finding locations in the environment (lower distance traveled) for the GPS group compared to the signage-only group. Münzer et al. (2012) found that the GPS group (route mode) showed better performance in following directions (less wayfinding errors) than a map and a compass group. Li et al. (2019) showed that the GPS group performed better in route retracing than the group that received verbal instructions for directions.

Two studies (Ishikawa, 2019; Ishikawa et al., 2008) found, however, that the GPS group had worse wayfinding performance: Ishikawa et al. (2008) found that the GPS group, compared to the paper map and no aids groups, traveled longer distances and made more stops during a wayfinding task, and Ishikawa (2019) found that the GPS condition performed worse than the paper map condition in a wayfinding task, showing longer travel time and distance and higher number of stops and deviations (within subject design). Only one study found no differences between groups: Fajnerová et al. (2018) showed similar performance between the GPS group and the CG in a wayfinding task requiring navigating without a marked trajectory.

Finally, of the eleven studies, one study on wayfinding measured GPS use with eye tracking (fixation times of GPS aid; Hejtmánek et al., 2018) and one with self-reported measures (Dickerson et al., 2020). Hejtmánek et al. (2018) showed that the GPS-like map use (fixation) was associated with lower wayfinding performance in terms of path redundancy. Dickerson (2020) instead asked older adults questions on difficulties in using GPS after driving four roads with GPS and found that 91% of the participants subjectively reported that GPS tools are useful for wayfinding.

Overall, of the eleven studies that measured wayfinding performance, seven showed a positive relationship (Cochran & Dickerson, 2019; Dickerson, 2020; Münzer et al., 2012; Vaez et al., 2020; Wang et al., 2020; Young et al., 2008) with GPS use, three showed a negative relationship (Hejtmánek et al., 2018; Ishikawa, 2019; Ishikawa et al., 2008), and one study found no relationship (Fajnerová et al., 2018).

3.2.3. Sense of direction

A total of eleven studies (see Table 1) self-reported navigation ability (sense of direction) using questionnaires. Specifically, five studies used The Santa Barbara Sense of Direction questionnaire (SBSOD; Hegarty et al., 2002), five studies included other questionnaires on navigation ability, and one study used a single question to score navigation expertise subjectively (see Supplemental Materials, Table S6). All these studies used GPS self-reported measures (e.g., McGill GPS questionnaire, Dahmani & Bohbot, 2020), except for one study that registered the time fixation of the GPS map during a navigation task.

Regarding the results, nine studies found that GPS use negatively correlated with sense of direction (Dahmani & Bohbot, 2020; He & Hegarty, 2020; Hejtmánek et al., 2018; Ishikawa, 2019; Meneghetti et al., 2019; Miola et al., 2023; Ruginski et al., 2019; Steele, 2016; Zeng et al., 2022), one study found that the use of GPS positively predicted a sense of direction (Nori et al., 2022), and two studies did not find any relationship (Dahmani & Bohbot, 2020; Muffato et al., 2022). Dahmani and Bohbot (2020) counted twice as they found, in addition, no significant correlations between a sense of direction and GPS reliance and GPS experience. The same authors in a longitudinal assessment (post-test after three years) found no significant correlation between a change in a sense of direction with hours of GPS use since pre-test or GPS reliance.

Overall, of the eleven studies that measured a sense of direction, nine studies indicated negative relationships with GPS use, whereas two studies failed to find an association, and only one study found a positive association.

3.2.4. Risk of bias of the literature considered in the systematic review

We evaluated the methodological quality of the studies, calculating the risk of bias using a revised version of the Joanna Briggs Institute (JBI) critical appraisal checklist (Munn et al., 2020; see Supplemental Materials). However, it should be specified that the manual JBI is appropriate especially for experimental studies in the healthcare field and is not perfectly suitable for the cognitive-behavioral studies described in the present systematic review.

Concerning the overall methodological quality of the studies included in the review, 30% (n = 7) resulted in a low risk of bias; 47% (n = 11) in a moderate risk, and 21% (n = 5) in a high risk.

For the cross-sectional studies (n = 12), most studies provided adequate descriptions of the sample (n = 11, 92%), addressed confounding effects (n = 10, 83%), and reported appropriate statistical analyses (n = 11, 92%; see Supplemental Materials, Part 3). The primary sources of bias were the lack of a clear definition of inclusion criteria for participants (n = 7, 58%) and the lack of information regarding the reliability and validity of the measurements used (n = 5, 42%).

As for the experimental studies (n = 11) JBI checklist for randomized controlled trials was used; however, in the final count of risk of bias we did not count three questions because they applied to clinical trials. Indeed, the questions investigated the adequacy of follow-up, intention to treat, and information about specific trial design that are not suitable for experimental studies comparing conditions/groups.

For the experimental studies, a source of bias is the lack of information regarding the reliability and validity of the measurements used in the studies (n = 10, 91%); only one study reported measures such as Cronbach's alpha or agreement between judges for scoring. The assessment of measurement reliability in experimental studies was lower compared to the cross-sectional studies, as the latter predominantly used subjective measures, which measures of validity more commonly accompany (see Supplemental Materials, Fig. S1; and Tables S4 and S5).

In addition, indications are never given with respect to the blinding of subjects or investigators in the assigned conditions/groups (n = 11, 100%). Finally, only a portion of the studies indicated the randomized and casual assignment of participants to conditions (n = 7, 63%).

