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Published online: 16 Mar 2022.

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Designing mobile spatial navigation systems from the user's perspective: an interdisciplinary review

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ABSTRACT

Navigation systems have become increasingly available and more complex over the past few decades as maps have changed from largely static visual and paper-based representations to interactive and multimodal computerized systems. In this introductory article to the Special Issue on Human-computer Interaction, Geographic Information, and Navigation, we review literature across a variety of fields to generate nine design principles to guide future research and development of navigation systems. Specifically, we suggest making mobile navigation systems more accessible and multimodal, which will make the systems more inclusive and usable for all types of users. We also introduce the research articles contributed to the present special issue and suggest future research directions to empirically evaluate emerging and untested features of user-adapted and context-aware mobile navigation systems.

1. Introduction

Most people travel outside of their homes every day, whether for work, play, or to fulfil basic needs. Beyond its personal value, efficient and effective navigation can ensure that cities operate smoothly or that search and rescue missions are successful. Often during travel, people utilize navigation systems to support wayfinding through the environment. The availability and complexity of navigation systems have increased over the past two decades now that smartphones and small assistive computers are widely available. For example, 81% of adults aged 18 and older in the United States own GPS-enabled smartphones as of 2019, which has increased dramatically since 2011, when only 35% of U.S. adults possessed smartphones (Pew Research, 2019).

Scientists across many disciplines have claimed that navigation systems may degrade the user's spatial learning and spatial problem solving abilities but generalizations are difficult to make because not all navigation systems provide equivalent information and individuals utilize navigation systems in different

ways (Dahmani & Bohbot, 2020; Hejtmánek, Oravcová, Motýl, Horáček & Fajnerová, 2018; Ishikawa, Fujiwara, Imai & Okabe, 2008; Ruginski, Creem-Regehr, Stefanucci & Cashdan, 2019; Willis, Hölscher, Wilbertz & Li, 2009) . For example, people can use navigation systems as a visual map, as a provider of auditory route directions, or to check traffic patterns to choose an uncongested travel path. As such, it is critical to synthesize findings across the fields of geography (cartography in particular), cognitive psychology, and human-computer interaction on the design, implementation, use, and impacts of navigation systems (Coughlan, Laczó, Hort, Minihane & Hornberger, 2018). Recently, there have been several calls for usability research on mobile geographic information aids, with many challenges and opportunities outlined for future work (Delikostidis, van Elzakker & Kraak, 2016; Roth, 2018).

To this end, in this introductory article to the Special Issue on "Geographic Information, Human-computer Interaction, and Navigation," we aim to provide a review of recent literature to identify gaps in understanding across disciplines and suggest future research directions and challenges based on the consideration of these gaps. We start by defining navigation-relevant geospatial information and describing the implementation of this information on navigation systems. We then offer some key design recommendations and future research opportunities based on these systems.

2. Geospatial information and navigation

Navigation systems have been shown to affect the user's spatial learning (e.g., landmark location and configural knowledge) and navigational efficiency (e.g., travel time and navigation accuracy). Often, while the user may reach their goal successfully, their spatial learning is negatively affected (Dahmani & Bohbot, 2020; Gardony, Brunyé, Mahoney & Taylor, 2013; Hejtmánek et al., 2018; Ishikawa, 2019; Ishikawa & Takahashi, 2014; Ruginski et al., 2019). Although some navigation systems can have short-term negative effects on wayfinding and spatial learning (e.g., poor immediate recall of the traversed environment; Gardony et al., 2013; Hejtmánek et al., 2018; Ishikawa et al., 2008) and others lead to long-term deficits (e.g., degradation of spatial cognitive skills and awareness; Dahmani & Bohbot, 2020; Ishikawa, 2019; Ruginski et al., 2019), the problem of when and how to best use these systems remains multi-faceted. We do not argue that we should dispense with navigation systems; they are definitely convenient and support self-navigation, for example, for people with various disabilities, and the fact that the tools are popular and help simplify navigation tasks suggests that people will continue using them. What, then, do we still need to do, and how can we specifically improve these systems? What aspects of device design elements are associated with degraded spatial learning and navigational efficiency, in terms of cartographic visualizations or the method of providing directions? We posit that, to be truly effective, design elements should match how individuals categorize and

process spatial information, especially in reference to the difficulty that they have with accurate spatial orientation and the existence of large individual differences in this ability. This line of reasoning – that design should be based on cognitive abilities and constraints – reflects a philosophy that has been referred to as "cognitive engineering" (Montello, 2002; Montello, Fabrikant & Davies, 2018; Raubal, 2009; Richter, Tomko & Coltekin, 2015) and can be discussed in relation to the idea of *universal design* (often also called *inclusive design*). Universal design is the idea that making systems accessible to specific users, such as people with disabilities, makes the systems more accessible and inclusive for all users and more usable in a wider range of use cases (Iwarsson & Ståhl, 2003; Story, 1998). Throughout this paper, we leverage empirical research and cognitive theories to argue for design principles that support universal design of mobile navigation systems.

