Effects of Turn-by-Turn Navigation Assistance on Spatial Memory in Large-Scale Environments and Improvement Methods

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Date: 2024-09-04T00:00:00+00:00

Abstract

Rapid technological development has rendered human behavior increasingly "automated"; through turn-by-turn navigation, individuals can efficiently reach destinations via optimal routes. However, such a highly efficient wayfinding approach may engender a weakening of spatial memory. Extensive research demonstrates that turn-by-turn navigation assistance is detrimental to spatial knowledge acquisition, motivating researchers to either enhance existing turn-by-turn navigation systems or devise novel navigation solutions. Building upon these efforts, this paper proposes a theoretical model delineating the influence of turn-by-turn navigation assistance on spatial memory and offers pertinent recommendations for its improvement. Future investigations should refine measurement methodologies for spatial knowledge in large-scale environments, elucidate the neural mechanisms underlying the spatial memory degradation caused by turn-by-turn navigation assistance, consider individual difference factors to construct a more comprehensive explanatory framework, and develop innovative navigation systems that concurrently optimize wayfinding efficiency and spatial knowledge acquisition.

Full Text

The Effect of Turn-by-Turn Navigation on Spatial Memory in Large-Scale Environments and Ways to Improve It

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Abstract: The rapid development of science and technology has made human behavior increasingly "automated." Turn-by-turn navigation enables people to reach their destinations quickly by following correct routes. However, such an efficient wayfinding method may come at the cost of weakened spatial memory. Numerous studies have shown that turn-by-turn navigation impedes the acquisition of spatial knowledge, prompting researchers to improve turn-by-turn navigation or design new navigation systems. Building on this foundation, this paper proposes a model of how turn-by-turn navigation affects spatial memory and offers recommendations for improvement. Future research should refine measurement methods for spatial knowledge in large-scale environments, investigate the neural mechanisms underlying the spatial memory deficits caused by turn-by-turn navigation, examine individual factors to construct a more comprehensive explanatory framework, and develop new navigation systems that balance wayfinding efficiency with spatial knowledge acquisition.

Keywords: turn-by-turn navigation, navigation aids, spatial memory

1 Introduction

Navigation refers to an individual's ability to plan a route and reach a destination through spatial movement (Ishikawa et al., 2008). In ancient times, people relied on methods such as the position of the sun or Polaris, or the growth patterns of plants to find their way, expending considerable time and effort to arrive at their destinations. As science and technology advance rapidly, navigation aids have become ubiquitous in daily life, such as various devices equipped with Global Positioning System (GPS) (Gardony et al., 2015). GPS-based mobile navigation assistance systems can improve wayfinding efficiency (Hergan & Umek, 2017), greatly facilitating people's lives.

In modern society, people generally no longer need to master these traditional wayfinding skills; they can simply follow navigation instructions to reach their destinations easily. While navigation systems help individuals arrive at destinations faster, they also reduce the mental effort required for wayfinding (Brügger et al., 2018), making it difficult for individuals to learn the spatial structure of the environment (Münzer et al., 2012). The long-term negative effects of using navigation systems outweigh the benefits of having a good sense of direction and mental rotation ability (Ishikawa, 2019), and the resulting cost may be impaired spatial memory of the environment. Spatial memory representation in large-scale environments consists of three components: landmark knowledge, route knowledge, and survey knowledge. Landmark knowledge primarily refers to salient locations in the environment; routes connect these landmarks as external reference points, so route knowledge consists of a series of points; survey knowledge refers to concepts about the structure of landmarks and routes in a map-like environment, linking everything together to form a spatial relational representation (Siegel & White, 1975). During navigation, route knowledge requires less cognitive effort than survey knowledge (Van Asselen et al., 2006). Route knowledge enables people to travel from one location to another along known paths, while survey knowledge includes structural information that allows people to discover shortcuts between locations and explore new routes (Chrastil & Warren, 2012). Navigation aids are primarily used to guide people to specific destinations in unfamiliar environments (Münzer et al., 2012) and can be categorized into turn-by-turn navigation, non-turn-by-turn navigation (Kuo et al., 2023), and paper maps. Most current navigation software employs turn-by-turn navigation, such as Amap and Baidu Maps. This paper systematically reviews research on the effects of turn-by-turn navigation aids on spatial memory. Current research can be divided into two aspects: comparing turn-by-turn navigation aids with paper maps to explore their impact on spatial knowledge acquisition, and designing new navigation assistance systems different from turn-by-turn navigation to improve and innovate traditional approaches.

2 Negative Effects of Turn-by-Turn Navigation

Turn-by-turn navigation provides instructions based on turning points, with routes being completely predefined (Mazurkiewicz et al., 2023). Instructions generally include turning direction and distance information, though sometimes only turning direction is provided. A typical turn-by-turn navigation instruction is “turn left after 300 meters.” The characteristic of turn-by-turn navigation is its implementation on mobile devices using GPS technology, enabling real-time updates of the individual’s current location. This differs from paper maps (Figure 1 [Figure 1: see original paper]), traditional navigation aids based on paper and printing technology that are static and lack interactivity (Ding, 2015). Turn-by-turn navigation can utilize different interface technologies to convey instructions, such as Augmented Reality (AR). Accordingly, turn-by-turn navigation can be divided into GPS-based 2D mobile maps and GPS-based AR mobile maps (Huang et al., 2012; Mazurkiewicz et al., 2023) (Figure 2 [Figure 2: see original paper]).