3.3. Meta-analysis of the relationship between the use of a GPS and navigation ability

A total of 18 studies and 81 effect sizes were included to estimate the relationship between GPS use and navigation ability. Concerning the type of outcome (see Figs. 2–4 for environmental knowledge, wayfinding, sense of direction, respectively), the Pearson's coefficient estimated for the correlation between GPS use and environmental knowledge was $r = -.18$ [CI: −.28, −.08], $p < .001$; heterogeneity was significant, Q(df = 8) = 25.875, $p = .001$, $\sigma^2 = .02$. Wayfinding performance was Pearson's $r = .07$ [CI: −.28, .41], $p > .05$; heterogeneity was significant, Q(df = 6) = 77.554, $p < .001$, $\sigma^2 = .19$. The self-reported sense of direction was Pearson's $r = -.25$ [95% CI: −.39, −.12], $p < .001$; heterogeneity was significant, Q(df = 11) = 200.443, $p < .001$, $\sigma^2 = .05$. Overall, considering both experimental and cross-sectional studies, the correlation between GPS use and navigation ability is significant for two of the three outcomes, and the magnitude of the relationship is small.

4. Discussion

In the current systematic review and meta-analysis, we examined for the first time whether the GPS is related to people's navigation and orientation abilities. Given the rapid development and access to technologies that provide spatial information (Hein, 2020), as well as the growing body of literature on this topic in the last 15 years, this study was intended to clarify whether and how is the relationship between the use of assistive navigation systems and navigation abilities defined regarding (a) environmental knowledge (environmental learning and its recall; Wolbers & Hegarty, 2010; assessing egocentric or allocentric knowledge; Burgess, 2006), (b) wayfinding performance (reaching destinations and locations, performance during wayfinding; Wiener et al., 2009), and (c) sense of direction (subjective navigation ability; Hegarty et al., 2002).

In the systematic review, we selected and finally included 23 studies, 12 cross-sectional and 11 experimental, exploring the relationship between GPS system use and navigation ability. In the meta-analysis, following contact with authors to obtain missing data, we were able to include 18 studies. The results of all studies regarding environment knowledge, wayfinding, and sense of direction are discussed below.

As for environment knowledge, studies that compared the actual use of GPS by one group/condition with a control group/condition showed mixed results: Some studies showed that the GPS users performed better, some worse, and some showed no differences. Notably, in the studies in which GPS users showed better performance in egocentric (direction estimation) and allocentric (map drawing) tasks, this improvement was seen in only one of the indicators of environmental knowledge included (for map drawing in number of paths but not for number of landmarks, nodes, or roads; Sönmez & Önder, 2019) or when GPS use was allowed during the direction estimation testing phase (* Johansson et al., 2013), which could have influenced the results by helping and facilitating the recall thanks to the GPS device. Therefore, the positive effects of GPS use are limited, possibly due to differences in the methodology used (i.e., allowing GPS use during the testing phase). The results of the systematic review regarding the effect of GPS use on environmental knowledge in experimental studies seem to suggest that GPS use in learning an environment can potentially lead to poorer acquisition of spatial knowledge. It is noteworthy that GPS use can still allow for some level of spatial learning and accurate acquisition of the number of paths in an

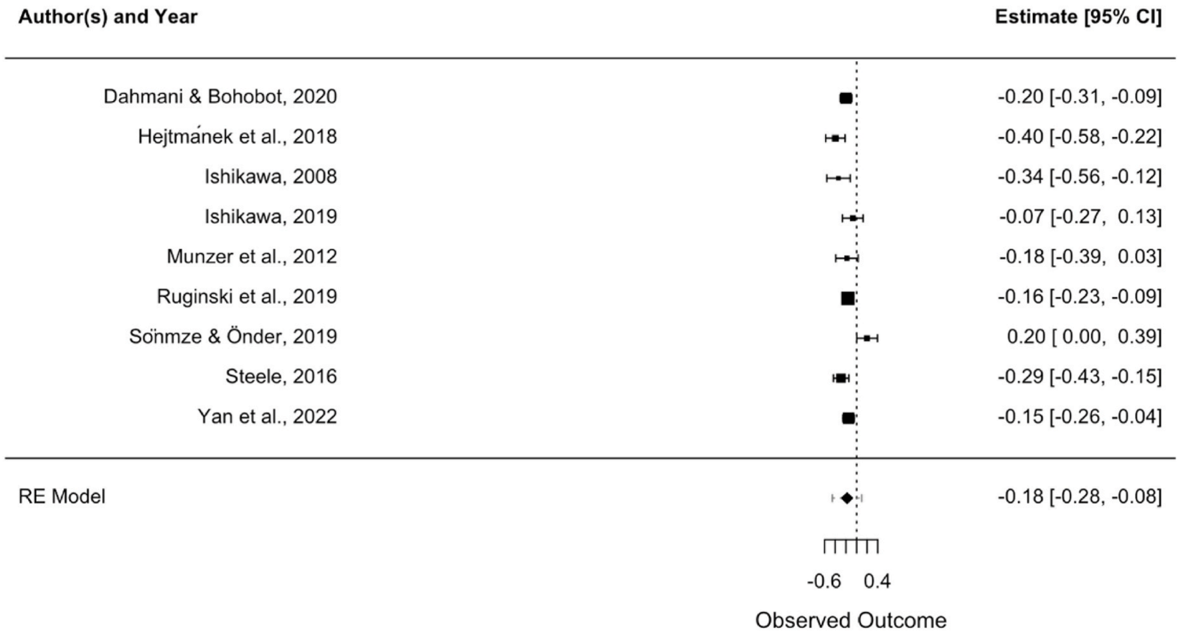

Fig. 2. Environmental Knowledge.
Note. Forest plot showing the estimated true effects to the meta-analytic model. Error bars represent 95% Cis of the random effects.

