Neuroadaptive mobile geographic information displays: an emerging cartographic research frontier

Fabrikant, Sara I

Abstract: Mobility, including navigation and wayfinding, is a basic human requirement for survival. For thousands of years maps have played a significant role for human mobility and survival. Increasing reliance on digital GNSS-enabled navigation assistance, however, is impacting human attentional resources and is limiting our innate cognitive spatial abilities. To mitigate human de-skilling, a neuroadaptive (mobile) cartographic research frontier is proposed and first steps towards creating well-designed mobile geographic information displays (mGIDs) that not only respond to navigators' cognitive load and visuo-spatial attentional resources during navigation in real-time but are also able to scaffold spatial learning while still maintaining navigation efficiency. This in turn, will help humans to remain as independent from geoinformation technology, as desired. La mobilité, dont la navigation et l'orientation, est un besoin humain fondamental pour la survie. Pendant des milliers d'années, les cartes analogiques ont joué un rôle significatif pour la mobilité humaine et sa survie. Pourtant, la dépendance grandissante vis-à-vis de l'assistance à la navigation à l'aide de données numériques GNSS, impacte les ressources de l'attention humaine et limite nos capacités innées de cognition spatiale. Pour atténuer la perte de compétence humaine, un front de recherche sur la cartographie (mobile) neuroadaptative est proposé ainsi que des premières étapes pour la création d'écrans d'informations géographiques mobile (mGID) bien conçus, qui non seulement répondent à la charge cognitive et aux ressources de l'attention visio-spatiale des utilisateurs navigateurs pendant la navigation temps-réel mais aussi qui soient capables d'élaborer un apprentissage spatial tout en assurant l'efficacité de la navigation. Cela aidera les humains à rester aussi indépendant de la technologie de l'information géographique qu'ils le souhaitent.

DOI: https://doi.org/10.1080/23729333.2023.2253645

INTERNATIONAL JOURNAL OF CARTOGRAPHY
https://doi.org/10.1080/23729333.2023.2253645

RESEARCH ARTICLE

OPEN ACCESS

Check for updates

Neuroadaptive mobile geographic information displays: an emerging cartographic research frontier*

Sara Irina Fabrikant

Department of Geography and Digital Society Initiative, University of Zürich, Zürich, Switzerland

ABSTRACT
Mobility, including navigation and wayfinding, is a basic human requirement for survival. For thousands of years maps have played a significant role for human mobility and survival. Increasing reliance on digital GNSS-enabled navigation assistance, however, is impacting human attentional resources and is limiting our innate cognitive spatial abilities. To mitigate human de-skilling, a neuroadaptive (mobile) cartographic research frontier is proposed and first steps towards creating well-designed mobile geographic information displays (mGIDs) that not only respond to navigators' cognitive load and visuo-spatial attentional resources during navigation in real-time but are also able to scaffold spatial learning while still maintaining navigation efficiency. This in turn, will help humans to remain as independent from geoinformation technology, as desired.

RÉSUMÉ
La mobilité, dont la navigation et l'orientation, est un besoin humain fondamental pour la survie. Pendant des milliers d'années, les cartes analogiques ont joué un rôle significatif pour la mobilité humaine et sa survie. Pourtant, la dépendance grandissante vis-à-vis de l'assistance à la navigation à l'aide de données numériques GNSS, impacte les ressources de l'attention humaine et limite nos capacités innées de cognition spatiale. Pour atténuer la perte de compétence humaine, un front de recherche sur la cartographie (mobile) neuroadaptative est proposé ainsi que des premières étapes pour la création d'écrans d'informations géographiques mobile (mGID) bien conçus, qui non seulement répondent à la charge cognitive et aux ressources de l'attention visio-spatiale des utilisateurs navigateurs pendant la navigation temps-réel mais aussi qui soient capables d'élaborer un apprentissage spatial tout en assurant l'efficacité de la navigation. Cela aidera les humains à rester aussi indépendant de la technologie de l'information géographique qu'ils le souhaitent.

ARTICLE HISTORY
Received 11 August 2023
Accepted 28 August 2023

KEYWORDS
Neuroadaptation; Affect; human- and context-centered; Mobile electro encephalography (mEEG); Mobile eye tracking (mET)

CONTACT Sara Irina Fabrikant sara.fabrikant@geo.uzh.ch

*This is a revised and extended version of paper: Fabrikant, S. I. (accepted). Neuroadaptive mobile geographic information displays: an emerging cartographic research frontier. Advances in Cartography and GIScience of the International Cartographic Association (Advances of the ICA) 2023, International Cartographic Conference, Aug. 13-18, 2023, Cape Town, South Africa. Because the author was unable to attend the conference in person, organizers removed the paper from the proceedings.

