The Future of Geographic Information Displays from GIScience, Cartographic, and Cognitive Science Perspectives

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Abstract

With the development of modern geovisual analytics tools, several researchers have emphasized the importance of understanding users' cognitive, perceptual, and affective tendencies for supporting spatial decisions with geographic information displays (GIDs). However, most recent technological developments have focused on support for navigation in terms of efficiency and effectiveness while neglecting the importance of spatial learning. In the present paper, we will envision the future of GIDs that also support spatial learning in the context of large-scale navigation. Specifically, we will illustrate the manner in which GIDs have been (in the past) and might be (in the future) designed to be context-responsive, personalized, and supportive for active spatial learning from three different perspectives (i.e., GIScience, cartography, and cognitive science). We will also explain why this approach is essential for preventing the technological infantilizing of society (i.e., the reduction of our capacity to make decisions without technological assistance). Although these issues are common to nearly all emerging digital technologies, we argue that these issues become especially relevant in consideration of a person's current and future locations.

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1 Introduction

One serious consequence of global urbanization is the additional strain on cities' transportation networks. From the perspectives of engineers, economists, and planners, an apparent solution to this challenge is to allocate more resources towards public (and automated) modes of transportation (e.g., trains) and their optimization in terms of network efficiency [31]. However, people from different cultures vary with respect to their acceptance of public transportation and may consider public transportation as an affront to their own autonomy. Another possible solution to this transportation challenge is to indirectly improve network efficiency (in terms of user-centered metrics [31]) and user experience by improving individuals' spatial decision-making. This solution may be achieved with the design of geographic information displays (GIDs) that are context-responsive, personalized, and supportive for spatial learning. While a complete reliance on automated public transportation may require the development of artificial intelligence, our vision for the future of GIDs emphasizes the importance of intelligent assistance that provides relevant information to a person capable of reasoning.

For the present paper, we define GIDs as primarily visual displays that present spatial information and can facilitate navigation through a large-scale, real-world environment. Following Montello [37], we consider a large-scale environment as one that is larger than the human body and requires locomotion for apprehension. Our recommendations focus on the geographic information provided to individual pedestrians but may be extended to individuals within a multimodal transportation network. Previous research in this area tends to investigate spatial information, the visualization of spatial information, or users' knowledge of spatial information gained from different visualizations. We approach the problem from all three of these complementary perspectives: GIScience, cartography, and cognitive science (respectively).

2 GIDs from a GIScience perspective

From a GIScience perspective, some of the primary challenges associated with GIDs are context modeling, context inference, context management, and context adaptation. "Context" refers to the information used to characterize a person, place, or object that is relevant for human-system interaction [11]. Research on context modeling and GIDs attempts to derive a classification structure for sets of (spatial and non-spatial) information that are relevant for a particular task. For example, Sarjakoski and Nivala [53] classify contextual factors along seven dimensions, including user characteristics (e.g., demographics, goals, cognitive abilities), location/orientation, time, navigation history, technical properties, properties of the physical environment, and properties of the social situation. One open issue for context models and GIDs is the determination of appropriate methods for identifying and quantifying the relevance of particular sets of information.

Once relevant contextual factors are modeled, researchers can attempt to infer high-level context information from various sources of low-level raw data [24]. GIDs require context inference because raw sensor data would be uninformative for the user. Possible sources of ‘raw sensor data’ for GIDs include physical sensors (e.g., physiological sensors worn by the user), data from web applications and services (e.g., online social media), and users’ implicit (e.g., past experience) and explicit (e.g., button press) outputs. Context inference also requires methods for integrating these different data sources because a contextual factor may not be reducible to one particular source. For example, the relative difficulty of navigating two possible routes from the user’s current location to her destination may depend on both her past experience with that route and the current weather. Effective (and automated) methods and models for integrating different data sources and inferring context are still missing today [24]. Here, machine learning may prove to be an especially efficient and effective method for GIDs.