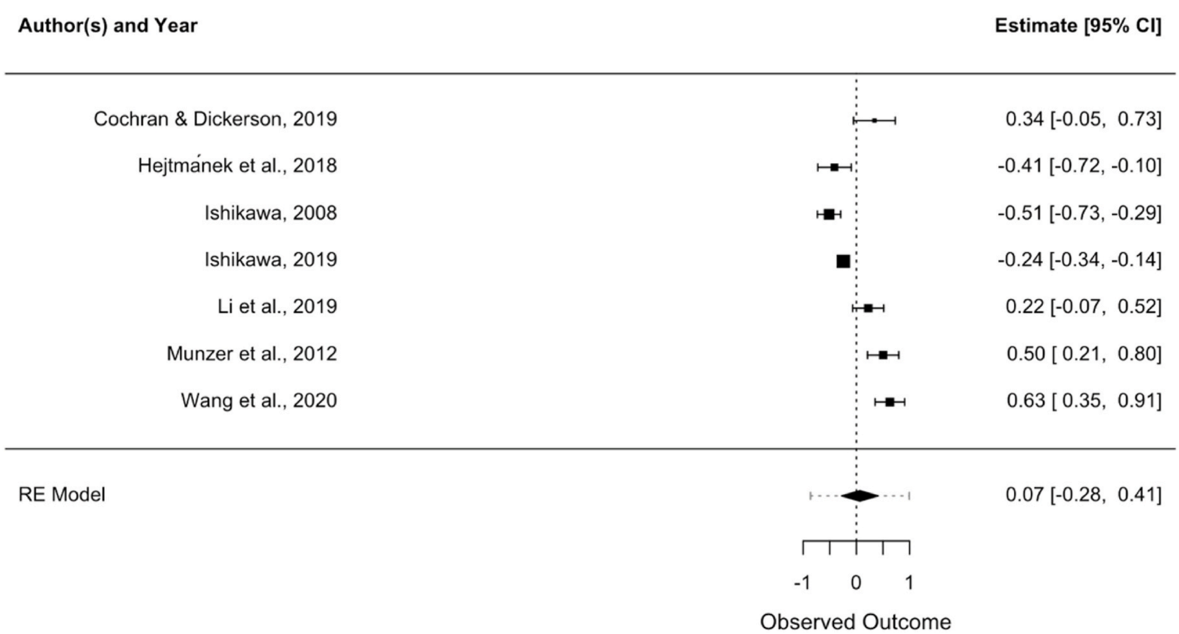

Fig. 3. Wayfinding.
Note. Forest plot showing the estimated true effects to the meta-analytic model. Error bars represent 95% Cis of the random effects.

environment (Sönmez & Önder, 2019), suggesting that GPS use is not disadvantageous in all spatial knowledge acquisition situations. However, taken together, our results seem to newly indicate that a negative relationship with the environmental (metrical and configurational) knowledge is present when assessed with egocentric (e.g., judging directions) and allocentric (e.g., map drawing) tasks (Ishikawa et al., 2008; Münzer et al., 2012).

The results of studies using self-reported measures of GPS use in everyday life consistently showed that GPS use is negatively associated with environmental knowledge, indicating that when individuals report high frequency of GPS use or high reliance on GPS in everyday life, they also report poorer mental representation of the surrounding environment (e.g., Dahmani & Bohbot, 2020; Ruginski et al., 2019).

To elucidate further the effect of GPS use (actual or self-reported) on environmental knowledge, we compiled the available data on the effects of GPS use across various environmental knowledge outcomes. The results of the meta-analysis indicated a statistically significant negative relationship between GPS use and environmental knowledge, $r = -.18$, 95% CI [$-.28$, $-.08$], $p < .001$. Overall, the results on environmental knowledge support the hypothesis that focusing on a GPS device while navigating an environment could interfere with subsequent recall. GPS use may impair the learning of landmarks, paths, and the configuration of the environment and does not allow for the use of basic spatial skills useful for learning the environment (mental rotation and perspective taking; Münzer et al., 2012; Ruginski et al., 2019). Moreover, GPS use could make learning an environment more passive, thus decreasing the