2.1. Navigation-relevant environmental information and processes

Navigation-relevant geospatial information can be broadly categorized into two types of knowledge: route knowledge and survey knowledge. Both route and survey knowledge include landmarks that people use to navigate the environment and locate themselves within it; route knowledge typically relies on proximal (close in space) landmarks and local cues, and these landmarks are not spatially integrated in the learner's mind (Siegel & White, 1975; see Taylor, Gardony, & Brunye, 2018, for a recent review). On the other hand, survey knowledge includes information about global features, such as cardinal directions and distal (far in space) landmarks, and they are represented in the learner's mind in a spatially integrated manner in a common frame of reference. These two types of knowledge are also related to navigational preferences and strategies, mapping onto, respectively, route-based and orientation strategies. There are well-studied individual differences in preference for each of these navigational strategies (Lawton, 1994; Pazzaglia & De Beni, 2001). Route-based strategies tend towards navigation decisions that can be considered "response-like" based on the sequences of locally encountered cues, whereas orientation (or survey) strategies are associated with the ability to take novel shortcuts based on a "cognitive map" closely resembling the environment in an approximately metric and configurational sense (Furman, Clements-Stephens, Marchette & Shelton, 2014; Marchette, Bakker & Shelton, 2011; Wiener, Tenbrink, Henschel & Ḧolscher, 2008).

Although the major source of information about these landmark cues is in many cases visual, other sense modalities are also important for our spatial learning and orientation. For example, non-visual cues such as local topography are also used in local navigation (Nardi, Newcombe & Shipley, 2013). Kinesthetic (sense of limb velocity and movement) and vestibular (sense of balance, translational and rotational movement through space) senses in

particular are especially important for spatial updating of one's position and orientation (heading direction – the direction that one is facing) in the environment (Chrastil, Nicora & Huang, 2019; Chrastil & Warren, 2013; Klatzky et al., 1990). Audition, smell, and haptics can also serve as cues for spatial location and orientation, either directly through the environment or via an assistive device (Hamburger & Knauff, 2019; Jacobs, Arter, Cook & Sulloway, 2015; Loomis, Klatzky & Giudice, 2013; Nardi, Twyman, Holden & Clark, 2020; Weisberg, Badgio & Chatterjee, 2018). Environmental information is thus multimodal and effectively redundant.

The issues of individual differences, navigational strategies, and the associated environmental cues used to navigate offer possible guidance for the information that navigation systems should provide to effectively aid navigators. This suggests a first design principle, that navigation systems should provide the option to deliver information about both local and global cues in the environment using multiple sensory channels in their user interface, since this matches how individuals reason about and categorize space (Arleo & Rondi-Reig, 2007; see the section on "Usability and accessibility" for more research on how multimodal cueing aids navigation). While self-selection of sensory feedback is critical to the avoidance of information overload, multisensory feedback in HCI systems reduces cognitive workload and increases usability (Freeman et al., 2017; Prewett, Elliott, Walvoord & Coovert, 2011; Prewett et al., 2006; Vitense, Jacko & Emery, 2003).

Note that there are many other navigation-relevant processes beyond the scope of the present article, such as dead reckoning (see Montello, 2005, for a review) and cognitive maps (see Golledge, 1978; Warren, Rothman, Schnapp & Ericson, 2017). Importantly, studies from the individual differences perspective emphasize that it is more informative to assess how and why people differ in the accuracy and developmental pattern of spatial knowledge, rather than discussing whether spatial knowledge is maplike – an approach that also applies to designing individually-adapted navigation systems (Ishikawa & Montello, 2006; Weisberg & Newcombe, 2018).

2.2. Presenting information using navigation systems

In this review, we discuss two essential methods of communicating navigation information through navigation systems: visually-represented maps and verbal navigational directions. We then review evidence for the effectiveness of multimodality in navigation systems, which makes systems more accessible to people with disabilities and a broader range of users more generally.

2.2.1. Visual information: Lessons from cartography, visualization, and the human visual system

Geographers have conducted years of research about how to best present map-based information to users to support navigation (see Montello, 2002, for a review). Creating maps involves a cognitive design process of cartographers abstracting from and modelling the complex world, and then communicating this information to end-users using visual conventions (Montello et al., 2018). This review will focus on cognitive and design issues related to the necessity of rapid understanding of environment-orientation information by users of mobile navigation systems with low information density. Low density displays are often envisaged as limited physical space on a visual display, but this idea also relates to other types of user interfaces and displays. For instance, down-sampling of information and selection of its conveyance is important to consider to ensure usability of speech-based information displays and haptic displays, both of which can convey similar spatial cues as visual interfaces do but via a much lower information bandwidth channel.

First, a navigation system should facilitate matching of the user's location in the real world to their location on a map quickly and accurately, avoiding what has been called the "alignment problem." (Montello, 2010; Presson, 1980). A map's topmost orientation should align with the viewer's facing direction to best facilitate map-environment matching and reduce the need for mental spatial rotation or perspective taking (Klippel et al., 2010; Montello, 2010; Richardson, Montello & Hegarty, 1999).

How can system design address the alignment problem? People typically travel more efficiently when using "track-up" maps, which rotate automatically on a digital device to match the user's heading direction (Taylor, Brunyé & Taylor, 2008). These map displays are contrasted with "fixed alignment" displays, which are consistently oriented with a cardinal direction (such as north) as the upwards direction regardless of the user's orientation and heading in the environment. Researchers have shown that determining a heading direction is easy with a track-up map, whereas fixed alignment maps facilitate relational (memory for position of landmarks relative to one another, which facilitates route following) and metric (memory for position of landmarks relative to a fixed metric grid or map, which facilitates taking shortcuts) spatial learning (Harwood & Wickens, 1991; Montello, 2010). This can result in fewer wayfinding errors with a track-up map, even though spatial learning is equivalent to, or worse than, that with a fixed alignment map (Münzer, Lörch & Frankenstein, 2019). This brings us to a second design principle: modern navigation systems should allow the user to choose between north-up and track-up maps, as the user's spatial abilities and usage context determine whether a track-up or north-up map is most supportive of wayfinding or spatial learning (Meneghetti, Muffato, Varotto & De Beni, 2017; Münzer et al., 2019).