Figure 1 A4 paper map at approximately 1:2000 scale, with red text and arrows not shown to participants (Source: Sugimoto et al., 2022)
Figure 2 GPS-based 2D mobile map (left) and GPS-based AR mobile map (right) (Source: Mazurkiewicz et al., 2023; Qiu et al., 2023)

2.1 Does Turn-by-Turn Navigation Weaken Spatial Memory?

Most research indicates that using turn-by-turn navigation impedes the formation of spatial memory. Hejtmánek et al. (2018) found that turn-by-turn navigation hinders individuals’ acquisition of spatial knowledge. In their experiment, participants performed a there-and-back navigation task in a virtual city with eye-tracking, revealing that the more time individuals spent on the GPS map during learning, the worse their navigation performance, pointing accuracy, and delayed spatial knowledge during recall. Fenech et al. (2010) had one group of participants drive with acoustic turn-by-turn navigation while another group drove without navigation assistance. After the simulated driving, participants completed a scene recognition paradigm, showing that the no-assistance group had better scene recognition ability than the turn-by-turn navigation group, indicating that using navigation systems while driving causes inattentional blindness, preventing individuals from "seeing" features of the surrounding environment. In Gardony et al.'s (2013) experiment, participants navigated a virtual wayfinding task using verbal voice instructions (e.g., "slight left, 400 feet"), tonal instructions (a synthesized tone played from a 90-degree azimuth when the turn was "right," with volume increasing as distance decreased), or no assistance (control group), followed by landmark recall, map drawing, and pointing tasks. Results showed that although both verbal voice and tonal instructions improved navigation efficiency, they still weakened participants' spatial memory to some extent compared to the control group.

Similar findings emerge when compared to paper maps. For instance, in Xu et al.'s (2022) study, participants completed navigation tasks at a university using a mobile map without instructions, a paper map, and a mobile map with voice instructions. Results showed that mobile maps had higher wayfinding efficiency than paper maps, yet route memory acquired using the instruction-free mobile map was worse than that from paper maps. However, there were no significant differences among the three conditions in landmark knowledge or survey knowledge. Sugimoto et al. (2022) required people to learn an urban environment using mobile phone maps and paper maps, finding that individuals using mobile phone maps had lower landmark recognition scores and worse route backtracking performance, though no significant differences in scene recognition. This differs from Fenech et al. (2010), possibly because the number of scenes participants needed to recognize varied, creating differences in task difficulty—11 scenes in the former study versus 22 in the latter. Ishikawa et al. (2008) assigned participants to wayfinding tasks in a residential area using paper maps, turn-by-turn navigation, or direct experience, followed by estimating the direction to the starting point and drawing a map. Results showed that the turn-by-turn navigation group had larger direction estimation errors and lower map accuracy than the direct experience group, but no differences from the paper map group. Ben-Elia (2021) required drivers to navigate a route in an urban residential area using either a paper map or Google Maps' audiovisual turn-by-turn navigation, finding that drivers who memorized the paper map beforehand had better landmark recognition than those following audiovisual turn-by-turn navigation, with no significant differences in route or survey knowledge. However, Kelly (2022) found that turn-by-turn navigation did not affect route memory in virtual environments. The learning group received turn-by-turn navigation in all four driving simulations, while the test group used turn-by-turn navigation in the first two simulations and then completed route backtracking tasks in the subsequent two simulations. After 48 hours, all participants underwent a final test. Results showed that route knowledge acquired by repeatedly following turn-by-turn navigation (learning group) was not worse than that of individuals who initially received turn-by-turn navigation help but later retrieved routes from memory (test group).

In summary, regarding landmark knowledge, some studies show that landmark knowledge acquired using 2D mobile maps is worse than that from paper maps (Ben-Elia, 2021; Fenech et al., 2010; Sugimoto et al., 2022), while others show no significant differences (Xu et al., 2022; Yount et al., 2022). This may be due to different numbers of landmarks selected for landmark recognition tasks; smaller numbers may produce ceiling effects, reducing task discriminability. For example, Xu (2022) used only three landmarks for recognition, while Sugimoto (2022) asked participants to remember as many landmarks as possible along the route, such as convenience stores and traffic lights, with some studies using up to 22 landmarks (Fenech et al., 2010). Regarding route knowledge, some studies show no differences between paper maps and 2D mobile maps (Ben-Elia, 2021; Kelly et al., 2022; Yount et al., 2022), while others show paper maps are superior (Sugimoto et al., 2022; Xu et al., 2022). Differences in results may stem from experimental environments generally being unfamiliar to participants. Compared to walking navigation, driving requires avoiding collisions and thus demands more attentional resources, reducing the distracting effect of mobile navigation devices. This may lead to similar route memory when using 2D mobile maps versus paper maps while driving. Regarding survey knowledge, mobile maps hinder spatial memory formation (Hejtmánek et al., 2018) and are inferior to paper maps (Ishikawa et al., 2008; Yount et al., 2022), though some studies show no significant differences (Ben-Elia, 2021; Xu et al., 2022). The reason may be that methods such as distance estimation, time estimation, and pointing estimation cannot comprehensively assess individuals' memory of environmental structure (Ben-Elia, 2021; Xu et al., 2022). Therefore, despite differences among studies, turn-by-turn navigation is either inferior to paper maps or direct experience in spatial knowledge acquisition, or shows no significant difference.

When researchers found that GPS-based 2D mobile maps yielded poorer spatial knowledge than paper maps or direct experience, they hoped to use new technologies to compensate for the shortcomings of turn-by-turn navigation. Augmented Reality (AR) refers to the integration of digital information with the real world, presenting virtual and real content in real time, where the physical environment is part of the individual's AR experience (Rauschnabel et al., 2022). AR maps display virtual routes based on the real world.