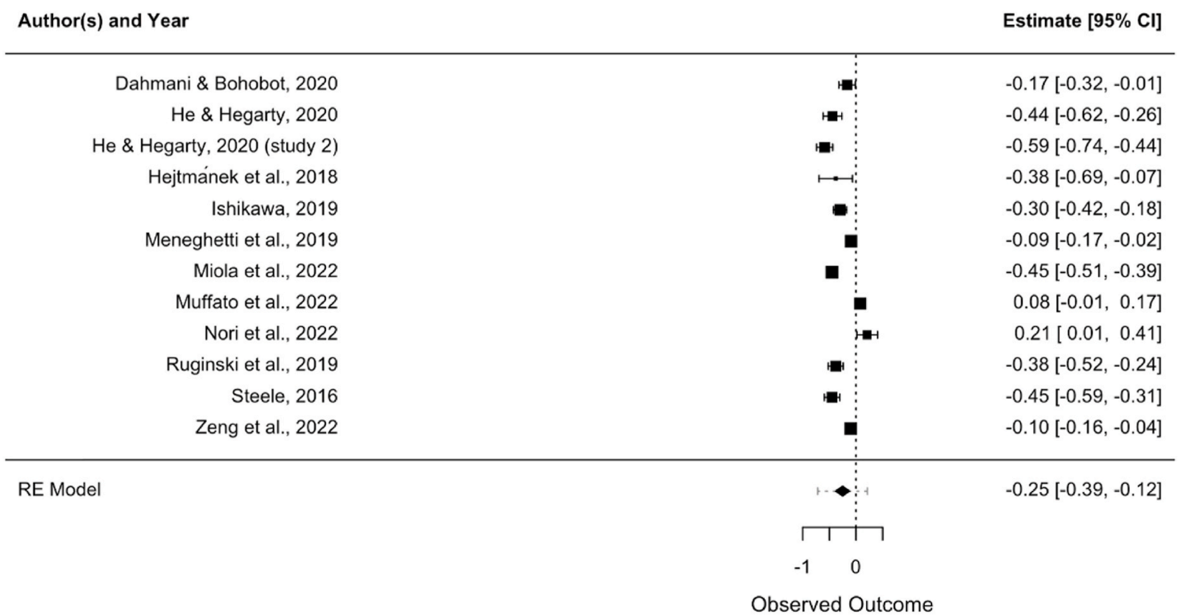

Fig. 4. Sense of Direction.
Note. Forest plot showing the estimated true effects to the meta-analytic model. Error bars represent 95% Cis of the random effects.

acquisition of information and not facilitating decision-making during exploration (Chrastil & Warren, 2015). Along this line, some authors (e.g., Huston & Hamburger, 2023; McKinlay, 2016; Montello & Raubal, 2013) interpreted such negative relationships in terms of technological infantilization*,* in which technology is assumed to do much of the cognitive work, consequently impoverishing people's resources.

As for wayfinding ability, all the experimental studies compared the performance/behaviors of GPS use during the user's course and control groups/conditions. The majority of them showed that GPS use during wayfinding helps people find a destination more effectively and quickly than controls. Specifically, when the wayfinding performance is measured at a behavioral level (e.g., speed, distance traveled, navigation errors) simultaneously with GPS use, the latter seems to enhance performance (Cochran & Dickerson, 2019; Li et al., 2019; Münzer et al., 2012; Vaez et al., 2020; Wang et al., 2020; Young et al., 2008). These results suggest that GPS use can facilitate online searches and help users find which route to take to reach a destination, supporting the idea that GPS, as navigational assistance, can be considered a strong wayfinding cue during navigation (Dalton et al., 2019). However, this benefit is not found in three studies showing that the GPS users performed worse than control groups (Ishikawa, 2019; Ishikawa et al., 2008) or that the usage of augmented-reality glasses with GPS (around 3 h per week) during navigation in a real environment for 3 months did not significantly affect the tested participants' wayfinding performance (Fajnerová et al., 2018). The mixed results regarding wayfinding performance with GPS may be explained by several factors. First, two of the three studies that showed worse performance of GPS users were conducted in real-world environments. Real environments and locations can introduce complexities during navigation, such as traffic, noise, and crowding, that are difficult to control in experimental situations. Furthermore, one of these studies was conducted in 2008, when participants may have been less familiar with GPS devices and screens were smaller.

Finally, the studies using self-reported measures or eye tracking to assess GPS use showed positive and negative relationship with wayfinding performance. Greater time fixation on the map with GPS was associated with lower wayfinding ability. However, when exploring people's beliefs about the utility of GPS use, people judge GPS as useful and not a deterrent during wayfinding. Overall, the results of a systematic review of wayfinding ability seems to suggest that GPS use can be useful during online navigation to efficiently search for destinations, which is part of wayfinding ability. It is plausible that to solve problems and find solutions during navigation (a key component of wayfinding; Montello, 2005), GPS can be a strong supporter (Dalton et al., 2019).

The advantage of GPS use for wayfinding, however, was not quantitatively detectable in the meta-analysis. The meta-analysis did not reveal a statistically significant relationship between GPS use and wayfinding performance, $r = .07$, 95% CI $[-.28, .41]$, $p > .05$. The null effect may stem from the various tasks adopted in the studies included: Real and simulated driving tasks related to safety, shortcut task, route retracing, and finding the exit of a maze. In these tasks, the requests and the indices adopted to calculate wayfinding performance were different (errors, accuracy, travel distance, walking speed, target finding). In addition, the types of environments were different (real or virtual, labyrinth or city). This heterogeneity underscores the diversity in research approaches to GPS use and highlights the complexity of the findings regarding the relationship between GPS use and wayfinding performance.

The tradeoff observed for wayfinding performance underlines the importance of conducting systematic reviews in addition to meta-analyses and serves as a starting point for new research on improving or standardizing wayfinding measurements to understand better GPS's role in various navigation behaviors (navigation errors, distance traveled, speed, etc.) and related performance (wayfinding performance with GPS or wayfinding after learning an environment with GPS based on the knowledge of the environment). Finally, the results on wayfinding show that there is a lack of evidence on wayfinding without the use of GPS. Studies, indeed, have been conducted to assess people's wayfinding ability as they passively follow GPS instructions, potentially creating a gap in our understanding of the processes of route planning and decision-making tested after GPS use. Future studies should also include these aspects of route planning and decision-making to better examine GPS use's effects on the various components of wayfinding (Wiener et al., 2009).