Context modeling, context inference, and context management often assume that human-system interactions will remain stable over time. Despite the growing number of raw data sources and the increasing complexity of context inference, GIDs must allow for the efficient retrieval and update of contextual information provided to the user. Human behavior changes as humans acquire more information regarding a system, and a particular contextual factor may not remain relevant forever. In order to address this challenge, technical systems must adapt to changes in context [21]. For example, during navigation, there are often frequent and rapid changes of spatial, attribute, and task contexts. Such context management is also critical for situations in which different contextual factors are interdependent. For example, users might realize that they are lost when they reach a particular boundary and then change their intended goal. Context adaptation requires an environmental awareness of changes in context and autonomous adjustments by the system in response to these changes. In addition, context adaptation can change the manner in which users interact with the system [9, 29].

3 GIDs from a cartographic perspective

From a cartographic perspective, the graphic elements represented by a GID (e.g., symbols indicating landmarks) should vary according to several “visual variables” in order to facilitate a user’s understanding [6, 51]. The seven original visual variables include location, size, shape, orientation, color hue, color value, and texture. Some visual variables are more appropriate for encoding categorical, ordinal, or continuous values [51]. For example, an ordinal value on a geographic representation should be encoded with respect to the size of the graphic element rather than its shape. In contrast, a categorical value may be better represented by different shapes instead of different sizes. Additional visual variables (i.e., color saturation, arrangement, crispness, resolution, transparency) have been used to characterize existing cartographic designs and tested with real users [34]. For example, transparency effectively focuses users’ attention on relevant geographic features compared to color saturation and color value [47, 62].

Visual variables may simplify geographic visualizations so that the encoded information is easy to comprehend, but new digital technologies allow for more realistic, 3D, high-resolution, animated, interactive visualizations than were previously possible. Animations have also been characterized in terms of dynamic visual variables, including moment, duration, frequency, order, rate of change, and synchronization [30, 12]. Users often prefer these relatively sophisticated visualizations over simpler visualizations of the same geographic information [22]. For example, Hegarty and colleagues [22] found that undergraduate students and expert meteorologists rated realism, animation, detail, and 3D as desirable and effective characteristics for visual displays.

Sophisticated visualizations can also lead to improvement in the performance of navigation-related tasks. Researchers have developed and tested GIDs with advanced features such as the simultaneous representation of to-be-walked routes at multiple scales [10]. Delikostidis and colleagues [10] found that their "LandNavin" prototype led to more efficient and effective navigation behavior compared to an earlier version of Google Maps. The simultaneous representation of routes at different scales also reduced the need to frequently zoom in and out in order to orient, although the authors note that this function was somewhat confusing for some participants [10].

However, some research may indicate a performance advantage for simple visualizations because of fewer extraneous details (or "clutter") that are not task-relevant [50]. For example, Hegarty and colleagues [22] found that realistic weather maps negatively affected novices' (but not experts') performance on map inference tasks. Similarly, Wilkening and Fabrikant [68] found that realistically shaded relief maps led to less accurate performance in a slope detection task than a simple contour map. These realistic relief maps also led to worse performance than a slope map that contained more visual clutter but explicitly represented task-relevant information [68].

The extent to which one visualization leads to better performance on a particular task than another visualization also depends largely on expertise [35, 22, 54] and emotional context [14]. Expertise may even influence the definition of a particular visualization as simple or sophisticated. For example, a circuit diagram or architectural plan might appear simple and concise to an expert engineer or architect (respectively), but the same visualization might appear sophisticated and confusing to the uninitiated [54]. Similarly, different visualizations may be more or less effective in different emotional contexts during navigation. Emotionally laden landmarks may also enhance users' experience of location-based services [17] and improve recognition for the landmarks themselves [3]. In turn, memory for specific landmarks may facilitate the mental representation of the overall environment in a flexible manner.

4 GIDs from a cognitive science perspective

From a cognitive science perspective, GIDs should promote the user's mental representation of the variety of spatial relations that can be employed during navigation. Humans are extremely flexible with respect to the types of spatial relations they can mentally represent, but researchers often fail to distinguish between the corresponding types of mental spatial representations [56]. For example, people can remember the structure of cells viewed through a microscope or the arrangement of galaxies viewed through a telescope. Our discussion of spatial memory is limited to mental and external representations of large-scale environments. However, spatial memory may vary along several additional dimensions of representation, including level of abstraction, reference frame, and metric [56, 66].