Dong et al. (2021) required participants to complete wayfinding tasks at a university using either AR maps or 2D mobile maps, finding that both map types had comparable wayfinding efficiency, but map drawing results showed that using AR maps made it more difficult to form clear route memories. This suggests that AR maps produce worse survey knowledge than 2D mobile maps. However, Qiu et al. (2023) conducted a similar study where participants used Baidu Maps (including both AR and 2D mobile map modes) to travel from a starting point to a destination at a university. Participants completed scene recognition and orientation judgment tasks, scene-sequencing tasks, and configurational representation tasks. Results showed that 2D mobile maps had better navigation efficiency than AR maps, while AR maps were superior in landmark and route knowledge. However, there was no difference between 2D mobile maps and AR maps in survey knowledge acquisition. Some researchers systematically compared paper maps, electronic maps (E-maps, similar to 2D mobile maps), and AR maps in a virtual environment (Yount et al., 2022). In the paper map condition, individuals studied the map before driving and could also refer to it while driving. In the electronic map condition, a small map displayed on the dashboard updated in real time based on the driver's location, providing turn instructions (e.g., "turn right at the next intersection"). In the AR map condition, a green route appeared on the road with floating arrows at turning points indicating direction. After completing the navigation task, participants performed landmark recognition, landmark ordering, and map selection tasks (choosing from ten maps, one perfectly matching the environment and nine containing one to nine errors). Results showed no significant differences among the three navigation aid types in landmark or route knowledge, but map selection errors were significantly fewer when using paper maps than AR maps, with no significant differences for electronic maps. However, one study found no differences among 2D mobile maps, AR maps, and voice navigation in spatial knowledge acquisition (Huang et al., 2012). Notably, the 2D mobile map used in that study did not provide turn-by-turn navigation but instead displayed a virtual green route, and voice navigation provided auditory instructions containing semantic information ("go straight, pass the theater, then walk to the intersection") rather than simple turn-by-turn commands ("turn left").

Overall, for landmark and route knowledge, AR maps may be superior to 2D mobile maps (Qiu et al., 2023), though some studies show no significant differences (Yount et al., 2022). This discrepancy may stem from different experimental environments: the former based on real-life settings and the latter using virtual environments, where AR maps may have advantages in complex real-world settings. Additionally, in Yount et al.'s (2022) study, the landmark recognition test included only two new landmark images and eight old ones, potentially yielding high accuracy across all participants. For survey knowledge, AR maps may be inferior to 2D mobile maps (Dong et al., 2021) or show no significant difference (Qiu et al., 2023; Yount et al., 2022). This may relate to different task types: the former used sketch drawing tasks, while others used landmark placement or map selection tasks. Sketch drawing tasks require participants to recall and draw cognitive maps, more effectively reflecting acquired survey knowledge. Therefore, whether AR maps or 2D mobile maps are superior for spatial knowledge acquisition remains controversial.

2.2 Why Does Turn-by-Turn Navigation Weaken Spatial Memory?

Turn-by-turn navigation automates certain cognitive processes, preventing deep information processing and making it difficult to form stable spatial memory. Successful navigation first requires determining one's location in space and orientation, then planning and executing a route based on the destination's location (Ishikawa et al., 2008). Therefore, encoding, storing, and recognizing environmental visual details are crucial parts of wayfinding (Afrooz et al., 2018). Using paper maps for wayfinding requires actively processing, transforming, and memorizing spatial information (Münzer et al., 2012), intentionally engaging in spatial orientation (Ishikawa, 2019), expending additional active effort (Münzer et al., 2006), and making decisions to determine routes. However, turn-by-turn navigation actively takes over these information processing steps, providing only the answer. For example, mobile navigation systems provide positioning information, eliminating the need for self-orientation (Xu et al., 2022) and reducing motivation to acquire spatial knowledge since such knowledge is no longer necessary for reaching the destination (Krüger et al., 2004). Using paper maps requires mental rotation to determine correct turning directions, a process eliminated by mobile maps (Yount et al., 2022). Turn-by-turn navigation also takes over decision-making processes, transforming individuals from route planners to instruction followers. When using paper maps, individuals as decision-makers must understand spatial relationships between their current location and environmental landmarks, establishing relationships between their body and the environment and making specific turning decisions, processing information at a deeper level. However, when using turn-by-turn navigation, following instructions is reactive, with individuals adopting an egocentric perspective without needing to represent the environment (Bakdash et al., 2008; Burnett & Lee, 2005). Research shows that increased route decision-making promotes survey knowledge acquisition (Lu et al., 2021); therefore, navigation systems should return route decision-making authority to individuals.

The way turn-by-turn navigation presents spatial information is not conducive to learning environmental structure or acquiring survey knowledge. Paper maps present spatial information in a non-centered, global representation, directly showing environmental structure and spatial relationships between locations, helping individuals understand environmental structure (Münzer et al., 2006, 2012). However, turn-by-turn instructions are incompatible with how individuals naturally process spatial information; people do not execute instructions one by one in isolation but integrate information, spontaneously learning spatial structure and building cognitive maps during wayfinding (Schwering et al., 2017). Furthermore, turn-by-turn navigation interfaces present information consistent with the individual's perspective, facilitating wayfinding, but environmental structure information is either not presented at all or presented incompletely (Münzer et al., 2006, 2012), eliminating the necessity of integrating spatial information. This may cause individuals using turn-by-turn navigation to adopt visually dominant strategies, while those using paper maps tend to adopt spatially dominant strategies. In visually dominant strategies, wayfinding decisions are based on visually identified decision points (e.g., landmarks) along the route, but these decision points are not integrated into a global representation. In spatially dominant strategies, individuals represent the environment as a global map from the outset (Aginsky et al., 1997). This may explain why paper maps may yield better survey knowledge.