Concerning the results of sense of direction and self-reported GPS use, most studies have shown a negative relationship between self-reported GPS use and self-reported sense of direction (adopting a widely used measure; Dahmani & Bohbot, 2020; He & Hegarty, 2020; Hegarty et al., 2002; Hejtmánek et al., 2018; Ishikawa, 2019; Meneghetti et al., 2019; Miola et al., 2023; Ruginski et al., 2019; Steele, 2016; Zeng et al., 2022). Consistently the meta-analysis showed a statistically significant negative effect of GPS use on individuals' self-reported sense of direction, $r = -.25$, 95% CI [−.39, −.12], $p < .001$. This finding implies that one's perceived sense of direction is negatively associated with GPS use. This trend is particularly evident when we consider self-reported measures (for GPS use and sense of direction). Overall, the results regarding subjective sense of direction confirm the link between beliefs about a sense of direction and behaviors, including GPS use (e.g., He & Hegarty, 2020; Miola et al., 2023), in which the awareness of people's navigation abilities consistently relates to the need for aids (expressed through self-reports). People with a low sense of direction may prefer to use GPS more as a form of reassurance for spatial situations and navigation. On the other hand, the relationship's bidirectionality suggests that continuous GPS use over time could also be associated with a poorer sense of direction.

4.1. Risk of bias

Regarding the methodological quality of the evidence, our review revealed that approximately 69% of the studies had a moderate or high risk of bias. One major weakness of these studies is the validity and reliability of the objective measures used to assess navigational ability. Each study used a different task, making comparing their results difficult, and they did not report indices of reliability and validity for the navigation measurements, especially for wayfinding performance. This problem, however, should be extended to the literature on navigation in general, which often uses nonstandardized navigation tasks, highlighting the importance of improving the navigation assessment to reach more sound conclusions (Wiener et al., 2020). Another aspect is the lack of multiple and repeated measurements of the navigation ability to better detect everyday habits (Schaie, 2014). Furthermore, no action was taken in the studies regarding the participants' and experimenters' blindness to the assigned conditions. Additionally, there are differences in the type of environment used. Studies conducted in a real-world urban environment necessarily had little control over environmental variables (from traffic or pedestrian density to walking space), which may have affected participants' navigation. These methodological limitations may have influenced the validity of these studies' estimates.

On the other hand, it is possible to highlight the included studies' strengths. For example, the fact that the studies used experimental procedures (group comparisons) and self-reported measures helps add information and clarify the relationship between variables. Another aspect that emerges, especially in experimental studies, is the control of baseline groups for various relevant factors: In some studies, the researchers ensured that the groups did not differ in age, gender, level of experience with virtual environments or GPS, or basic visuospatial abilities, making the groups comparable. In some studies, the researchers used and clearly explained their randomization techniques for conditions and participant assignment. Other strengths of the studies include appropriate statistical analyses (e.g., checking assumptions), large sample sizes, and within-subject procedures.

Although it provides new insights, some limitations of this review process should also be acknowledged. Among the studies, the disparity in when navigation abilities were assessed, before or during GPS use, and the limited number of studies in both scenarios restrict our ability to delve deeper into the GPS timing used in the studies. Another limitation of the review is the failure to consider individual characteristics, such as age, as moderating factors, which could have provided more comprehensive insight into the impact of GPS use. In the current review, we were unable to explore age-related differences due to the limited number of older participants. It is also worth noting that GPS technology is constantly improving, not only in terms of navigation precision and integration of new systems for spatial data (e.g., artificial intelligence; Ahmed & Raihan, 2024) but also in its usability, design, and immersion with new devices that could also impact spatial navigation (e.g., Lakehal et al., 2023; Ruginski et al., 2022). In addition, as new generations (e.g., millennials) become increasingly digitalized and more familiar with technology compared to previous generations (e.g., Alexopoulou et al., 2022), there may be a cohort effect in the evidence that should be investigated in future studies.

4.2. Implications

From a theoretical point of view, our results enhance the understanding of aided navigation. Despite the inclusion of navigational aids (in terms of tools or people) in theoretical wayfinding models (Dalton et al., 2019; Wiener et al., 2009), their role during spatial-information learning (wayfinding) in its final acquisition (environmental knowledge) and subjective navigation abilities has not been systematically analyzed. Moreover, in the models, evidence of unaided individual navigation ability prevails.

The results of the current review provide an initial framework for the effect of GPS use on the acquisition of environment information (wayfinding), the resulting environmental knowledge, and individual disposition (sense of direction). Researchers should consider the various components of navigation abilities and determine when and in which phase of navigation the GPS aid can be used in relation to other variables and conditions (such as the environment—real vs. virtual conditions—and the type of task used). This will enhance our understanding of when GPS use might create a disadvantage or potentially offer strategic advantages in navigation (as observed in the current paper with the use of GPS during wayfinding).

At the same time, the present findings have relevant practical implications. Technology is becoming omnipresent in daily life, with GPS being one of the most commonly used systems for navigation. As our review reveals, understanding the effects of GPS use and design (Ruginski et al., 2022) on our navigation abilities has become increasingly important and could provide implications for navigating our environment and offer insights into advancements in technology–human interaction in spatial navigation. Studying various types of technology design and information provided by navigation systems could make a difference in navigation abilities. Given that we cannot eliminate GPS technology from our lives, our results on its potentially detrimental role in some components of navigation abilities should raise future questions of how to help people use it as an aid.