Even if the alignment problem is solved, navigators should also be able to easily and quickly extract relevant information from a mobile map. Yet this is easier said than done – research has shown conflicting results regarding the benefits and pitfalls of the level of visual detail on maps. For example, people tend to prefer 3D information on maps, but preferences do not necessarily align with better performance (Hegarty, 2013). A detailed satellite imagery map can result in less efficient navigation, less attentional scanning of global landmarks, and more interactions with the map compared with a map containing only building and road footprints, but navigational errors do not differ depending on the level of detail (Dillemuth, 2005; Keil, Edler, Kuchinke & Dickmann, 2020). Other evidence suggests that landmark visualization in 3D increases navigational efficiency by reducing turning errors (Delikostidis et al., 2013; Li, Corey, Giudice & Giudice, 2016) and enhances spatial learning (Liao, Dong, Peng & Liu, 2017). More recent work shows that increased detail (satellite imagery) increases spatial memory for landmarks compared with a map depicting only building footprints and roads (Stevens & Carlson, 2019). Furthermore, individuals with a poor sense of direction perform navigation tasks more quickly using mobile maps that provide additional visual detail from a 2D perspective (Bienk, Kattenbeck, Ludwig, Müller & Ohm, 2013; Ohm, Bienk, Kattenbeck, Ludwig & Müller, 2016). Overall, the effects of visual detail on maps seem to depend on users' tasks, goals, and abilities – making this area ripe for future research from an individual differences perspective.

Regardless of visual detail, it is generally agreed that displays should avoid visual clutter. Visual clutter can be defined as task-irrelevant visual information that distracts the user's attention from task-relevant features, resulting in less accurate inferences or longer reaction times (Fabrikant, Hespanha & Hegarty, 2010; Hegarty, Canham & Fabrikant, 2010; Rosenholtz, Li & Nakano, 2007; Wilkening & Fabrikant, 2011). It includes multiple defining components, such as (1) feature congestion – the ability of a newly added item to draw attention; (2) subband entropy – the efficiency at which an image can be processed while maintaining quality, where higher entropy means that lesser prediction of the features of an item from the features of items close by in the display; and (3) edge density – the percentage of pixels in the display that are edge pixels (Rosenholtz et al., 2007). Visual clutter becomes an even greater problem when the user needs to gather information quickly by glancing, since peripheral vision is especially vulnerable to visual clutter (see Figure 1). Given this problem, the texture tiling model – a computational vision model that generates images with a simulated peripheral vision loss during eye fixations – is a powerful tool for assessing when displays may fail, particularly if the displays need to be used during multitasking or time-sensitive scenarios (Rosenholtz, 2016, 2020). Put simply, a third design principle suggests that navigation systems should avoid presenting non-essential information and should minimize visual clutter.

Figure 1. The phenomena of visual crowding in peripheral vision. Peripheral vision is extremely vulnerable to nearby clutter. Fixating on the white star in the top panel, it is very hard to see the path of the brown subway line. The task becomes trivially easy when other visual elements are removed, as in the rightmost panel. The task simplifies when the map is more abstract and less cluttered, even though the map is less geographically accurate (Berman, 2018). Top left and right figures reprinted with permission from Rosenholtz and Yu (2019). Bottom panel, Marco Vignelli inspired design, Wikipedia.org.

2.2.2. Providing directions and spatial language

Even if the visual display of a navigation system is well-designed, there remains the issue of verbally communicating directions and additional orientation information to the user to supplement the screen-based information. Many digital navigation assistants, such as Google Maps, provide *turn-by-turn* directions containing metric information, such as, "in 100 feet, turn left." However, these turn-by-turn directions typically contain little or no information about local or global landmarks in the environment, and assume that the user makes correct judgments about when and where to turn based on metric estimation (such as distance to a nearby intersection). In reality, when people provide directions to others in navigation, they often refer to landmarks and crucial decision points using gesture-based and natural language descriptions (Schroder, Mackaness & Gittings, 2011; Tenbrink & Winter, 2009; Weissensteiner & Winter, 2004). These types of directions could be either *chunking-based*, which combine different route elements to inform the

navigator about the next decision point (e.g., "turn right at the church after passing two streets"), or *orientation-based*, which provide local (near space) and global (far space) landmark information (Anacta, Schwering, Li & Muenzer, 2017; Klippel, 2003; Klippel, Hansen, Richter & Winter, 2009; Krukar, Anacta & Schwering, 2020; Schwering, Li & Anacta, 2013).