Turn-by-turn navigation reduces individual-environment interaction through distraction, hindering spatial knowledge acquisition. Wayfinding is the process of gathering information from the built environment to understand one's location relative to the destination and how to get there (Woyciechowicz & Shliselberg, 1903). Drivers using paper maps pay more attention to the driving environment (Burnett & Lee, 2005), whereas following simple turn-by-turn navigation instructions makes attention to navigation-relevant environmental features unnecessary (Gramann et al., 2017). GPS navigation may reduce environmental contact and gradually disconnect individuals from the environment (Leshed et al., 2008). Specifically, individuals focus attention on GPS navigation (Hejtmánek et al., 2018), reducing spatial exploration behavior and consequently decreasing spatial knowledge acquisition (Schade et al., 2023). Since turn-by-turn instructions provide turning commands based on distance determined by the individual's current location and the next intersection, and the interface updates the individual's position in real time, instructions repeatedly remind individuals of the remaining distance. Therefore, individuals must attend to constantly updating information on the screen (Ishikawa et al., 2008), dividing attention between the mobile device and the environment (Willis et al., 2009). This attentional division conflicts with spatial information integration (Huston & Hamburger, 2023), hindering spatial memory formation. Turn-by-turn navigation is typically used on mobile devices, and research shows that the mere presence of navigation aids impairs spatial memory even without secondary tasks, but this effect is not exacerbated when secondary tasks are present (i.e., when attention is divided), suggesting that navigation devices themselves are sufficiently distracting (Gardony et al., 2015). In summary, researchers have conducted in-depth theoretical discussions on why turn-by-turn navigation weakens spatial memory, but most discussions remain at the theoretical level, and future research should provide empirical support with data.

3 Approaches to Improving Turn-by-Turn Navigation

Built-in GPS navigation systems in cars and pre-installed applications on most smartphones (e.g., Google Maps) are currently common navigation aids (Huston & Hamburger, 2023). Research shows that turn-by-turn navigation impairs individuals' spatial memory (Hejtmánek et al., 2018; Qiu et al., 2023; Lanini-Maggi et al., 2023; Yount et al., 2022; Xu et al., 2022). As GPS navigation use increases, individuals' spatial cognitive abilities may decline, potentially affecting their independence, autonomy, and quality of life (Gramann et al., 2017). Consequently, many researchers have begun proposing new navigation systems to promote spatial knowledge acquisition. These different navigation systems are called non-turn-by-turn navigation.

3.1 Improving Instructional Information: Landmark-Based Navigation

Environmental legibility refers to the clarity of urban landscapes (Kumar et al., 2023), comprising five components: landmarks, paths, nodes, edges, and districts (Lynch, 1964). Research shows that landmarks increase environmental legibility, helping individuals recognize the built environment. Routes with internal or external landmarks are easier to remember than those without, and individuals remember nodes with landmarks more accurately than those without

(Ahmadpoor et al., 2021). A legible city has clear spatial structure and physical form, enabling individuals to orient and navigate relatively easily, thereby forming clear cognitive maps (Taylor, 2009). Landmarks are the primary urban image in cognitive maps (Erçevik Sönmez & Erinsel Önder, 2019), and setting prominent landmarks can clarify environmental structure, making it easier for individuals to acquire spatial knowledge. Landmarks should have three characteristics: visual distinctiveness, referring to objective features that differ physically from the surroundings; inferred distinctiveness, related to structure or form that makes them stand out; and functional distinctiveness, referring to salience related to individuals' goals or sub-goals (May & Ross, 2006). Landmark-based navigation is characterized by instructions containing salient landmark information. Compared to simple turn-by-turn instructions (e.g., "turn right after 100 meters"), instructions containing landmark information (e.g., "please turn right at the concert hall, where you can listen to concerts") can effectively improve individuals' spatial knowledge (Gramann et al., 2017; Wunderlich et al., 2023).

Researchers have conducted a series of studies on the role of landmarks in navigation. One study used spontaneous blinks as event markers in continuously recorded EEG data to assess cognitive load during mobile map navigation tasks, finding that mobile maps with a moderate number of landmarks (i.e., five) may be the optimal choice for supporting spatial learning without excessively consuming attentional resources (Cheng et al., 2023). Displaying realistic 3D landmark symbols at intersections may help individuals remember routes in urban environments better than abstract 3D landmark symbols (Kapaj et al., 2022). Intersections with landmarks are more likely to be accurately represented by individuals than those without landmarks (Ahmadpoor & Smith, 2020). Using holographic images to display virtual semantic landmarks in indoor environments helps acquire landmark knowledge (Liu et al., 2021). Providing virtual global landmarks in navigation environments can promote the formation of mental maps (Liu et al., 2022). Good landmarks can significantly increase individuals' confidence before turning, while using distance information to locate turning points leads more people to look at the display (May & Ross, 2006). EEG evidence shows that highlighting landmark information in navigation instructions promotes significant long-term spatial learning effects (Wunderlich & Gramann, 2018). Therefore, the presence of landmarks in the environment helps individuals acquire more accurate spatial knowledge.

In Lakehal et al.'s (2023) study, landmark-based navigation used GPS to track individuals' current locations, displaying navigation instructions containing landmark information when they approached decision points (e.g., "turn right when you see the bus stop; 20 meters"). Participants completed pedestrian navigation tasks in residential areas using smartphones or AR glasses. Results showed that AR glasses enabled better memory for landmarks and routes. Note that this experiment examined how different interactive devices (smartphones and AR glasses) affect spatial knowledge acquisition in landmark-based pedestrian navigation but did not compare landmark navigation with turn-by-turn navigation. Some researchers have compared turn-by-turn navigation instructions with landmark navigation instructions (Wunderlich & Gramann, 2021b). The experiment required individuals to navigate along predetermined routes following auditory navigation instructions. Turn-by-turn instructions were: "turn right at the next intersection." Short landmark instructions simply named landmarks: "turn right at the bookstore." Long landmark instructions provided additional semantic information about landmarks: "turn right at the bookstore, where public reading sessions are held every week." Two weeks later, participants completed a cued-recall task, recognizing landmarks while judging route directions based on landmark locations. Results showed that both short and long landmark instructions yielded better landmark and route knowledge than turn-by-turn instructions. Similarly, one study compared reference-based (or landmark) navigation, orientation-based navigation, and turn-by-turn navigation based on 2D and AR maps (Kuo et al., 2023). Participants used one of these methods to complete two navigation tasks: an assisted navigation task with continuous navigation aid support, followed by a pointing task after reaching the destination and returning to the start; and an independent navigation task where participants could only ask the navigation system via a virtual phone when confused, finally marking the destination on a virtual city map. Results showed that individuals using landmark navigation could locate destinations with high accuracy compared to those using both types of turn-by-turn navigation, indicating that landmark navigation helps acquire survey knowledge. Moreover, landmark navigation's wayfinding efficiency in the independent navigation task was comparable to turn-by-turn navigation and was the only navigation system where participants spent less time in the independent navigation task than in the assisted navigation task, suggesting that landmark navigation enables individuals to acquire sufficient spatial knowledge and enhances their independent navigation ability. Schwering's (2017) oriented path following is essentially similar to landmark navigation; its direction instructions (e.g., "walk toward the city center"; "turn left at the supermarket, circle around the city center") highlight landmark information, and research shows that people can acquire survey knowledge through appropriate oriented path following navigation.