5. Conclusions

In conclusion, the present review and meta-analysis clarify and confirm some findings in the literature, namely that the GPS use is negatively associated with navigation ability, specifically environmental knowledge and sense of direction, indicating that the more individuals rely on GPS to reach destinations, the more poorly they perceive their navigation skills and the poorer is their knowledge of the environment. At the same time, it is important to mention the bidirectionality of the relationship between GPS use and navigation abilities: Individuals with poorer ability to learn spatial information and form environmental knowledge tend to use assisted navigation systems more frequently in daily life, thus weakening their navigation abilities. This intriguing link might suggest that individuals who have a weaker "internal" ability to use spatial knowledge to navigate their surroundings are also more prone to rely on "external" devices or systems to navigate successfully. Therefore, other psychological factors (e.g., self-efficacy; Miola et al., 2023) might moderate this bidirectional relationship, and researchers need to further elucidate it.

The results regarding wayfinding, in contrast, seem to support GPS's positive role when combined during navigation (systematic review), even if it is not supported by quantitative evidence (meta-analysis).

Future studies should better clarify the impact of GPS use through the use of reliable procedures and measurements regarding navigation ability and GPS use. Moreover, to better understand the long-term impact of GPS use, more extensive longitudinal research will be required with the aim of determining the direction of causality.

Researchers should also examine the role of individual differences, such as how age is involved in the relationship between GPS use and navigation ability (few studies consider a large age range, including older adults; Dickerson, 2020; Ishikawa, 2019). Another important aspect of future research could be the examination of strategic GPS use. Devices with GPS offer various strategic functionalities that enable users to explore their surroundings, plan routes, or view maps of their environments. Investigating whether strategic GPS use is positively associated with everyday navigation abilities would be a valuable aspect to explore in subsequent studies, together with a comparison of types of use.

Finally, these findings are important because they underline how the use of devices may play a role in how we learn about environments and how people think about their spatial abilities. Given these devices' increasing use and accuracy earlier in the life span, this negative relationship may remain or even become more pronounced. Therefore, in light of the negative effect of GPS use on spatial learning and sense of orientation, it is important to study how the use of GPS devices can effectively support the various aspects of navigation. These results provide evidence and a foundation for new research on how to best use these devices without weakening our abilities. Positive use of GPS devices could involve mindful use, employing strategic approaches, or providing less information.

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Laura Miola: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Veronica Muffato:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Enrico Sella:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Chiara Meneghetti:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Francesca Pazzaglia:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest

Data availability statement

Data are available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2024.102417.

References

References marked with an asterisk indicate studies included in the meta-analysis

Ahmed, I., & Raihan, A. S. (2024). Spatiotemporal data analysis: A review of techniques, applications, and emerging challenges. In N. N. Gaw, P. M. Pardalos, & M. R. Gahrooei (Eds.), *Multimodal and tensor data analytics for industrial systems improvement* (Vol. 211). Springer. https://doi.org/10.1007/978-3-031-53092-0_7.

Alexopoulou, S., Åström, J., & Karlsson, M. (2022). The grey digital divide and welfare state regimes: A comparative study of European countries. *Information Technology & People, 35*(8), 273–291.

Arnold, A. E., Protzner, A. B., Bray, S., Levy, R. M., & Iaria, G. (2014). Neural network configuration and efficiency underlies individual differences in spatial orientation ability. *Journal of Cognitive Neuroscience, 26*(2), 380–394. https://doi.org/10.1162/jocn_a_00491

Booth, A., Clarke, M., Dooley, G., Ghersi, D., Moher, D., Petticrew, M., & Stewart, L. (2012). The nuts and bolts of PROSPERO: An international prospective register of systematic reviews. *Systematic Reviews, 1*(1), 2–9. https://doi.org/10.1186/2046-4053-1-2

Borenstein, M. (2009). Effect sizes for continuous data. In H. Cooper, L. Hedges, & J. C. Valentine (Eds.), *The handbook of research synthesis and meta-analysis* (pp. 221–235). Russell Sage Foundation.

Burgess, N. (2006). Spatial memory: How egocentric and allocentric combine. *Trends in Cognitive Sciences, 10*(12), 551–557. https://doi.org/10.1016/j.tics.2006.10.005

Chrastil, E. R., & Warren, W. H. (2015). Active and passive spatial learning in human navigation: Acquisition of graph knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41*(4), 1162–1178. https://doi.org/10.1037/xlm0000082

* Cochran, L. M., & Dickerson, A. E. (2019). Driving while navigating: On-road driving performance using GPS or printed instructions. *Canadian Journal of Occupational Therapy, 86*(1), 61–69. https://doi.org/10.1177/0008417419831390.

* Dahmani, L., & Bohbot, V. D. (2020). Habitual use of GPS negatively impacts spatial memory during self-guided navigation. *Scientific Reports, 10*(1), 6310. https://doi.org/10.1038/s41598-020-62877-0.