Introduction

Mobility, including navigation and wayfinding, is considered an universal and cross-cultural requirement (Coutrot et al., 2022). For thousands of years, maps have played a significant role in supporting humans' mobility activities, and thus survival (Brotton, 2012). Along with the recent digital transformation, however, increasing reliance on assistive, location-aware, mobile geographic information displays (mGIDs) to support mobility in various movement modalities have already shown to negatively influencing our daily space–time behavior, i.e., 'death-by-GPS' (Aporta & Higgs, 2005; Lin et al., 2017), and cognitive resources (Ruginski et al., 2019). Relying more and more on digital GNSS-enabled navigation assistance and off-loading spatial abilities to its self-localization capacity is impacting our attentional resources away from the traversed environment towards the abused geographic information technology (Gardony et al., 2015) and is thus limiting our innate cognitive spatial abilities and perceptional resources (Ishikawa et al., 2008; Ruginski et al., 2019; Sugimoto et al., 2022). This is worrisome, because humans' navigation abilities influenced by long-term acquired, and repeatedly trained spatial abilities is a significant indicator for and have respective consequences on the success of human life courses. Spatial abilities and skills are critical already early in life, such as being a strong predictor for success in science, technology, engineering, and math (STEM) education fields (Uttal & Cohen, 2012) and thus they are relevant for employability for well-paying jobs (Ishikawa & Newcombe, 2021). Moreover, these skills are also important for healthy aging and well-being late in life, as they have also shown to be predictive of onset of Alzheimer's (Coughlan et al., 2018). Some even warn about technological infantilizing and de-skilling of society because of over-reliance of location-aware mGIDs for navigation (Thrash et al., 2019). Smart assistive devices are attractive to use during cognitively challenging navigation and wayfinding tasks, e.g., specifically when navigating in unfamiliar environments, because they allow us to off-load strenuous perceptual and cognitive resources, innate abilities, and skills to easy-to-use technology (Ishikawa et al., 2008; Thrash et al., 2019). This happens often in parallel to for various other activities. This is akin to the now ubiquitous use of pocket calculators or digital cashiers that have taken over our mental arithmetic calculation skills. However, recent mGIDs, as typical cartographic interfaces to location-aware assistive navigation systems (Ricker & Roth, 2018), are still not yet well adapted to the mobile needs of the individual wayfinder or to different groups of navigators and their specific navigation and wayfinding requirements, contexts (Bartling et al., 2023; Nivala & Sarjakoski, 2007), and tasks. They are also not well suited to respond to navigators' changing neurocognitive and psychophysiological resources during navigation, their spatial learning (Bertel et al., 2017), and/or (rapidly) changing environmental-, mobile map- and task-contexts (Bartling et al., 2022; Ruginski et al., 2022).

While ongoing cartographic research and the cognate visualization communities have focused predominantly on building smart geographic information tools and respective highly interactive graphic human–computer interfaces – also now available on hand-held and finger-driven small-screen–location-aware assistive devices (Ricker & Roth, 2018; Roth, 2017) and in augmented reality (Dickmann et al., 2021; Narzt et al., 2006) – fundamental investigations based on the empirical evidence of the *who*, *what*, *how*, *when,* and *why* of mobile human- and context-dependent spatio-temporal inference and decision making, spatial learning, and resulting human mobility behavior with mGIDs have received considerably less attention (Griffin & Fabrikant, 2012; Reichenbacher et al., 2022; Ruginski et al., 2022; Thrash et al., 2019). This is limiting for the cartographic research community because humans rarely make mGID-assisted space–time decisions in isolation, and only with map displays (Abowd et al., 1998; Bartling et al., 2022; Dalton et al., 2019; Delikostidis et al., 2013, 2015, 2016; Ruginski et al., 2022), as they need to acquire spatial knowledge from different sources during navigation (Ahmadpoor & Shahab, 2019) to be successful (Ruginski et al., 2019). Location-based Services (LBS) research for increasingly mobile citizens of the information society that solely focuses on technical improvements (Michael & Michael, 2011) or only on graphic interface design (Ricker & Roth, 2018) issues are likely doomed to failure because (1) they miss how different humans with varying training, backgrounds, and expertise reason and learn about different kinds of environments (Coutrot et al., 2022), and how humans make different mGID-assisted decisions depending on their task context, respectively (Ruginski et al., 2022), (2) they ignore the dynamically changing situatedness of the visuo-spatial decision-making context and navigation task domains (Delikostidis et al., 2016), and (3) they ignore humans' varying neurocognitive (Cheng et al., 2022, 2023) and psychophysiological resources (Credé et al., 2019, 2020) in specific mGID-assisted decision making contexts.

This paper further emphasizes a long-standing cartographic aim, that is, serving geographic information that can be easily understood, learnt and recalled, but this aim must now be extended to the citizens of the digital information society with increasingly mobile needs and uses. For such a mobile citizen, this could mean that geographic information would have to be adapted on the fly to their specific changing visuo-spatial decision-making needs and contexts, for example, their changing familiarity with traversed environments during navigation (Dijkstra et al., 2014; Gokl et al., 2019; Lovelace et al., 1999; Manrique-Sancho et al., 2018; Merriman et al., 2016; Quesnot & Roche, 2015; Zhu et al., 2022), and making appropriate mGID-assisted wayfinding decisions. In this contribution, we emphasize the need for user-centered LBS and mGIDs that are neuroadaptive (Fabrikant, 2022; Fairclough & Zander, 2022), to not only support diverse individuals or groups of navigators for reaching their desired destinations rapidly, effortlessly, and safely (Savino, von Sawitzky, et al., 2021), but more importantly, to also scaffold their individual spatial learning, considering their variable spatial abilities and skills. In doing so, we wish to reduce the danger of humans' spatial abilities further deteriorating because of increased passive navigation system use (Aporta & Higgs, 2005; Lin et al., 2017; Sugimoto et al., 2022). The goal would be for digital citizens to not get lost and to remain as independent as necessary from technology (Thrash et al., 2019) should the digital assistance fail for whatever reason (Ruginski et al., 2022).