In summary, landmark navigation may match turn-by-turn navigation in wayfinding efficiency, though more research is needed. Landmark navigation may be superior to turn-by-turn navigation in spatial knowledge acquisition. One study using mobile EEG recorded participants' brain activity during urban navigation while they received either voice turn-by-turn navigation or voice landmark navigation. Results showed that compared to participants receiving turn-by-turn instructions, those receiving landmark instructions showed higher EEG amplitude values in fronto-central leads within a 300-millisecond time window after blinking, and subsequent spatial tasks also improved, indicating that following landmark instructions involves higher-level cognitive processes and deeper processing of existing information (Wunderlich & Gramann, 2021a). Future research should continue to compare landmark navigation with turn-by-turn navigation, considering how to improve landmark navigation's wayfinding efficiency and apply it to mobile devices.

3.2.1 Enhancing Sensory Modalities Beyond Vision

In addition to landmark navigation, researchers have designed other navigation types to improve or replace turn-by-turn navigation. Some studies aim to adjust how individuals receive information by enhancing sensory modalities beyond vision to promote spatial memory formation. For example, Clemenson et al. (2021) proposed a sensory augmentation-based GPS navigation system using a 3D spatial audio system similar to an auditory compass, enabling individuals to reach destinations without explicit instructions and encouraging active participation in spatial navigation. Results showed that compared to turn-by-turn navigation, auditory compass navigation stimulated more exploration behavior and formed more accurate cognitive maps. Similar approaches include tactile feedback for pedestrian navigation systems, which provide route instructions through vibration patterns, allowing individuals to receive instructions without vision and thus pay more attention to the environment (Pielot et al., 2012), and tactile foot feedback navigation systems for blind and visually impaired individuals (Velázquez et al., 2018).

3.2.2 Enhancing Autonomy in Navigation

Promoting spatial knowledge acquisition by returning to individuals the freedom to explore environments and plan routes. One study designed a Potential Route Area Navigation (PRA) interface based on dynamic potential route areas containing all possible routes individuals would accept, allowing them to freely choose and change routes. Results showed that compared to traditional turn-by-turn navigation represented by Google Maps, PRA navigation significantly improved both spatial knowledge acquisition and user experience (Huang et al., 2022). Similar to this is Mazurkiewicz's (2023) Free Choice Navigation, whose core idea is to give individuals more freedom rather than providing predefined routes, requiring individuals to make decisions at intersections and thus become more engaged with the environment. However, research results show little difference between free choice navigation and turn-by-turn navigation in spatial knowledge acquisition.

3.2.3 Applying Augmented Reality Technology

Using augmented reality technology to improve turn-by-turn navigation. Quadcopter-Projected In-Situ Navigation uses AR technology with projector-equipped quadcopters to present navigation instructions directly in the environment, thereby enhancing individuals' ability to observe points of interest in the real world (Knierim et al., 2018). In summary, besides improving instructional information, turn-by-turn navigation can be enhanced through other sensory channels, increasing individuals' environmental exploration behavior, or other methods. However, new navigation systems may not match turn-by-turn navigation in wayfinding efficiency (Knierim et al., 2018), and future research should focus on how to promote spatial knowledge acquisition while improving wayfinding efficiency.

4 Summary and Outlook

Regarding the effects and mechanisms of turn-by-turn navigation on spatial memory, research results often differ due to variations in experimental environments (urban residential areas, university campuses, or virtual environments), methods for measuring spatial knowledge, and participant populations (college students, drivers, or other groups). However, it is certain that turn-by-turn navigation use weakens some aspect of spatial knowledge (landmark knowledge, route knowledge, or survey knowledge). This paper also discusses improvements to turn-by-turn navigation systems, including new navigation systems such as landmark navigation and potential route area navigation. These new systems effectively promote spatial knowledge acquisition compared to turn-by-turn navigation but may be lacking in wayfinding efficiency, offering hope for further improvement to become alternatives to turn-by-turn navigation.

4.1 A Model of Turn-by-Turn Navigation's Effects on Spatial Memory

Based on current research findings (Ahmadpoor et al., 2021; Dong et al., 2021; Parush et al., 2007; He & Hegarty, 2020; Ishikawa et al., 2008; Leshed et al., 2008; Schwering et al., 2017), this paper proposes a model of how turn-by-turn navigation affects spatial memory, focusing on explaining the impact of turn-by-turn navigation on spatial memory and examining other navigation aids such as paper maps and landmark navigation (Figure 3 [Figure 3: see original paper]).

Figure 3 Model of turn-by-turn navigation's effects on spatial memory

4.1.1 Individual Differences in GPS Turn-by-Turn Navigation Individual differences can be divided into three categories of factors. Stable, unchangeable factors such as gender and age are inherent individual characteristics. Relatively stable but changeable factors have some plasticity and can be improved through training, such as sense of direction, spatial perspective-taking ability, mental rotation ability, and spatial anxiety. Factors related to individual experience concern life experiences and habits, such as video game experience, GPS navigation dependence, and GPS usage.