Changes in the scale of an external representation of an environmental space (i.e., a map) are often accompanied by a change in the generalization of features represented by that map [61]. Specifically, less features tend to be visible at smaller map scales (i.e., for larger spaces). Similarly, mental representations tend to be more abstract (i.e., grouped into higher-level categories with fewer details) when they are acquired among a larger stimulus set with partially overlapping features (i.e., via interference) [23] or when there is a larger delay between learning and testing (i.e., via decay) [26]. In order to account for cognitive processes that result in abstraction, modern map applications automatically generalize features with changes in map scale [5]. However, these schematized maps may not perfectly match the intentions of the human cartographers, and human cartographers may not always predict the most effective map design a priori. Thus, future research on GIDs may focus on both the implications of map design for abstraction in spatial memory and the incorporation of expert knowledge into schematization/generalization algorithms.

Spatial reference frames are the contextual information required to specify a location and orientation in space [57]. Researchers often investigate the extent to which different sources of contextual information result in a spatial memory that is oriented with respect to one source or another as evidenced by patterns of error or response time during recall [40, 20]. While people tend to prefer one reference frame over another [18], navigation often requires the translation of spatial information from one reference frame to another [63]. Mental translations between map and bodily reference frames are needed, for example, when navigators use GIDs to find a goal.

In the spatial cognition literature, researchers often manipulate reference frames using stimuli from either a bird's-eye or ground-level perspective. Cartographic maps from a bird's-eye perspective may vary with respect to their orientation (e.g., north-up versus track-up) [39]. The primary differences between north-up and track-up maps are the alignment of bodily and map reference frames and variability in the orientation of the map [39]. GIDs may simplify the mental translations required during navigation by providing a track-up map and thus improve navigation efficiency [41]. However, maps with a consistent orientation (e.g., north-up) may facilitate spatial memory for object-to-object relations (i.e., allocentric memory) [41]. In addition, images or prompts from a ground-level perspective may reflect past first-person experience of a space without aligning with the observer's current orientation [19].

Spatial memories may also vary in terms of metric (i.e., a distance function relating each location to each other location in a space). In the spatial cognition literature, a metric may be defined with respect to the underlying coordinate system of a mental representation or a property of the space being learned. According to the "dominant" theory of spatial knowledge acquisition [8, 27, 60], spatial memories become more metric and more Euclidean as the observer learns a space during navigation. In other words, with experience, the distances between mentally represented locations become more consistent, and the distance function relating different remembered locations begins to resemble the straight-line distance normally experienced in the physical environment (assuming no obstacles). However, people rarely develop an Euclidean spatial memory of familiar environments [64, 52], and spatial memories with different metrics may be acquired from the same environment simultaneously [27, 55].

The metrics of spatial memories also tend to vary because of properties of the space being learned. Euclidean memories may be rare because environments contain physical obstacles. Thus, the functional distance between locations (i.e., the amount of time required to move from one location to another) may be a more relevant metric for understanding mental spatial representations [49]. In addition, GIDs can provide spatial information with an underlying metric that is not Euclidean or functional. Indeed, many public transportation maps represent graph distances between locations. For example, signs in the London tube indicate the number of stops between locations. Some researchers suggest that people tend to mentally represent navigable spaces as graphs [28, 36], but the consequences of GIDs that represent spaces as graphs for spatial memory are largely unknown.

In general, a closer correspondence between the external representation of spaces provided by GIDs and the internal representation of spaces acquired in spatial memory is assumed to improve navigation efficiency (i.e., the speed with which one finds a goal location), although this correspondence is often under-specified in the literature [54]. In addition, there are several reasons to consider whether this improvement in efficiency necessarily corresponds to an improvement in the accuracy of spatial memory. First, external representations of environmental features reduce the necessity of actively encoding these features in spatial memory [42, 44, 45]. Active encoding (e.g., rehearsing and elaborating familiar content) improves most types of memory, including survey knowledge [67]. Second, by providing navigation instructions along a route, GIDs reduce the need for users to make explicit navigation decisions [2, 9]. Explicit decision-making may be especially important for learning a route so that the route may be reproduced in the future without the GID. Third, GIDs draw visual attention away from the environment, so users experience the space less directly [15, 16]. Visual attention on the environment is especially important for incorporating landmark knowledge into spatial memory [14].