This contribution, thus, advocates for a novel empirical research frontier, and presents first steps taken towards a neuroadaptive (mobile) cartography, an already emerging interdisciplinary research community at the intersection of thematically complementary research fields related to human mobility, such as cartography, geography, GIScience (e.g., geographic information visualization, spatial cognition, LBS, etc.), computer science (e.g., human–computer interaction, information visualization, etc.), and use-inspired cognitive neuroscience (e.g., experimental psychology, neuroergonomics, etc.). This cartographic research frontier is guided by a fundamental and use-inspired question: *How do we need to design future human- and context-adaptive mGIDs that guide visual attention, mitigate cognitive load, and support spatial learning*

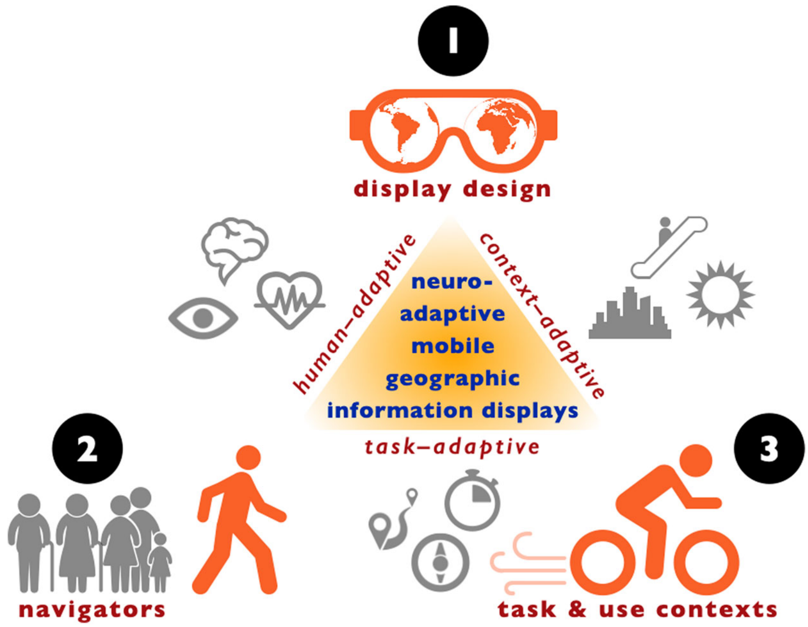

Figure 1. Long-term, three-pronged neuroadaptive mobile geographic information display research framework, considering human-, task- and context-adaptive research dimensions (Fabrikant, 2022: Fig. 1).

of diverse wayfinders when they navigate through various types of environments in varied mobility task contexts?

We propose to advance in this new cartographic research frontier along three intertwined paths, as shown in Figure 1. In doing so, we can further contribute to long-standing key research challenges related to communicating geographic information effectively and efficiently to a variety of target audiences, as formulated by the various research commissions of the *International Cartographic Association (ICA)* (Andrienko et al., 2010, 2014; Fabrikant & Lobben, 2009), including the *ICA Visual Analytics commission* (Çöltekin et al., 2017; Robinson et al., 2023); the *ICA Location-based Services* commission (Huang et al., 2018), and the *ICA Designing the User Experience* commission (Ricker & Roth, 2018; Roth, 2017). More specifically, it extends the research agenda of the ICA *Cognitive Issues in Geographic Information Visualization* (Andrienko et al., 2014; Griffin et al., 2017; Griffin & Fabrikant, 2012; Robinson et al., 2023),

Researchers have already begun to investigate ***neuroadaptive mGIDs (namGID)*** with a human-centered, empirical methodology, capitalizing on recent advances in psychophysiology and neuroadaptation, by focusing on human- and context-adaptive mGID use situations, as summarized in Figure 1.

The various answers to this proposed fundamental and use-inspired neuroadaptive cartographic research challenge will inform evidence-based design guidelines for future namGIDs that not only respond to navigators' mental workload and available visuospatial attentional resources during navigation, but that are also able to scaffold spatial learning while maintaining navigation efficiency. More specifically, we propose this cartographic research frontier to let *the cartographic design be the function of an interplay of humans' individual differences, group differences, varied backgrounds, trainings, behaviors,* *task needs and knowledge requirements, within changing contexts of mGID use* (Griffin et al., 2017; Griffin & Fabrikant, 2012). The author posits herein that *human wayfinding and navigation must include spatial learning as a performance measure,* thus going beyond the current paradigm of only relying on accuracy and time to evaluate mobility performance. *A future successful namGID design thus must mitigate deteriorating spatial abilities, even with navigation assistance over-reliance.* To achieve this goal, it is suggested to first focus on a deeper understanding of how wayfinders' and mGID users' visuo-spatial attention, cognitive load, and spatial learning interact during mGIDs-assisted navigation in varying (e.g., familiar and unfamiliar urban) environments (Fabrikant, 2022). In a second step, one must address how this relationship can be shaped in a future neuroadaptive setting. This is necessary, to then develop evidence-based design guidelines for future namGIDs that are not only human- and context-adaptive for maintaining navigation efficiency, but also scaffold spatial learning in changing environments.

Related work

While researchers in fragmented research fields have been tackling individual corners of proposed triangle in Figure 1 (Coutrot et al., 2022; Delaux et al., 2021), and/or worked along one of the three axes (Huang et al., 2018; Ruginski et al., 2022; Thrash et al., 2019), it is still very rare to find this kind of empirical research in cartography and GIScience, probably because it is a wicked problem[1], and thus very challenging to be tackled by cartographers alone, without any training in psychology, cognitive science, and neuroscience. Prior empirical cartography research focused on the design of the mobile map interface (Bartling et al., 2022; Ricker & Roth, 2018; Roth, 2017; Van Elzakker & Delikostidis, 2014), and studied the effects of mGIDs-assisted navigation and wayfinding for human spatio-temporal decision making and behavior, i.e., supporting efficient and effective navigation (Delikostidis et al., 2016; Rohs et al., 2007; Savino et al., 2019; Savino, Sturdee, et al., 2021; Savino, von Sawitzky, et al., 2021). The impact of mGID use on spatial learning while humans navigate in naturalistic, typically dynamically changing environments, has been less studied (Brügger et al., 2019; Ruginski et al., 2022; Thrash et al., 2019). We posit that mGID-assisted navigation is only effective when navigators are not only accurately and timely reaching their desired destinations, but more importantly, when they are not spatially de-skilling. We need to know more about how mGID-assisted navigators, for instance, with changing environmental familiarity, are seeing and remembering locations and routes in their everyday lives or in novel environments; how do they identify and attend to task-relevant geographic features (i.e., landmarks) in their vision field along the way; how they are choosing and remembering the path they took at street intersections, and how these activities relate to human's visuo-spatial attention, mental work load, and spatial learning during their mGID-assisted movement through changing environmental contexts (e.g., weather, time of the trip, familiarity, etc.)? So, why should cartographers focus, for instance, on environmental familiarity, as one example of a variable environmental context, and why is this important (Zhu et al., 2022)?