The likelihood of using GPS navigation decreases with age. A survey of 456 healthy adults aged 25 to 84 found that age negatively predicted GPS navigation use, while visuospatial working memory positively predicted GPS navigation use (Muffato et al., 2022). This may be because the study's age span was large, and individuals with better visuospatial working memory were more likely to actively use technological aids. Regarding gender differences, overall, males show significant advantages in spatial navigation ability (Nazareth et al., 2019; Zhang et al., 2023). Males have better sense of direction, mental rotation ability, and spatial perspective-taking ability, and lower spatial anxiety (He & Hegarty, 2020; Ishikawa, 2019; Ruginski et al., 2019). Miola et al. (2023) found that in males, spatial self-efficacy (wayfinding self-efficacy and sense of direction) mediated the relationship between growth mindset and orientation behavior.

Believing in one's wayfinding ability can improve self-efficacy, leading to more environmental exploration and less GPS use. In females, while this indirect effect remained significant, unlike males, the direct relationship between growth mindset and GPS use and exploration tendency was no longer significant. This suggests that women's GPS use and environmental exploration tendencies are more influenced by spatial self-efficacy than directly by growth mindset.

Sense of direction refers to the perception and determination of current orientation (Xu et al., 2010), typically measured using the Santa Barbara Sense of Direction Scale (Hegarty, 2002). Individuals with a good sense of direction are more likely to integrate landmark and route knowledge into survey knowledge (Wen et al., 2011) and produce more accurate sketch maps (Dong et al., 2021). Research shows that in independent navigation tasks, participants with better sense of direction completed tasks faster. However, when participants used landmark navigation rather than turn-by-turn navigation in assisted navigation tasks, even those with poor sense of direction had similar task completion times as those with good sense of direction (Kuo et al., 2023). This suggests that landmark navigation can help people with weaker sense of direction improve wayfinding efficiency to some extent, while turn-by-turn navigation cannot provide this assistance.

He and Hegarty (2020) also examined the role of spatial anxiety. Model fitting results showed that individuals with higher spatial anxiety were less likely to actively explore the environment, more dependent on GPS navigation, and consequently had poorer navigation ability (sense of direction). Conversely, individuals with better sense of direction had lower spatial anxiety, less dependence on GPS, and greater tendency to explore the environment. Ruginski et al. (2019) explored the effects of mental rotation and perspective-taking. After controlling for navigation ability (sense of direction), mental rotation and perspective-taking abilities jointly mediated the effect of GPS use on environmental learning (virtual SILCton task). This suggests that long-term GPS use negatively affects environmental learning indirectly by reducing mental rotation and perspective-taking abilities. However, when mental rotation and perspective-taking jointly predicted GPS use, which then predicted environmental learning ability, model fit was consistent with the former. Thus, the causal relationship between GPS use and individual navigation ability seems difficult to determine. One possibility is that navigation is a "use it or lose it" skill (McKinlay, 2016), and abandoning autonomous navigation in favor of GPS assistance may lead to navigation ability degradation. Ishikawa's (2019) model showed that although mental rotation ability positively predicted wayfinding efficiency and sense of direction negatively predicted pointing errors, long-term in-car navigation system use affected individuals' spatial memory to a greater extent, with negative effects potentially outweighing benefits from better sense of direction and higher mental rotation ability. A longitudinal study (Dahmani & Bohbot, 2020) found no significant correlation between poor sense of direction and increased GPS use time, suggesting that frequent GPS users may not use it because of poor sense of direction; individuals accustomed to GPS navigation showed poorer spatial memory when completing independent navigation tasks. This provides further evidence for a causal relationship between GPS use and poor spatial memory. However, with a sample size of only 13, this conclusion should be viewed cautiously. Although using GPS navigation may lead to poorer spatial memory compared to other navigation aids, making individuals' navigation performance worse in real-world independent navigation tasks (Sugimoto et al., 2022), most studies are cross-sectional and cannot reflect the effects of long-term GPS use on navigation ability.

Over-reliance on navigation systems may cause individuals to become "indifferent" to the environment, unable to develop wayfinding and orientation skills, and unable to acquire spatial knowledge that may be needed when navigation systems fail (Parush et al., 2007). However, gaming experience may help mitigate negative effects of GPS dependence. Research shows that participants with higher GPS dependence scores spent more time and effort observing and memorizing targets and their surroundings in target-finding tasks. However, gaming time moderated this effect, with high-frequency gamers showing less negative impact than non-frequent gamers (Yan et al., 2022). Yavuz et al. (2024) used multiple linear regression to analyze the effects of gender, GPS navigation dependence, and weekly video game time on wayfinding distance in the Sea Hero Quest task. Results showed no significant correlation between GPS dependence and wayfinding distance, indicating that GPS dependence does not lead to poorer wayfinding performance. Longer weekly video game time was associated with shorter wayfinding distance, while gender effects were not significant. However, when game time was not considered, gender effects were significant, with males showing better navigation performance. This suggests that video game experience may have a stronger effect on navigation performance than gender. It also indicates that GPS navigation dependence is not always negatively correlated with spatial navigation ability. The reason may be that target-finding tasks reflect mental rotation ability, while the Sea Hero Quest task focuses more on assessing spatial navigation skills. Notably, although Yavuz et al.'s (2024) task more effectively reflects individual spatial navigation ability, it is essentially in video game form, differing greatly from real navigation environments and being influenced by individual gaming experience. Therefore, future research should use tasks with more realistic environments to study the effects of GPS navigation dependence.