How should navigation systems provide directions? Klippel (2003) found that both Germans and Americans employ various directional chunking strategies to generate route directions, such as landmark chunking ("turn right at the main building, go straight after the church"), numerical chunking ("turn right at the second intersection, it's the third street to the right"), or structure chunking ("turn right at the roundabout"). Even though there is evidence that these types of descriptions are routinely used in natural language directions across cultures, there has been relatively little empirical work assessing their effectiveness in supporting spatial learning and wayfinding. Recently, Krukar et al. (2020) compared the effects of turn-by-turn directions ("turn right onto Clark St. in 500 meters"), chunking-based directions ("turn right at the church after passing the school"), and orientation-based directions (referring to global landmarks such as the city center; "go around the city center towards the church, then go through the park") on the recipient's spatial learning. They found that chunking-based and orientation-based directions improved spatial learning compared with turn-by-turn directions. Furthermore, orientation-based directions resulted in better survey knowledge than chunking-based directions without compromising route knowledge. In tandem, this research suggests a fourth design principle: that navigation systems should implement chunking or orientation information in their directions, or, at least, allow users to choose task-appropriate directions depending on the relevance of global information.

Other researchers have focused on the general role of landmarks in verbal navigational directions (see Richter & Winter, 2014, for a review). People typically express a desire for landmark inclusion in directions, particularly when encountering critical decision and re-orientation points in the environment, such as intersections or globally visible landmarks (Denis, Michon & Tom, 2007; Michon & Denis, 2001; Snowdon & Kray, 2009). Directions that cue navigators to landmarks help to increase navigational efficiency and spatial learning, particularly when salient landmarks are emphasized (Klippel & Winter, 2005; Nothegger, Winter & Raubal, 2004; Richter, 2007; Schwering et al., 2013). Including landmark information in directions improves both pedestrians' and drivers' procedural and configural spatial learning, particularly at navigation decision points (Gramann, Hoepner & Karrer-Gauss, 2017; Wunderlich & Gramann, 2019).

At the same time, landmark cueing can also lead to difficulties or disorientation. For example, when there are multiple turns available at critical decision points, navigators become confused about the correct turning point

(Hirtle, Richter, Srinivas & Firth, 2010; Tomko & Richter, 2015). However, these errors can be minimized by focusing directional cueing on landmarks that are salient (such as a major city hall) or provided by the user explicitly (Krieger, Kattenbeck, Ludwig, Helmbrecht & Giannopoulos, 2020; Tenbrink, 2018). Further, urban planners have recommended tailoring urban design so that it supports mobile map users, by building simple junctions with landmarks that are easily recognizable at intersection corners (Ahmadpoor & Smith, 2020; Ahmadpoor, Smith & Heath, 2021). Based on this research, we suggest a fifth design principle: that navigation systems explicitly cue users to decision-relevant and salient landmarks in the environment. A challenge for future research includes providing landmark information for global, off-route, off-screen, and non-visible landmarks (Dillemuth, 2009; Krukar, Mavros & Hoelscher, 2020; see the section on "Providing accessible global and orientation information" for further discussion).

2.2.3. Usability and accessibility

Making navigation systems more accessible and multimodal for people with sensory impairments will facilitate navigation for many users and in various navigation contexts. Although the major source of information for spatial cognition and navigation is often visual, environmental information is intrinsically multimodal and the human brain encodes spatial layout in a modality independent manner (Huffman & Ekstrom, 2019; Wolbers, Klatzky, Loomis, Wutte & Giudice, 2011). A large body of evidence suggests a *functional equivalence* between vision and other senses due to common perception, processing, and representation of spatial information between the senses; for example, highly similar navigation performance can be attained when learning is based on visual cues and haptic or auditory cues (see Giudice, 2018, for a review). This suggests that navigation devices should provide redundant spatial information to most effectively support the user's navigation, and that visual information is not necessarily better for supporting navigation than information from other sensory modalities.

Much of the navigation system literature has focused on making this technology accessible to blind and visually impaired (BVI) people. Navigation by BVI travellers poses several practical problems, such as obstacle avoidance and spatial updating using varying levels of residual vision and non-visual cues (Barhorst-Cates, Rand & Creem-Regehr, 2017; Giudice, 2018; Rand, Creem-Regehr & Thompson, 2015; Schinazi, Thrash & Chebat, 2016). Although canes and guide dogs are efficient for solving the problems of mobility and obstacle avoidance, obtaining relevant information about global landmarks and environmental configurations and updating or maintaining one's orientation in the environment remain difficult and cognitively effortful tasks for BVI travellers, something that can be greatly assisted through the use of navigation systems to aid in providing updated orientation information (Giudice & Legge, 2008). BVI

navigators often only have access to route information since (1) non-visual sensing (and degraded visual access) is limited to the immediate environment, meaning access to off-route information is generally limited and error prone (Giudice & Long, in press) and (2) most navigation systems only provide route instructions, rather than global environmental information. However, the most accurate navigation and orientation behavior requires knowledge of both route information and off-route environmental configuration, as this allows for an understanding of spatial relations and global layout, which is important for supporting spatial inference, route detours, cognitive mapping, and other complex spatial behaviors (Ahmadpoor & Shahab, 2019; Shelton, Marchette & Furman, 2013). For this reason, navigation systems that provide access to off-route information or that include the use of complementary accessible maps are particularly important for this community. Knowledge about global orientation cues and physical mobility information are rarely available to blind users from an integrative navigation system and it is important to determine how that information should be presented. Three options that have been extensively tested are spatial language, touch, and spatialized acoustics (see Gallay, Denis & Auvray, 2013, for a review).