Navigation context: environmental familiarity

Familiarity with an environment has been an elusive concept in geography (Gale et al., 1990) and because of this difficulty, it may have been rarely studied in spatial cognition research and navigation (Lovelace et al., 1999; Manrique-Sancho et al., 2018; Merriman et al., 2016; Quesnot & Roche, 2015; Zhao et al., 2023). Unfamiliar environments are easier to control for various confounding variables, including environmental configurations, path properties, and task-relevant features. Also, unwanted background knowledge and prior training of participants can be effectively screened. However, the level of environmental familiarity may even often change during (ecologically valid) everyday navigation. Most empirical wayfinding and navigation research have been carried out in unfamiliar environments (Ishikawa, 2020), where knowledge of meaningful locations (i.e., destination/landmark knowledge), the shape and distance of routes (i.e., route knowledge), and/or geometric knowledge of the layout of the traversed environment (i.e., survey knowledge) are not available at the outset to navigators (Figure 2) or vary in studied participant groups. For a neuroadaptive cartographic research frontier, the changing navigation context, for example, navigators' familiarity of a traversed environment and how it relates to mGID-assisted navigation and spatial learning serves as an ecologically valid, naturalistic use-inspired study case. It is more common in everyday life that wayfinders have at least basic familiarity with an entirely traversed environment in an everyday mGID-assisted navigation situation (Coutrot et al., 2022; Dalton et al., 2019; Savino, Sturdee, et al., 2021). Moreover, the level of familiarity can change during an everyday navigation experience. Totally unfamiliar environments are probably least often encountered, except perhaps for extra-terrestrial explorers who should not be considered first here. The role of spatial knowledge (i.e., landmark, route, survey knowledge) and its availability for navigators across wayfinding tasks have been systematically classified by Wiener et al. (2009)' wayfinding taxonomy, specified for unaided navigation tasks. We propose to adapt it for today's ubiquitous aided navigation, as shown in Figure 2.

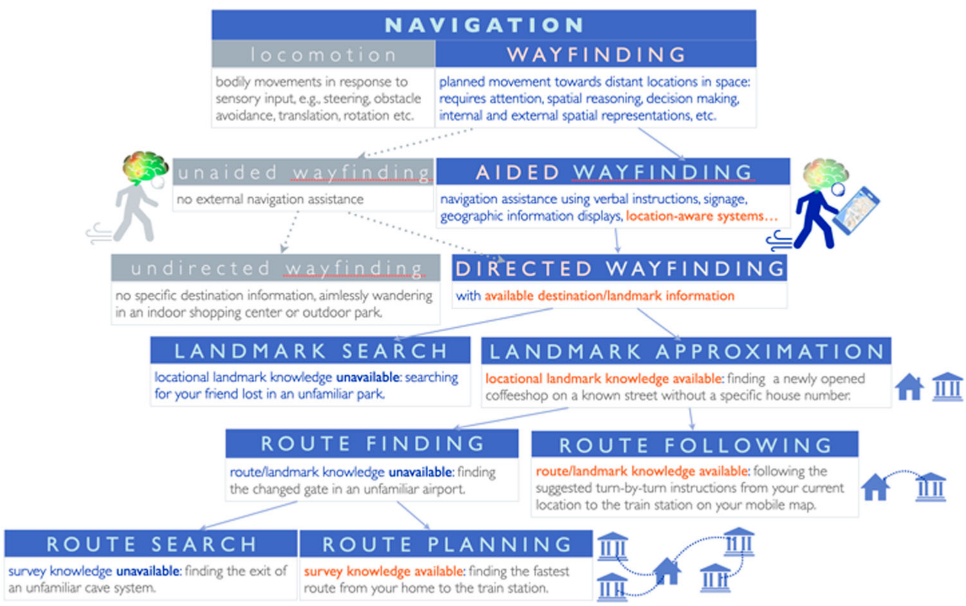

Figure 2. Navigation taxonomy by task type and available spatial knowledge types during wayfinding, adapted from Wiener et al. (2009, Fig. 1) for the assisted navigation case [mobile map source: https://www.google.com/maps].

Wiener et al. (2009) acknowledge that aided and unaided wayfinding are not mutually exclusive categories in everyday navigation tasks. Consider, for instance, using your public transport route on your morning commute to work, without using any navigation assistance, to later in the day rely on map-assisted wayfinding to find a newly opened restaurant for your lunch break, in a little explored, and thus novel neighborhood. Herein lies a great opportunity for the cartographic research community concerned with communicating geographic information with cartographic displays dependent on navigators available spatial knowledge. Location-aware navigation devices are popular, precisely because they offload cognitively demanding tasks such as self-localization and orientation from navigators to a digital assistive system (Brügger et al., 2019), with already known detrimental consequences for human navigators (Ruginski et al., 2019). We thus highlight (orange text) environmental knowledge requirements relevant for aided wayfinding in Figure 2, including landmarks, route, and survey knowledge with varying degrees of familiarity by navigators. What role the degree of familiarity plays in a traversed environment, and how respective varying cognitive demands can be supported by an mGID, or rather, as we propose, a namGID, and how this can further support spatial learning is what we suggest cartographers to jointly work on with others in an interdisciplinary context from now onwards. As a step towards this, passive neurocognitive and psychophysiological and cognitive mobile sensors recording in a highly controlled virtual reality (VR) lab seems very useful (Mavros et al., 2022; Zhao et al., 2023).