Additionally, environmental familiarity may moderate the relationship between sense of direction and GPS turn-by-turn navigation use. People familiar with environments typically draw more landmarks in sketch map tasks (Zhu et al., 2022) and have clearer representations of environmental structure. Research shows that individuals with poor sense of direction are more likely to use GPS for turn-by-turn navigation. However, as environmental familiarity increases, GPS turn-by-turn navigation use decreases (Topete et al., 2024).

4.1.2 Cognitive Mechanisms of Turn-by-Turn Navigation's Effects on Spatial Memory Because individuals must check instruction information and current location, using turn-by-turn navigation may cause frequent shifts of attention from the external environment to the mobile device. This attentional division may prevent individuals from adequately acquiring environmental information. Turn-by-turn navigation saves individuals the time-consuming and effortful processes of self-orientation and route planning, leading to lack of volitional effort and processing of surrounding environmental information. The navigation perspective presented on turn-by-turn navigation mobile device interfaces usually aligns with the individual's current orientation, and the segmented, sequentially delivered instructions may cause discontinuous acquisition of environmental information, making individuals more likely to form egocentric spatial memory that is not conducive to learning environmental structure. These four aspects all make turn-by-turn navigation detrimental to spatial knowledge acquisition, which may hinder the development of spatial navigation abilities in the long run. Compared to turn-by-turn navigation, paper maps directly present the overall environmental structure, requiring individuals to actively expend cognitive effort to obtain orientation information from the environment, process surrounding environmental information, and plan routes, making it more likely for individuals to acquire knowledge about environmental structure. Landmark navigation provides meaningful landmark information to individuals, promoting deep semantic processing. Meanwhile, its instructions increase intentional attention to environmental landmarks, inputting environmental stimulus information into working memory for processing, thereby forming stable spatial memory. Additionally, environmental legibility affects spatial memory, with clear environmental structure promoting cognitive map formation.

4.2 Recommendations for Improving Turn-by-Turn Navigation

As the saying goes, "the weather is unpredictable, and misfortune may strike at any moment." Spatial knowledge can be used for reorientation, distance judgment, and location recall. When mobile navigation devices are unexpectedly lost or damaged, how to rely on spatial knowledge acquired from the environment to escape predicaments is crucial (Aslan et al., 2006). Therefore, improving turn-by-turn navigation to promote spatial knowledge acquisition can focus on the following recommendations.

Improve the content of turn-by-turn navigation instructions by adding meaningful information. For example, prominent landmark information can be added. Unique environmental features (i.e., landmarks such as restaurants and churches) are important for cognitive map formation (Burnett & Lee, 2005). When people learn routes in new environments, they seek out prominent landmarks (Miller & Carlson, 2011), and research shows landmarks can be effectively used in pedestrian navigation aids (Goodman et al., 2005). Lanini-Maggi et al. (2023) required participants to complete virtual space navigation tasks using narrative instructions and standard instructions. Narrative instructions were: “When you arrived at this restaurant, the aroma of delicious food greeted you, lifting your spirits. Suddenly, you found your friends already waiting there, ready to celebrate your birthday with you! After the meal, one friend prepared to go home, and you decided to go together. Starting from the restaurant, turn left and go straight until you reach your friend’s home!” Standard instructions were: “Please take a photo at the photography studio in front of you, then turn left to go to the bank.” Results showed that narrative-based navigation instructions could improve individuals’ memory for landmark sequences.

Based on the testing effect and forward testing effect, spatial knowledge tests can be administered multiple times during navigation to consolidate spatial memory. The testing effect refers to the phenomenon that testing during learning improves later memory retention more than additional study, even without feedback (Zhang et al., 2008). In the forward testing effect, taking tests enhances memory for subsequent learning materials (Cho et al., 2017). Research shows that both testing effects (Kelly et al., 2015) and forward testing effects (Ma et al., 2022) exist in large-scale environments, so spatial knowledge can be promoted through multiple tests of acquired spatial knowledge during route learning.

Design game modes aimed at exercising spatial navigation abilities. Research shows that experienced video game players perform better in virtual navigation tasks, especially those playing games containing navigation elements (Murias et al., 2016). As an audio-visual device-based game form, video games positively affect key stages of cognitive processing such as perception, attention, and memory (Shi & Shang, 2024). For example, the game Tetris can improve mental rotation ability (Martin-Gutierrez et al., 2009). Lin et al. (2014) developed a spatial treasure hunting game and found that it effectively enhanced individuals’ spatial orientation ability and spatial memory in a short time, while also helping narrow the gap between females and males in spatial orientation ability. Some researchers designed a mobile application with gamification elements (e.g., tasks, statistics, and social competition), requiring individuals to actively explore the environment to discover maps, experiencing pleasure from the game and thereby strengthening their spatial knowledge (Schade et al., 2023). In view of this, future navigation software could incorporate game modules that promote spatial navigation abilities to mitigate potential negative effects of over-reliance on GPS navigation.

Provide adaptable services to meet diverse individual needs. Adaptable services allow users to change service functions, thereby maintaining user control. Navigation systems should consider individuals’ travel purposes—whether prioritizing navigation efficiency or environmental exploration (Kuo et al., 2023). High-automation navigation system behavior refers to systems automatically executing cognitive processes, while low-automation navigation system behavior refers to systems delegating decision-making processes to individuals (Brügger et al., 2019). For individuals needing high navigation efficiency, high-automation navigation systems should be provided, such as offering turn-by-turn instructions, short routes, and track-up map modes. For individuals 倾向于 exploring environments, low-automation navigation systems should be provided, such as offering landmark-highlighting instructions, multiple routes, and north-up map modes, thereby promoting more interaction with the environment and spatial knowledge acquisition. Additionally, individuals unfamiliar with environments prefer image landmark symbols, while those familiar with environments prefer text landmark symbols. Researchers have designed pedestrian navigation maps that account for different user familiarity levels, and using these maps significantly reduced map zooming compared to using 2D mobile maps (Zhu et al., 2022). Therefore, for individuals new to or unfamiliar with environments, navigation software can provide landmark maps with prominent visual features to reduce environmental adaptation difficulty. Meanwhile, to meet the needs of elderly users, navigation interface design should be simple and elegant while also considering color effects. Research shows that compared to cool or warm virtual environments, elderly people have longer wayfinding times, more turning errors, and worse route memory in neutral-tone virtual environments (Süzer & Olguntürk, 2018). Therefore, when designing navigation modes for elderly groups, cool or warm color schemes should be prioritized.