Learning via spatial language can support exploration and goal-directed wayfinding, not just route following. For instance, describing local landmarks and layout configuration in an updated manner (e.g., with respect to the navigator's changing heading and position in the environment as they move) facilitates learning of off-route knowledge such as self-to-object relations and global structure (Giudice, Bakdash & Legge, 2007). More recently, Giudice, Whalen, Riehle, Anderson and Doore (2019) found that a navigation device providing spatial descriptions assisted a group of blind individuals in navigating complex, multifloor indoor environments, similarly to a sighted group who had visual access to the same information (Giudice et al., 2020, 2019). Importantly, blind individuals performed much better when this information was accessible during wayfinding compared with when the same information was only accessible during route planning.

Touch-based feedback has been implemented successfully in navigation systems for people with visual impairments, and has historically taken the form of raised-line paper maps, force feedback, or cutaneous feedback via joysticks, mice, buttons, and pins (Ducasse, Brock & Jouffrais, 2018). Yet touch feedback presents unique challenges on mobile touchscreen devices, which have a smooth, 2D surface. Klatzsky, Giudice, Bennett, & Loomis (2014) recommended combining touch-based and auditory information, given that sound spectrum information contains and can convey spatial location information (Auvray, Hanneton & O'Regan, 2007; Klatzky et al., 2014). Another option involves combining touch-based vibration information with descriptions in spatial language. Recent evidence using such a system suggests that a vibro-audio map, rendered on the touchscreen of a smartphone, results in

better wayfinding efficiency and route knowledge development than a traditional raised-line tactile map of the same area, even when the auditory information is equivalent between the two interfaces (Giudice, Guenther, Jensen & Haase, 2020; see also Brock, Truillet, Oriola & Jouffrais, 2010; Brock, Truillet, Oriola, Picard & Jouffrais, 2015).

There are instances where a specific modality provides advantages for BVI navigators. For instance, spatial sound (sonification) results in better navigation performance than spatial language for BVI people when navigation is conducted under cognitive load (Klatzky, Marston, Giudice, Golledge & Loomis, 2006). More generally, sonification results in shorter wayfinding times, more accurate spatial memory, and more favorable subjective experience ratings than spatial language instructions (Clemenson, Maselli, Fiannaca, Miller & Gonzalez-Franco, 2021; Loomis, Golledge & Klatzky, 2001; Marston, Loomis, Klatzky, Golledge & Smith, 2006). This line of research suggests that multisensory user interfaces are important for the design of navigation systems, as they (1) support a bio-inspired design philosophy built on how the brain actually performs spatial information processing and representation, and (2) allow for maximum potential user benefit, for example, universal design, essentially designing with the idea that supporting disability is simply the outcome of supporting diversity of users in the design process. Thus, this research suggests a sixth design principle: to adopt design conventions that provide redundant, accessible information using multiple sensory modalities (e.g., visualization, text, and auditory information).

While we highlighted a rich history of research on building more accessible navigation systems for BVI users, there remains a vast array of challenges given common map applications' overreliance on visual information and gesture-based feedback. Froehlich and colleagues recently began a special interest group "Making Maps Accessible and Putting Accessibility in Maps" which hopes to tackle the challenge of providing more pedestrian, accessibility-focused information in map applications (Brock et al., 2018; Froehlich et al., 2019).

Froehlich et al. (2019) segment user abilities into three categories: sensory, cognitive, and physical. Each set of ability should be considered separately during design in order to ensure that the navigation system can be used by the widest array of users, that is, support the core tenet of universal design. In particular, the group notes that while strides in accessibility for low vision individuals have been made, much less research has been done around physical accessibility (e.g., Tannert & Schöning, 2018) and cognitive accessibility (e.g., language comprehension, attentional, or memory degradation issues). Age is a great example, as people over 65 are the fastest growing demographic (at least in the United States), and experience many (often co-existing) changes in sensory, memory, attentional, and other cognitive factors, but are little studied in the domain of navigation. A few applications, such as Opensidewalks.com and Wheelmap are in early development, but have sparse

data and are in need of further research (see Froehlich et al., 2019, for more). This leads us to form a seventh principle of navigation system design, that systems should provide physical accessibility information, such as availability of wheelchair-friendly routes.

Deaf individuals also require different design principles in order to facilitate effective navigation. While deaf individuals can utilize visual map applications and read directions, this becomes difficult when environmental monitoring or a secondary task (e.g. driving) is co-occurring with navigation. To reduce cognitive load due to risk monitoring and facilitate effective navigation, wearable devices are being developed that classify environmental sounds and describe their content and location using textual descriptions and vibrational feedback (Findlater et al., 2019; Jain et al., 2020). Research is in the early stages of development for navigation systems in this area and presents a major opportunity for future investigation. This brings us to an eighth design principle: navigation systems should strive to provide information about non-visual orientation cues, such as auditory, tangible, and olfactory/smell properties of the environment.