Neuroadaptation

Neuroadaptive Systems (NaS) is an emergent form of context-aware computing (Fairclough, 2023). It is a closed-loop approach to human–computer interaction (Fairclough, 2022), emerging from cognitive neuroscience and neuroergonomics (Fairclough & Zander, 2022). Neuroadaptation has evolved as an interdisciplinary and use-inspired research field on its own (Fairclough & Zander, 2022), with dedicated journals and conferences proceedings in the emerging field of neuroergonomics, which also includes brain-computer interfaces (BCI: Hettinger et al., 2003). Hettinger et al. (2003) define a neuroadaptive interface as an '*ensemble of computer-based displays and controls whose functional characteristics change in response to meaningful variations in the user's cognitive and/or emotional states*' (p. 220). Neuroadaptation can be used for supporting human decision making and behavior in all sorts of human contexts and user tasks (Fairclough & Zander, 2022), and it has also been successfully applied to changing human behavior, if used in a neurofeedback context (Sitaram et al., 2017). Dehais et al. (2020), for example, demonstrated that neuroadaptive systems (NaS) can improve users' task performance, attention, and engagement, but in studies that are not yet related to maps, geographic information, and mGID-assisted navigation, which we suggest to the cartographic community as a new research frontier.

Neuroadaptive cartography: the new research frontier

While adaptive cartography has been discussed in the cartographic literature already since the early 2000s (e.g., Reichenbacher, 2001) the GIScience community has not yet explored the possibilities of neuroadaptation for human-centered geoinformation technology (GIT) and geographic information systems (GIS), and thus has not yet made neuroadaptations to the user interface of mGIDs, especially used for navigation, and based on in-situ human sensing, and respective real-time analyses of human sensor data collected during navigation (Bartling et al., 2022; Ruginski et al., 2022; Thrash et al., 2019). First steps into a namGID future must rely on expertise in neurocognitive and psychophysiological human sensing and data analytics.

There are significant research challenges ahead before a neuroadaptive mobile geographic information display (namGIDs) can be deployed that would be assisting navigators in wayfinding in naturalistic settings, and specifically to scaffold spatial learning (Fabrikant, 2022). For example, passive human sensor data including, mobile eye tracking (mET), mobile galvanic skin response recordings (mGSR), and mobile electroencephalography (mEEG) should be collected in real time to study humans' situated neurocognitive, and psychophysiological responses and their effect on mGID-assisted navigation performance and spatial learning during navigation in unfamiliar (virtual and real) urban environments (Dey et al., 2019; Wascher et al., 2023).

As a unique novel and first-time contribution to this cartographic (including LBS and GIScience) research frontier, and cognate neuroergonomics fields, we have employed mEEG coupled with mET to study navigators' spatial learning by assessing cognitive load when using mGIDs in the VR lab (Cheng et al., 2022, 2023) and in-situ outdoors (Hilton et al., 2023; Kapaj et al., 2022, 2023).[2] We were able to leverage the EEG processing pipelines that specifically relate to evaluating EEG signals collected in a mobile context (Wunderlich & Gramann, 2021) (Figure 3).[3]

Virtual environments (VR) provide rich opportunities to study phenomena with high fidelity that may be otherwise difficult or impossible to do out in the real world

Figure 3. Real-time ambulatory assessment of a navigator's visual attention using mobile eye tracking (mET) and mobile encephalography (mEEG) measurements to assess cognitive load in during a mGID assisted wayfinding task outdoors (Fabrikant, 2022: Fig. 5).

(Delikostidis et al., 2013; Jerald, 2015). Because of its controlled laboratory nature, VR allows to measure human responses and behaviors using psychophysiological and neuropsychological sensors of various kinds precisely and implicitly (Dey et al., 2019; Zhao et al., 2023), while offering high experimental control over the surrounding context of the observed behavior (Baker & Fairclough, 2022).