5 Vision for the future of GIDs

The future of GIDs requires a better understanding of users' cognitive and emotional processes. From this interdisciplinary perspective, we need new design guidelines for the development of effective and efficient GIDs that are adapted to different contexts, application domains, and presentation forms. These GIDs should also be personalized in terms of individual and group differences such as spatial learning abilities and familiarity with the environment [4]. To conclude, we propose several examples of design recommendations for future GIDs in the context of pedestrian wayfinding (see Table 1 for a summary).

Table 1 Summary of design recommendations for future GIDs.

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

To ameliorate the negative side effects of GIDs on different aspects of spatial memory, researchers should develop GIDs that support active encoding, explicit decision-making, and visual attention on the physical environment. For active encoding, users should be required to use the information provided by the GID in a more effortful way than current systems demand. For example, to promote explicit decision-making, GIDs could provide several route options to users at various decision points [65]. The provision of additional options (up to a point) may increase satisfaction with the option eventually chosen and improve memory for that particular option. GIDs could also employ this approach in order to provide more personalized route recommendations in the future. Finally, augmented reality applications could enhance the visualization of critical landmarks along a route in order to maintain users' attention on their immediate surroundings. Increased visual attention towards landmarks at critical decision points may improve recognition of those landmarks, and improved recognition for particular landmarks can facilitate route knowledge [55]. Together, the evidence suggests that such changes to the visualizations and instructions provided by GIDs could improve spatial memory without incurring a substantial cost or requiring significant advances in GID technologies [7].

Interaction with technology is an omnipresent and integrated part of our everyday lives. Importantly, the way we design technologies will change their everyday use, as well as the way in which we think and interact with the world in general [38]. The rise of mobile navigation technologies has a variety of benefits for users and for the efficiency of wayfinding and transportation in a complex urban society. However, scientific evidence for the negative influences of current GIDs on spatial memory and human cognition have led to discontent and worry regarding the autonomy of the navigator. More generally, technological systems with different “levels of automation” [43, 59, 7] result in different levels of user engagement while performing a particular task. For example, a passenger airplane does not require the pilot to constantly monitor and steer the vehicle over the course of a long flight, but the pilot should be sufficiently engaged with the task of flying to intervene in case of an emergency [13]. At the societal level, such GIDs are now widely accepted and intensively used, increasing the efficiency of transportation networks and sometimes preventing dangerous situations. However, given the visibility of accidents attributable to autonomous systems, they are also sometimes considered a threat to human safety [33]. Indeed the future technological progress of society may depend on the extent to which humans accept being part of an autonomous system.

The term “technological infantilizing” has been used to describe the process by which technology acquires the responsibility of humans for reasoning and leads to a gradual decrease in cognitive skills [38]. With the growing number of smartphones in the world, users may tend to extensively rely on mobile applications such as GIDs. The practical and ethical implications of a potential large-scale decrease in individuals’ spatial abilities are far-reaching. A widespread dependency on mobile technology might weaken the individual and empower the corporations and institutions that provide these services, leading to oppression and control. It is therefore necessary for us to understand the extent to which the technological infantilization may surpass a users’ ability to reason about space. When one seeks to develop a novel GID, he should consider the ratio between the potential benefits of such technologies and these associated risks [58].

The core functionality of future systems will still be the efficiency with which they guide us from one location to another by providing cognitively economic route instructions. With the capabilities of new GIDs to identify contextual states (e.g., traffic jams) and users’ psychological states (e.g., positive or negative moods) in real time using advanced sensors, there is the potential for developers to extend beyond this core functionality. For example, a device may be able to combine movement data (e.g., velocity) with data from physiological sensors (e.g., arousal in terms of electrodermal activity) and assess users’ level of stress. In a high stress state (i.e., high velocity and high arousal), the information display may emphasize sparse route information. In a low stress state (i.e., low velocity and low arousal), the user’s attentional resources might allow for the processing of richer information, and devices could display additional details and/or landmarks.

Emerging technologies such as augmented reality may be useful for providing an additional layer of support for spatial navigation [48] and spatial learning [32]. One remaining challenge is the design of experimental tasks that can be used to evaluate the usability of augmented reality in a meaningful manner [25]. Here again, we must carefully consider responsive designs [46]. While such technologies provide additional data for the creation of context-responsive and personalized GIDs, we must also consider new social, ethical, and legal aspects of GID usage, including user privacy [24, 1].

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