Differences in cognitive abilities and other factors, such as dementia due to aging, also require specific design constraints to fit user needs. For older individuals, general declines in cognitive and sensory functioning (e.g., visual acuity, working memory, and linguistic comprehension) have to be considered when designing navigation systems (see Wiener & Pazzaglia, 2021, for a comprehensive review of aging-friendly navigation design). Users' varying cognitive abilities and constraints suggest a ninth and final design principle: that navigation systems should strive to minimize users' cognitive load when possible, and at the least avoid cognitive overload. Recent work has developed simulation models for non-digital navigation systems, such as signage and architectural design, in order to create easy to navigate environments with accessible signage (Dubey, Thrash, Kapadia, Hoelscher & Schinazi, 2019; Gath-Morad, Aguilar, Dalton & Holscher, 2020). For individuals with intellectual and cognitive disabilities, augmented reality has shown better spatial learning and wayfinding outcomes compared to Google Maps and paper maps, but there is a dearth of research in this domain and future work and application development is needed (Gomez et al., 2015; McMahon et al., 2015; Smith et al., 2017). Simulation, virtual reality, and augmented reality offer promising mediums for assessing low-cost navigation system prototypes prior to implementation in real-world systems.

Importantly, there is not necessarily a "one size fits all" solution for making devices more accessible, nor is there a best implementation strategy or user interface modality (Loomis, Klatzky, Giudice, Manduchi & Kurniawan, 2012). Rather, navigation systems should be tested extensively with respect to user abilities and task-based needs, and provide empirically validated options that suit the user and situation. Making systems more accessible will contribute to

making them easier and more enjoyable to use for all types of users, and following the recommendations in the above principles will go a long way towards supporting more inclusive design.

3. Lessons learned, open questions, and opportunities for future research

3.1. Mobile navigation system design principles

Our review helped to generate design principles for mobile navigation systems based on past empirical work that will ensure that future systems are more accessible and usable for all navigators. In summary, mobile navigation systems should strive to:

(1) Provide the option to present both route (e.g., information about local turns) and global orientation information (e.g., information about global landmarks and cardinal directions).

(2) Allow users to easily choose a preferred map alignment, such as track-up or north-up.

(3) Avoid presentation of non-essential information and visual clutter.

(4) Implement chunking and orientation information in verbal directions, or, at least, allow users to choose directions based on the importance of global spatial information to the user's goals. Chunking can be landmark-based ("turn left at the church after passing the school"), numeric ("turn left after passing the second intersection"), or a combination of the two.

(5) Cue users to decision-relevant, perceptually-salient landmarks in the environment. Decision-relevant landmarks include those at intersections and other junctions, while perceptually-salient landmarks could include structurally prominent landmarks such as a city hall, or landmarks specified by the user that are memorable or salient to them.

(6) Adopt design conventions that provide redundant, accessible information using multiple sensory modalities (e.g., visualization, text, and auditory). Sonification and use of vibrotactile information on commercially available smart devices (phones or tablets) is especially promising for facilitating spatial learning for low-vision and blind individuals.

(7) Provide physical accessibility information, such as wheelchair-friendly routes.

(8) Provide information about non-visual orientation cues (e.g., sound, tactile, and smell properties of the environment).

(9) Minimize users' cognitive load when possible, and at the least avoid cognitive overload (e.g., providing too much information in concurrence such that it is not useful, able to be efficiently filtered, or able to be remembered by the user).

What challenges remain, and where is mobile navigation systems research headed? We briefly discuss three major challenges and potential approaches: adjusting for context, providing accessible global orientation information, and providing insights into navigation processes and development over time.

3.2. Adjusting for context

Years of spatial cognition and navigation research point to vast individual differences in navigational abilities (Ishikawa & Montello, 2006; Montello, 1998; Weisberg & Newcombe, 2018) and situational strategies (e.g., navigating under stress; Credé, Thrash, Hölscher & Fabrikant, 2019; Frei, Richter & Fabrikant, 2016; Gagnon et al., 2018; Ruginski, Stefanucci & Creem-Regehr, 2018). Designing navigation systems that take into account and adapt to these individual abilities, preferences, and contexts remains a challenge. Several contextual design recommendations have been recently proposed (Thrash et al., 2019), outlined in Table 1. For example, landmarks could be emotionally relevant due to the observer's emotional state or to the emotional valence of the landmark itself (Balaban, Roser & Hamburger, 2014) and may change performance. Measures of individual differences in preference and performance rely on self-report or behavioral responses and can inform the route elements presented.

Many researchers have demonstrated that mobile navigation systems result in poorer spatial learning as the result of reducing cognitive workload and diverting attention from the environment (Brugger et al., 2019, Parush, Ahuvia & Erev, 2007). But often, navigation systems are designed with the purpose of making wayfinding as easy and efficient as possible, often during a concurrent task, such as driving. At the same time, navigation systems can be used by pedestrians similarly to a map, where spatial learning is the primary goal, and not necessarily arriving at a wayfinding goal as quickly as possible. The negative effects of navigation systems on spatial learning are likely only problematic if they (1) contribute to a cognitive decline more generally and causally over a long time period,

Table 1. Design recommendations for geographic information display (GID) elements based on context. originally appearing in (Thrash et al., 2019).

GID element	Design recommendation
Landmarks	Emphasize emotionally relevant landmarks
Landmarks	Provide virtual landmarks via augmented reality
Landmarks	Emphasize landmarks at critical decision points
Routes	Provide multiple route options
Routes	Personalize route options to match individual preferences
Topography	Only provide sparse information under time pressure
Topography	Provide richer details without time pressure

or (2) affect the user's wayfinding goals and user experience negatively. Because of this, it is important to further study the interaction between navigation systems and wayfinders' goals in real-world contexts. Designing navigation systems to serve various navigation contexts and understanding how navigation systems affect users' differing wayfinding goals is an important area for future research.