For example, Cheng et al. (2022, p. 2023) examined cognitive load with mEEG during map-assisted navigation (i.e., route following tasks) through an urban VR. The mGID either depicted 3, 5, or 7 landmarks, selected from the followed route. Participants' spatial learning performance did not further improve as hypothesized (Münzer et al., 2012) when seeing seven landmarks on mGID compared to the 3- and 5-landmark conditions (Cheng et al., 2022, 2023). Still, the mEEG signal suggests that more cognitive resources were expended in the 7-landmark condition. These findings suggest participants' attentional resources might not be effectively directed to the relevant landmarks in the virtual environment for the 7-landmark condition, because studying 7 landmarks on the mGID during navigation might lead to cognitive overload, compared to showing only 3 or 5 landmarks on the mGID. Possibly a cognitive load spillover effect during map-assisted wayfinding during map viewing might affect cognitive load during goal-directed locomotion in the environment. By means of mEEG (Cheng et al., 2022, 2023), mGSR (Credé et al., 2019, 2020), and mET (Zhao et al., 2023) – that have already been successfully deployed to track humans' cognitive states, affective states, and visuo-spatial attention in VR passively – it is now possible to actively adapt the VR display in a closed-loop neuroadaptive fashion (Dey et al., 2019; Fairclough, 2022). Based on the adaptive regulation of navigators' visual attention (mET), their cognitive state (mEEG), and their affective state (mGSR), we can, for instance, adapt the experienced VR display immersion (monoscopic vs. stereoscopic views), mGID abstraction levels, such as 2D vs. 3D landmarks (Kapaj et al., 2022; Starrett et al., 2021), various levels of mGID system automations, e.g., GPS localization on vs. off, (Brügger et al., 2019, (Zhao et al., 2023)), etc. The namGID also seen in the VR can be made to blink to alert the user, or to make decision-irrelevant information visually less salient (Caduff & Timpf, 2008), and thus, further regulate human visuo-spatial attention (Fairclough, 2022). In doing so, the namGID can influence the navigator as to which of the seen environmental features (controlled stimuli) should be prioritized for effective spatial learning, how visuo-spatial attention should be divided between concurrent stimuli for efficient spatial learning, etc. A neuroadaptive technology that accurately monitors the process of attentional regulation can thus shape the direction and intensity of human information processing via targeted adaptations at the human-system interface, e.g., enhanced stimulus salience, suppression of distracting stimuli, introduction of additional information formats (Fairclough, 2022). Another exciting opportunity for such a closed-loop namGID is the dynamic adjustment of task demand, e.g., the direction (increase/decrease), magnitude, or timing, of information presentation based on navigator's ongoing psychophysiological and neuropsychological states (Fairclough, 2022). Figure 4 suggests schematically a closed neuroadaptive loop that adjusts the saliency of landmarks displayed on the namGID. This is based on individual navigators' changing familiarity of the traversed environment, and ongoing task demands, during navigation which is captured by changing cognitive and attentional resources used during wayfinding in an urban setting and measured continuously via cognitive load through an mEEG. If navigators' cognitive and psychophysiological

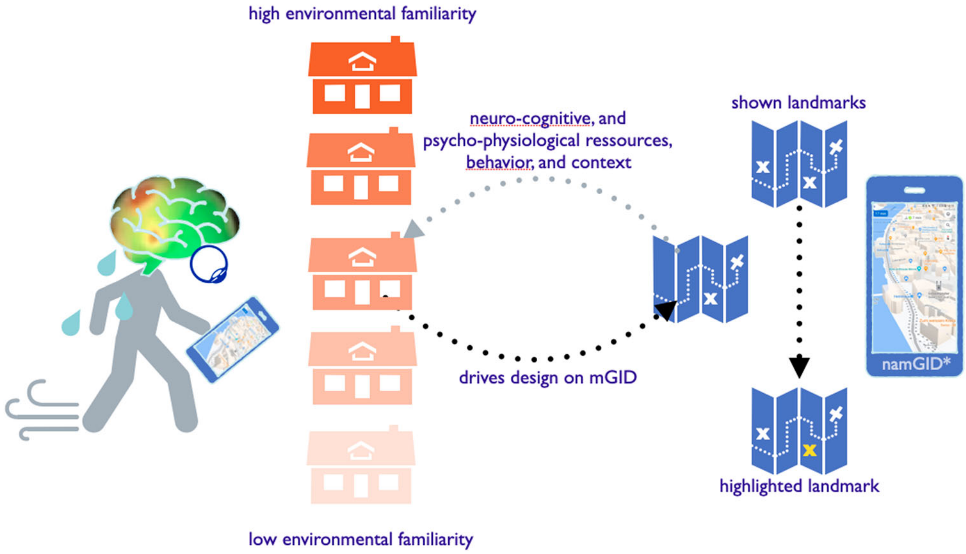

Figure 4. Closed loop namGID-assisted navigation based on (1) human factors (i.e., navigator's background, abilities, neuro-cognitive and psychophysiological resources, etc.), (2) context factors (e.g., time pressure, navigation modality, etc.), and (3) environmental factors (e.g., indoor, or outdoor, landscape type, weather, etc.) [*map source: https://www.google.com/maps].

resources are reaching an individually assessed threshold during navigation, suggesting over-taxation of neurocognitive resources, the graphic information density on the namGID is reduced, to not further overload their visuo-spatial resources, for continued spatial learning to happen.

Neuroadaptive mGID (namGID) testbed

Fabrikant (2022) and team members have begun to build a neuroadaptive testbed to update human- and context-dependent namGIDs in a closed-loop approach, to pilot first steps along the research avenues suggested in Figure 1 for the proposed new

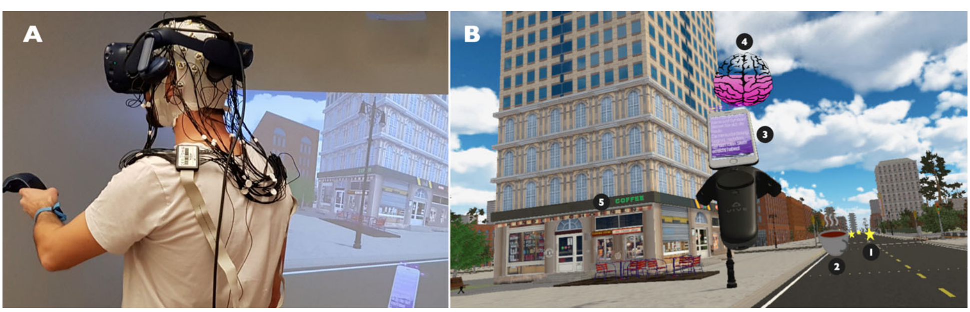

Figure 5. Neuroadaptive mGIDs in own gamified navigation setting: (b) The world a test participant is experiencing wearing the HMD VR over an EEG cap (a) is projected onto a large, screen-based CAVE VR system (https://www.geo.uzh.ch/en/units/giva/services/cave-automatic-virtual-environment.html; https://www.geo.uzh.ch/en/units/giva/services/virtual-reality-HMD.html) (Fabrikant, 2022: Fig. 6) seen in the background of (a).