Individuals should cultivate awareness of independent navigation and avoid overreliance on mobile assistive devices. Although GPS systems can make our lives easier, they are often used to automate functions originally performed entirely by our brains (Clemenson et al., 2021). A controversial but widely accepted consensus is that increased use of navigation aids is associated with declines in navigation skills (i.e., cognitive skills) and social interaction (Huston & Hamburger, 2023). In the long run, habitual passive following of navigation instructions changes individuals' spatial awareness, making the situation worse (Ishikawa, 2021). However, individuals do not need to avoid using turn-by-turn navigation devices but should be cautious and avoid blindly following instructions (Kuo et al., 2023).

4.3 Future Research Directions

Current research still has limitations, and future studies can focus on the following aspects.

Improving measurement methods for spatial knowledge in large-scale environments. Some researchers have only examined one aspect of spatial memory (Kelly et al., 2022). However, spatial memory in large-scale environments comprises multiple levels (landmark knowledge, route knowledge, survey knowledge). Even when most researchers measure all three types of spatial knowledge, methods often vary considerably. For example, route knowledge is measured using landmark ordering tasks (Lanini-Maggi et al., 2023), route backtracking tasks (Sugimoto et al., 2022), or scene recognition and orientation judgment tasks (Qiu et al., 2023). Survey knowledge is measured using pointing tasks (Ben-Elia, 2021), distance estimation tasks (Ruginski et al., 2019), blank map tasks (Hejtmánek et al., 2018), or map drawing tasks (Ahmadpoor

& Smith, 2020; Dong et al., 2021). Although these methods can measure route or survey knowledge, they undoubtedly fail to reflect the complete picture, and different methods produce different measurement errors. Therefore, establishing an effective and comprehensive paradigm for measuring individual spatial knowledge is crucial. Future research should use unified measurement methods or employ multiple different methods to measure the same type of spatial knowledge.

Investigating the neural mechanisms by which turn-by-turn navigation impairs spatial memory. Although most behavioral experiments show that turn-by-turn navigation is detrimental to spatial knowledge acquisition, neurophysiological evidence remains limited. The posterior hippocampus may be related to individuals' spatial representation of the environment (Maguire et al., 2000). Research found that as taxi drivers' navigation experience increased, gray matter volume in the right posterior hippocampus increased while anterior volume decreased (Maguire et al., 2006). A longitudinal study by Woollett and Maguire (2011) showed that among participants who successfully obtained taxi driver qualifications, posterior hippocampal gray matter volume increased significantly over four years, while control groups showed no similar brain structural changes. This indicates that daily navigation experience can cause brain structural changes, but whether daily turn-by-turn navigation experience similarly affects hippocampal volume remains to be investigated. Fajnerová et al. (2018) required experimental group participants to wear AR glasses with the OsmAnd application (featuring GPS turn-by-turn navigation) for daily navigation for three consecutive months, while the control group used no GPS devices during navigation. Although both groups performed similarly on virtual navigation tasks, the experimental group showed significantly reduced functional connectivity in the right hippocampus, while the control group showed enhanced connectivity. In summary, future research should further explore the effects of daily GPS turn-by-turn navigation use on the hippocampus to more comprehensively understand the potential impacts of turn-by-turn navigation on brain function and behavior.

Focusing on individual factors to establish a more comprehensive explanatory mechanism, such as gender, sense of direction, spatial anxiety level, and perspective-taking ability. Research shows gender differences in spatial memory (Chen et al., 2020), and individuals with good sense of direction are more likely to integrate landmark and route knowledge to form survey knowledge (Wen et al., 2011). Currently, many studies do not measure individuals' sense of direction (Ben-Elia, 2021; Cheng et al., 2023; Hejtmánek et al., 2018; Lanini-Maggi et al., 2023; Yount et al., 2022), some control for sense of direction as an extraneous variable (Lakehal et al., 2023; Qiu et al., 2023), and some treat sense of direction or spatial anxiety as experimental factors along with navigation aids (Dong et al., 2021; He & Hegarty, 2020; Ishikawa, 2019; Kuo et al., 2023). However, only a few studies have considered multiple individual factors simultaneously. For example, research found that after controlling for existing navigation ability (i.e., sense of direction), turn-by-turn navigation use still had negative effects on mental rotation and perspective-taking abilities (Ruginski et al., 2019). Therefore, future research should incorporate individual factors to broaden the applicability of findings.

New navigation systems should aim to achieve high levels of both wayfinding efficiency and spatial knowledge acquisition. There appears to be some trade-off between navigation efficiency and environmental structure learning: paper maps display wayfinding information in bird's-eye view, associated with a stable external reference frame, which benefits structural learning, but this advantage promotes survey knowledge acquisition at the expense of accurate wayfinding (Münzer et al., 2012), and their wayfinding efficiency is generally lower than mobile maps (Hergan & Umek, 2017). Using turn-by-turn navigation allows individuals to reach destinations in optimal ways (e.g., fastest, simplest, easiest, safest) (Schwering et al., 2017), with high wayfinding efficiency but detrimental to spatial knowledge acquisition. Landmark navigation is similar, with wayfinding efficiency generally slightly inferior to turn-by-turn navigation but helping individuals acquire spatial knowledge. Therefore, how to design a navigation system that is both efficient and promotes spatial memory formation remains a problem to be solved.

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Note: Figure translations are in progress. See original paper for figures.