3.3. Providing accessible global and orientation information

3.3.1. Restricted displays and global information

Limited screen space is a major challenge when displaying maps on mobile navigation systems. Many modern map applications such as Google Maps and OpenStreetMap allow users to dynamically change map scale by panning and zooming. Still, global landmarks may be difficult to find efficiently using map panning and zooming operations. Some methods have sought to solve this issue by portraying landmark information on the borders of device screens, which provides additional information about landmarks that are not in view (Baudisch & Rosenholtz, 2003; Li, 2019; Schwering, Krukar, Li, Anacta & Fuest, 2017).

Even if an optimal visualization is chosen, selecting which specific landmarks to display has important implications for spatial learning and wayfinding. Löwen, Krukar and Schwering (2019) found that highlighting local landmarks on a mobile map supported route knowledge acquisition, whereas highlighting global landmarks supported survey knowledge acquisition. Systems have also been developed that change the level of detail of navigational directions depending on the stage of the navigator's route (Klippel et al., 2009; Tenbrink & Winter, 2009). One recent solution implements guiding arrows that point to off-screen goal landmarks on navigation systems, and has promise as a solution to achieve both efficient navigation and effective spatial learning (Maidenbaum, Patel, Gedankien & Jacobs, 2020). Implementing off-screen, global landmark visualization in real time will be a challenge for future work, considering the problems of contextual landmark selection, varying landmark granularity, and non-visual navigation system design (Palani, Giudice & Giudice, 2016; Rastogi, Pawluk & Ketchum, 2013; Schwering et al., 2017).

3.3.2. When GPS is challenging, noisy, or unavailable

Many challenges with retrieving global positioning information have been largely solved by the increasing availability of location-based services to support navigation (Hirtle & Raubal, 2013). GPS devices often possess fairly accurate knowledge of the world assuming the signal arrives to the device, and can provide this information via mobile map applications, such as Google Maps. When there is uncertainty in GPS signalling, research suggests the viability of visualizing position

using blurry visual boundaries and providing users with additional information about local environmental cues to aid self-localization (McKenzie, Hegarty, Barrett & Goodchild, 2016; Ranasinghe, Heitmann, Hamzin, Pfeiffer & Kray, 2018; Ranasinghe et al., 2018; Ranasinghe & Kray, 2018).

Location information remains especially challenging to provide for indoor environments due to technological limitations (no consistent GPS signals or inconsistent building maps) and perceptual limitations (limited sight lines or multiple floors) (Basiri et al., 2017; Giudice et al., 2019; Riehle, Anderson, Lichter, Whalen & Giudice, 2013). A recently developed solution, *NavCog*, utilizes Bluetooth beacons to provide turn-by-turn, point of interest, and accessibility information for effective indoor navigation using auditory cues (Ahmetovic et al., 2016). To our knowledge, there are no standards or broadly accepted conventions for indoor GIS and digital building maps, leaving this an open research area ripe for future work.

3.4. Providing insights into navigation processes

Beyond determining whether navigation systems affect wayfinding efficiency and spatial knowledge positively or negatively, future research should systematically examine how navigation systems affect navigation processes and different levels of spatial knowledge. This will help clarify system effectiveness within specific contexts. For example, a navigation system used in a car might be "good enough" and facilitate efficient navigation even if the driver only gains sequential knowledge of turns. We present a summary of previously validated measures of spatial learning and navigation efficiency in Table 2, and hope that it is helpful to researchers who aim to empirically evaluate navigation systems.

Future work should also incorporate more ecologically valid, real-world usage contexts to increase generalization of results. In these cases, wayfinding trajectories, specifics of application use, familiar environment knowledge, and learning of new environments could all be measured or manipulated to increase insights into behavior–system–environment interactions. For example, mobile eye tracking has been proposed as a rich tool to measure individuals' dynamic wayfinding behaviors using navigation systems (Kiefer, Giannopoulos, Raubal & Duchowski, 2017; Kiefer, Straub & Raubal, 2012) and to model gaze-based landmark salience (Krukar et al., 2020; Wang, Chen, Zheng, Yuan & Wang, 2020). In addition, MapRecorder is a recently developed tool that provides insights into interaction with common navigation systems such as Google Maps (Savino et al., 2020)

The effects of navigation systems on navigational processes throughout the lifespan also need to be further investigated (Unrau & Kray, 2019). To our knowledge, there is still no *causal* evidence of long-term detriments to spatial cognitive abilities from navigation system use, and thus a need for longitudinal studies to assess open questions of causality based on within-person, repeated-

Table 2. Behavioral measures of spatial learning and navigation efficiency.