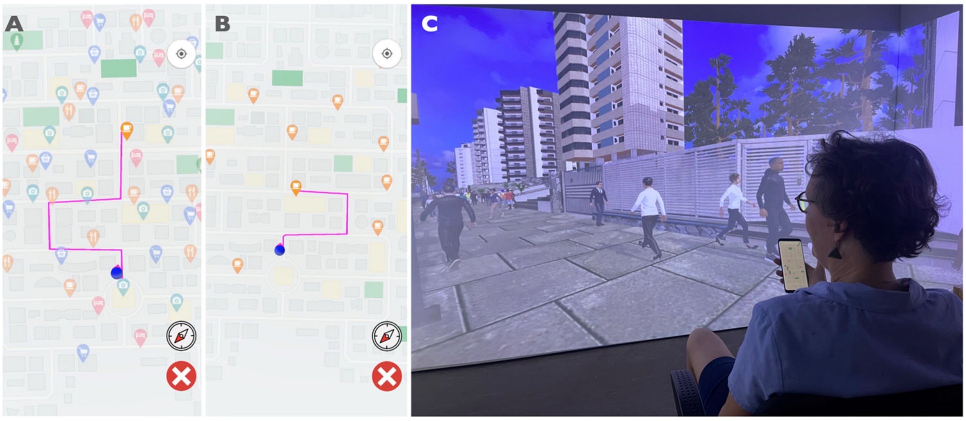

Figure 6. Hand-held GID-assisted navigation in urban VR: The mGID (a) shows a navigator's current location and viewing direction in the urban VR (c), and the route to the nearest café is highlighted. The namGID (b) automatically filters task-irrelevant landmarks and highlights the route to the nearest café [image source: Dr. Mona Bartling].

cartographic research frontier. Figure 5 depicts a working namGID prototype, deployed in a serious (navigation) gaming context, firstly introduced to the public at a science fair at the University of Zurich in 2021 (see note 4). The left image (a) shows a player with a head-mounted VR display (HMD) coupled with mEEG, immersed in the virtual navigation game. What they are seeing is projected onto a cave automatic virtual environment (CAVE) system in the author's VR lab. This virtual urban navigation game is inspired by Pokémon GO where pedestrian navigators need to collect given objects (i.e., stars in Fig. 5.1) or other items during a wayfinding task in an urban VR. Landmarks and other symbols are shown along the route (Fig. 5.5) in the urban scene (Fig. 5.2) and on the virtual mGID (Fig. 5.3). Depending on players current cognitive load, captured in real-time with an mEEG, the empty black brain outline in the middle of the player's vision field fills up in magenta (Fig. 5.4). In another game versions a pumping heart symbol changes dynamically, based on navigators' affective state, captured in real-time with a smart watch that records a navigator's mGSR and heart rate.[4]

Another namGID test case could be deployed in a hybrid setting, as shown in Figure 6, in closed-loop neuroadaptation, triggered by neurocognitive (e.g., Dey et al., 2019), affective,[5] and behavioral (i.e., task completion time, navigation accuracy, etc.) measurements in real-time. The namGID (Figure 6(b)) is synched with the urban VR will automatically filter out task-irrelevant landmarks from traditional mGIDs that look like GoogleMap, AppleMap, BingMap, etc. (e.g., Figure 6(a)), dependent on participants' mental workload. With concurrent mET we can monitor how often and how long participants visually attend to task-relevant landmarks in the traversed environment or on the mGID/namGID (i.e., at turning points at intersections, landmarks, etc.) to support spatial learning, and how this correlates with changing environmental contexts, task demands, etc. measured by CL.

As with very recent artificial intelligence developments (i.e., LLMs), we need to carefully consider emerging ethical concerns related to privacy and informed consent issues that arise for novel neuroadaptive applications in this emerging mobile cartographic research frontier which we touch on briefly below.

Ethics and privacy issues in neuroadaptation

Of course, we must be aware of new ethical concerns related to privacy and informed consent that arise in new ways for neuroadaptive applications, including how NaS can influence self-awareness, self-knowledge, and a sense of agency (Fairclough, 2023). Neuroadaptive systems continuously collect data and learn from users' behavior, and possibly might respond automatically or adapt in ways that namGID users are not being aware of happening, and/or might not wish or nor prefer to happen, if they were fully made aware of it, or if they were presented first with alternatives choice sets (Fairclough, 2022). For location-based neuroadaptive services, personalized location data can be especially sensitive, which might generate additional privacy concerns to neuroergonomics research in general. It is therefore critical for empirical cartographers to pro-actively addressing these concerns right from the beginning of their research trajectories, for example, by (1) adhering to well-established current human research standards assessed in national and local ethics board reviews and by adhering to their respective codes of conduct,[6] (2) apply the good practice of fully informed consent for all study participants, and (3) by following the best available standards in privacy and data protection laws, including (4) by applying the parsimony principle of human data collection, and (5) by relying on pre-registration of empirical studies,[7] etc.

Conclusions and outlook

The future is bright for this proposed neuroadaptive cartographic research frontier. Moving it forward, the cartography, GIScience and LBS communities can achieve a deeper understanding of how our mobile map designs interact in real-time with users' visuo-spatial attention, cognitive load, and spatial learning during mGID-assisted navigation. In doing so, we can develop evidence-based design guidelines for neuroadaptive mGIDs that are not only human- and context-adaptive for maintaining navigation efficiency, but also support spatial learning in varying environmental contexts. This in turn will support humans to remain as independent as desired from evolving geoinformation technology.