Dalton, R. C., Hölscher, C., & Montello, D. R. (2019). Wayfinding as a social activity. *Frontiers in Psychology, 10*, 142. https://doi.org/10.3389/fpsyg.2019.00142

Dickerson, A. E. (2020). Use of GPS for older adults to decrease driving risk: Perceptions from users and non-users. *Geriatrics, 5*(3), 60. https://doi.org/10.3390/geriatrics5030060

Fajnerová, I., Greguš, D., Hlinka, J., Nekovářová, T., Škoch, A., Zítka, T., … Horáček, J. (2018). Could prolonged usage of GPS navigation implemented in augmented reality smart glasses affect hippocampal functional connectivity? *BioMed Research International*. https://doi.org/10.1155/2018/2716134

* He, C., & Hegarty, M. (2020). How anxiety and growth mindset are linked to navigation ability: Impacts of exploration and GPS use. *Journal of Environmental Psychology, 71*, Article 101475. https://doi.org/10.1016/j.jenvp.2020.101475.

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. https://doi.org/10.1016/j.intell.2005.09.005

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. https://doi.org/10.1016/S0160-2896(02)00116-2

Hein, G. W. (2020). Status, perspectives and trends of satellite navigation. *Satellite Navigation, 1*, 22. https://doi.org/10.1186/s43020-020-00023-x

* 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. https://doi.org/10.1016/j.ijhcs.2018.04.006.

Horsley, T., Dingwall, O., & Sampson, M. (2011). Checking reference lists to find additional studies for systematic reviews. *Cochrane Database of Systematic Reviews*, (8)https://doi.org/10.1002/14651858.MR000026.pub2

Huston, V., & Hamburger, K. (2023). *Navigation aid use and human wayfinding: How to engage people in active spatial learning*. KI-Künstliche Intelligenz. https://doi.org/10.1007/s13218-023-00799-5

* 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. https://doi.org/10.1080/00330124.2018.1479970.

* 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. https://doi.org/10.1016/j.jenvp.2007.09.002.

Ishikawa, T., & Montello, D. R. (2006). Spatial knowledge acquisition from direct experience in the environment: Individual differences in the development of metric knowledge and the integration of separately learned places. *Cognitive Psychology, 52*, 93–129. https://doi.org/10.1016/j.cogpsych.2005.08.003

** Johansson, B. J., Hellgren, C., Oskarsson, P. A., & Svensson, J. (2013). Supporting situation awareness on the move-The role of technology for spatial orientation in the field. In *Iscram* (pp. 442–451).

Lakehal, A., Lepreux, S., Efstratiou, C., Kolski, C., & Nicolaou, P. (2023). Spatial knowledge acquisition for pedestrian navigation: A comparative study between smartphones and ar glasses. *Information, 14*(7), 353.

* Li, Y., Li, W., Yang, Y., & Wang, Q. (2019). Feedback and direction sources influence navigation decision making on experienced routes. *Frontiers in Psychology, 10*, 2104. https://doi.org/10.3389/fpsyg.2019.02104.

McKinlay, R. (2016). Technology: Use or lose our navigation skills. *Nature, 531*(7596), 573–575. https://doi.org/10.1038/531573a

Meneghetti, C., Grimaldi, F., Nucci, M., & Pazzaglia, F. (2019). Positive and negative wayfinding inclinations, choice of navigation aids, and how they relate to personality traits. *Journal of Individual Differences*. https://doi.org/10.1027/1614-0001/a000302

Meneghetti, C., Miola, L., Toffalini, E., Pastore, M., & Pazzaglia, F. (2021). Learning from navigation, and tasks assessing its accuracy: The role of visuospatial abilities and wayfinding inclinations. *Journal of Environmental Psychology, 75*, Article 101614. https://doi.org/10.1016/j.jenvp.2021.101614

* Miola, L., Meneghetti, C., Muffato, V., & Pazzaglia, F. (2023). Orientation behavior in men and women: The relationship between gender stereotype, growth mindset, and spatial self-efficacy. *Journal of Environmental Psychology, 86*, Article 101952. https://doi.org/10.1016/j.jenvp.2022.101952.

Montello, D. R. (2001). Spatial cognition. In N. J. Smelser, & B. Baltes (Eds.), *International encyclopedia of the social and behavioral sciences*, 7–14771.

Montello, D. R. (2005). Navigation. In P. Shah, & A. Miyake (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 257–294). Cambridge University Press.

Montello, D. R., & Raubal, M. (2013). Functions and applications of spatial cognition. In D. Waller, & L. Nadel (Eds.), *Handbook of spatial cognition* (pp. 249–264). American Psychological Association. https://doi.org/10.1037/13936-014.

* Muffato, V., Borella, E., Pazzaglia, F., & Meneghetti, C. (2022). Orientation experiences and navigation aid use: A self-report lifespan study on the role of age and visuospatial factors. *International Journal of Environmental Research and Public Health, 19*(3), 1225. https://doi.org/10.3390/ijerph19031225.

Muffato, V., Miola, L., Pellegrini, M., Pazzaglia, F., & Meneghetti, C. (2023). Investigating the different domains of environmental knowledge acquired from virtual navigation and their relationship to cognitive factors and wayfinding inclinations. *Cognitive Research: Principles and Implications, 8*(1), 50. https://doi.org/10.1186/s41235-023-00506-w

Munn, Z., Barker, T. H., Moola, S., Tufanaru, C., Stern, C., McArthur, A., Stephenson, M., & Aromataris, E. (2020). Methodological quality of case series studies: An introduction to the JBI critical appraisal tool. *JBI Evidence Synthesis, 18*(10), 2127–2133. https://doi.org/10.11124/JBISRIR-D-19-00099

* Münzer, S., Zimmer, H. D., & Baus, J. (2012). Navigation assistance: A trade-off between wayfinding support and configural learning support. *Journal of Experimental Psychology: Applied, 18*(1), 18. https://doi.org/10.1037/a0026553.