	Spatial learning	Navigation efficiency

Survey knowledge: take shortcuts beyond previously traversed routes; cognitive map with landmark relations	● Distance estimation or metric knowledge
	  ○ Blind walking[1]
	  ○ Verbal estimate
	  ○ Visual matching task[2]
	● Cognitive map or relative environmental configuration
	  ○ Sketch map drawing[3]
	  ○ Bidimensional regression[4]
	  ○ Judgment of relative direction task[5]
	  ○ Egocentric pointing task[6]
	  ○ Shortcut tasks
	● Latent spatial learning
	  ○ Combination of pointing, cognitive map, distance estimation[7]
		● Distance travelled to goal
		  ○ Deviation from shortest straight-line path
		  ○ Choice of shortcut or route following (e.g. dual solutions paradigm[8])
		● Time to goal
		● Natural exploration
		  ○ Revisiting[9]
		  ○ Diffusion[9]
		  ○ Directional persistence[10]
		  ○ Pausing[10]

Route knowledge: Landmark recognition and memory of turns	● Landmark recognition[11] ● Sequential memory (ordering landmark images) ● Route retracing[12] ● Pointing to landmarks on the same route[13]	● Distance travelled to goal ● Time to goal ● Number of turning errors

Numbers reference the following studies: 1. (Loomis et al., 1993); 2. (Rand, Barhorst-Cates, Kiris, Thompson & Creem-Regehr, 2019); 3. (Schwering et al., 2014); 4. Friedman & Kohler, 2006; 5. Shelton & McNamara, 1996; 6. (Mou, McNamara, Valiquette & Rump, 2004); 7. (Hegarty, Montello, Richardson, Ishikawa & Lovelace, 2006); 8. (Marchette et al., 2011); 9. (Gagnon et al., 2018); 10. (Munion, Stefanucci, Rovira, Squire & Hendricks, 2019); 11. (Wunderlich & Gramann, 2019); 12. (Brügger, Richter & Fabrikant, 2019); 13. (Weisberg, Schinazi, Newcombe, Shipley & Epstein, 2014)

measures experimental designs (Newsom, 2015). In this line of work, device use can be monitored over periods of weeks, months, or years to better understand how devices affect spatial cognition over time, as well as how users adapt to device interfaces over time. This research will also help expand an understanding of navigation in familiar environments, even though most studies cited in this review assess navigation in unfamiliar environments.

4. Introduction to the special issue

The current special issue features six articles, in addition to the present introductory review article, that contribute to open questions regarding the study of mobile navigation systems. These articles take on important questions in the areas of navigation systems regarding navigation behavior in an emergency context (Snopkova et al.), provision of navigational directions on navigation systems (DeCock et al.; Kattenbeck et al.), and visual design of navigation system maps (Gardony et al.; Smith et al.; Sugimoto et al.).

Research included in the issue broadly shows that context plays an important role in wayfinding with navigation systems. Snopkova et al examined people's route choice in emergency evacuation using virtual-reality simulation. They found that the tendency to apply a route-retracing strategy was lower when a designated evacuation path was wide and straight. Also,

availability of a floor plan during evacuation facilitated the choice of a designated evacuation path. These results provide implications for the design of a building and the provision of evacuation information with an understanding of people's spatial behavior in emergency situations. De Cock et al. found that navigation instructions reduce wayfinding errors to a greater degree when wayfinding instructions are adapted to the type of decision point in the environment, compared to when the same type of instructions is used across all decision points – suggesting that systems should provide different types of instructions based on environmental context. Kattenbeck et al. examined when and where to provide landmark-based navigational instructions to the traveller along a route, with a view to developing automated navigation tools. They found that preferred timing of route instructions was related to personality traits, orientation abilities, route length, land cover types, and familiarity. The results shed light on the discussion of user-adapted and context-aware navigation assistance.

The next series of papers examined the effects of visual map design on wayfinding with navigation systems. Smith et al. developed two different types of mobile maps that depicted off-screen landmarks as symbols and varied whether the maps had game-like dynamic updating of symbols versus fixed locations of symbols. Using a route-following task in a real-world city and a task of pointing to previously visited landmarks, their findings suggest that dynamically updating landmark locations on a map can facilitate abilities to update one's spatial location and orientation along a novel route. They also discuss the benefits and challenges of interdisciplinary and mixed-methods approaches across geospatial science and experimental psychology. Further, Gardony et al. assessed the impact of graphical detail of 3D terrain models on spatial localization and orientation in large-scale environments. Their surprising results, based on an interactive geo-visualization paradigm, showed that rendering a moderate (rather than maximum) level of detail was sufficient for supporting these behaviours. Findings were used to motivate new perceptually-driven guidelines for collecting and communicating 3D terrain models for accurate end-user visualization of spatial data.

Lastly, Sugimoto et al. compared people's spatial memory and navigation performance when they learned route using a smartphone map and a paper map. Their results demonstrated that route learning was reliably less accurate when using the smartphone map. Of interest however, this performance deficit was not perceptually obvious to the participants, as their self-evaluation data revealed no significant differences between the two map conditions on ratings of state anxiety and confidence. These findings suggest that users are not only worse when using smartphone-based maps but that they are unaware of the learning and memory impairments caused by the use of this technology.

The study of navigation systems is a wide-ranging, interdisciplinary effort that has only just begun given the increasing complexity of digital navigation systems. While some may argue that overreliance on GPS devices is problematic for navigational skills, our review finds a more nuanced story – that navigation systems can aid wayfinding and spatial learning when designed based on theories of human behaviour, perception, and cognition; which in turn makes the devices more accessible. For instance, they should provide access to landmarks and be inclusively designed to support users of varying abilities in their desired navigation goals. To further research in this area, we provide design principles and tangible goals for future work considering remaining research challenges. Our special issue is a first step in this direction, containing multiple studies across disciplines addressing open questions in the study of navigation systems.

Acknowledgments

Disclosure statement

Funding

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