* Nori, R., Zucchelli, M. M., Giancola, M., Palmiero, M., Verde, P., Giannini, A. M., & Piccardi, L. (2022). GPS digital nudge to limit road crashes in non-expert drivers. *Behavioral Sciences, 12*(6), 165. https://doi.org/10.3390/bs12060165.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *International Journal of Surgery, 88*, Article 105906. https://doi.org/10.1016/j.ijsu.2021.105906

Pazzaglia, F., Cornoldi, C., & De Beni, R. (2000). Differenze individuali nella rappresentazione dello spazio e nell'abilità di orientamento: Presentazione di un questionario autovalutativo. *Giornale Italiano di Psicologia, 27*(3), 627. https://doi.org/10.1421/310

Pustejovsky, J. E., & Tipton, E. (2022). Meta-analysis with robust variance estimation: Expanding the range of working models. *Prevention Science, 23*(3), 425–438. https://doi.org/10.1007/s11121-021-01246-3

* Ruginski, I. T., Creem-Regehr, S. H., Stefanucci, J. K., & Cashdan, E. (2019). GPS use negatively affects environmental learning through spatial transformation abilities. *Journal of Environmental Psychology, 64*, 12–20. https://doi.org/10.1016/j.jenvp.2019.05.001.

Ruginski, I., Giudice, N., Creem-Regehr, S., & Ishikawa, T. (2022). Designing mobile spatial navigation systems from the user's perspective: An interdisciplinary review. *Spatial Cognition and Computation, 22*(1–2), 1–29. https://doi.org/10.1080/13875868.2022.2053382

Schaie, K. W. (2014). What can we learn from longitudinal studies of adult development?. In *Successful aging* (pp. 133–158). Psychology Press.

Schardt, C., Adams, M. B., Owens, T., Keitz, S., & Fontelo, P. (2007). Utilization of the PICO framework to improve searching PubMed for clinical questions. *BMC Medical Informatics and Decision Making, 7*(1), 1–6. https://doi.org/10.1186/1472-6947-7-16

* 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. https://doi.org/10.1016/j.cities.2018.12.018.

Steele, S. J. (2016). *Predicting GPS usage: The relative importance of wayfinding ability, object-based spatial ability, working memory capacity, anxiety, and overall technology usage*. The University of Alabama [Doctoral dissertation.

Theiss, A., Yen, D. C., & Ku, C. Y. (2005). Global positioning systems: An analysis of applications, current development and future implementations. *Computer Standards & Interfaces, 27*(2), 89–100.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review, 55*, 189–208.

Vaez, S., Burke, M., & Yu, R. (2020). Visitors' wayfinding strategies and navigational aids in unfamiliar urban environment. *Tourism Geographies, 22*(4–5), 832–847. https://doi.org/10.1080/14616688.2019.1696883

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software, 36*(3), 1–48. https://doi.org/10.18637/jss.v036.i03

* Wang, Y. T., Punithakumar, K., & Boulanger, P. (2020). The impact of color coding in Virtual Reality navigation tasks. In *Optical architectures for displays and sensing in augmented, virtual, and mixed reality (AR, VR, MR)* (Vol. 11310, pp. 310–320). SPIE. https://doi.org/10.1117/12.2545154.

Wiener, J. M., Büchner, S. J., & Hölscher, C. (2009). Taxonomy of human wayfinding tasks: A knowledge-based approach. *Spatial Cognition and Computation, 9*(2), 152–165. https://doi.org/10.1080/13875860902906496

Wiener, J. M., Carroll, D., Moeller, S., Bibi, I., Ivanova, D., Allen, P., & Wolbers, T. (2020). A novel virtual-reality-based route-learning test suite: Assessing the effects of cognitive aging on navigation. *Behavior Research Methods, 52*, 630–640. https://doi.org/10.3758/s13428-019-01264-8

Wilmer, H. H., Sherman, L. E., & Chein, J. M. (2017). Smartphones and cognition: A review of research exploring the links between mobile technology habits and cognitive functioning. *Frontiers in Psychology, 8*, 605. https://doi.org/10.3389/fpsyg.2017.00605

Wolbers, T., & Hegarty, M. (2010). What determines our navigational abilities? *Trends in Cognitive Sciences, 14*(3), 138–146. https://doi.org/10.1016/j.tics.2010.01.001

* Yan, W., Li, J., Mi, C., Wang, W., Xu, Z., Xiong, W., Tang, L., Wand, S., Li, Y., & Wang, S. (2022). Does global positioning system-based navigation dependency make your sense of direction poor? A psychological assessment and eye-tracking study. *Frontiers in Psychology, 13*, Article 983019. https://doi.org/10.3389/fpsyg.2022.983019.

Young, M. S., Stanton, N. A., Walker, G. H., Jenkins, D. P., & Smart, W. (2008). Where do we go from here? An assessment of navigation performance using a compass versus a GPS unit. *Cognition, Technology & Work, 10*, 231–236. https://doi.org/10.1007/s10111-007-0095-7

* Zeng, Z., Chen, P. J., Xiao, X., Liu, P., & Zhang, J. (2022). The mediating and moderating effects on the intention to use navigation apps. *Journal of Hospitality and Tourism Technology, 13*(5), 972–991.