Notes

1. A wicked problem is a social or cultural problem that is difficult or impossible to solve (https://www.wickedproblems.com).
2. This paper received the best short paper award at the 15th Conference on Spatial Information Theory (COSIT 2022).
3. See: https://github.com/BeMoBIL
4. See technology used on the web at: https://www.geo.uzh.ch/en/units/giva/services/mobile-EDA-facial-emotions.html, and https://www.geo.uzh.ch/en/units/giva/news0/Scientifica.html
5. https://www.geo.uzh.ch/en/units/giva/services/mobile-EDA-facial-emotions.html
6. See: https://www.apa.org/ethics/code/index
7. See: https://aspredicted.org

Notes on contributors

Sara Irina Fabrikant is a professor of geography, leading the Geographic Information Visualization and Analysis (GIVA) group at the GIScience Center of the Geography Department at the University of Zurich, Switzerland. Her research and teaching interests lie in geographic information visualization and geovisual analytics, GIScience and cognition, graphical user interface design and evaluation, including dynamic cartography. She is currently an elected member of the Swiss Science Council (SCC), an invited member of SigmaXi, the scientific research honor society and a nominated member to AcademiaNet, the online database to excellent women academics. She is co-initiator and past co-director of the UZH Digital Society Initiative (DSI). Other service included vice-president of the International Cartographic Association (ICA) 2015-2019, and program committee co-chairing of the international AGILE 2008, GIScience 2010, and COSIT 2015 and 2022 conferences. In 2023 she received the Waldo-Tobler GIScience Prize by the Austrian Academy of Sciences.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Horizon Europe European Research Council [grant number 740426].

References

Abowd, D., Dey, A. K., Orr, R., & Brotherton, J. (1998). Context-awareness in wearable and ubiquitous computing. *Virtual Reality*, *3*(3), 200–211.

Ahmadpoor, N., & Shahab, S. (2019). Spatial knowledge acquisition in the process of navigation: A review. *Current Urban Studies*, *07*(01), 1–19.

Andrienko, G., Andrienko, N., Demsar, U., Dransch, D., Dykes, J., Fabrikant, S. I., Jern, M., Kraak, M.-J., Schumann, H., & Tominski, C. (2010). Space, time and visual analytics. *International Journal of Geographical Information Science*, *24*(10), 1577–1600. https://doi.org/10.1080/13658816.2010.508043

Andrienko, G., Fabrikant, S. I., Griffin, A. L., Dykes, J., & Schiewe, J. (2014). Geoviz: Interactive maps that help people think. *International Journal of Geographical Information Science*, *28*(10), 2009–2012. https://doi.org/10.1080/13658816.2014.937719

Aporta, C., & Higgs, E. (2005). Satellite culture. *Current Anthropology*, *46*(5), 729–753. https://doi.org/10.1086/432651

Baker, C., & Fairclough, S. H. (2022). Adaptive virtual reality. In *Current research in neuroadaptive technology* (pp. 159–176). Elsevier. https://doi.org/10.1016/B978-0-12-821413-8.00014-2

Bartling, M., Reichenbacher, T., & Fabrikant, S. I. (2023). Leveraging map use context for advancing cartography in the 21st century. *Proceedings of the ICA*, *5*, 1–7. https://doi.org/10.5194/ica-proc-5-2-2023

Bartling, M., Resch, B., Reichenbacher, T., Havas, C. R., Robinson, A. C., Fabrikant, S. I., & Blaschke, T. (2022). Adapting mobile map application designs to map use context: A review and call for action on potential future research themes. *Cartography and Geographic Information Science*, *49*(3), 237–251. https://doi.org/10.1080/15230406.2021.2015720

Bertel, S., Dressel, T., Kohlberg, T., & von Jan, V. (2017). *Spatial knowledge acquired from pedestrian urban navigation systems*. Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services (pp. 1–6). https://doi.org/10.1145/3098279.3098543

Brotton, J. (2012). *A history of the world in twelve maps*. Penguin Books.

Brügger, A., Richter, K.-F., & Fabrikant, S. I. (2019). How does navigation system behavior influence human behavior? *Cognitive Research: Principles and Implications*, *4*(1), Article 5. https://doi.org/10.1186/s41235-019-0156-5

Caduff, D., & Timpf, S. (2008). On the assessment of landmark salience for human navigation. *Cognitive Processing*, *9*(4), 249–267. https://doi.org/10.1007/s10339-007-0199-2

Cheng, B., Lin, E., Wunderlich, A., Gramann, K., & Fabrikant, S. I. (2023). Using eye blink-related brain activity to investigate cognitive load during assisted navigation. *Frontiers in Neuroscience*, *17*. https://doi.org/10.3389/fnins.2023.1024583

Cheng, B., Wunderlich, A., Gramann, K., Lin, E., & Fabrikant, S. I. (2022). The effect of landmark visualization in mobile maps on brain activity during navigation: A virtual reality study. *Frontiers in Virtual Reality*, *3*. https://doi.org/10.3389/frvir.2022.981625

Coughlan, G., Laczó, J., Hort, J., Minihane, A.-M., & Hornberger, M. (2018). Spatial navigation deficits — overlooked cognitive marker for preclinical Alzheimer disease? *Nature Reviews Neurology*, *14*(8), 496–506. https://doi.org/10.1038/s41582-018-0031-x

Coutrot, A., Manley, E., Goodroe, S., Gahnstrom, C., Filomena, G., Yesiltepe, D., Dalton, R. C., Wiener, J. M., Hölscher, C., Hornberger, M., & Spiers, H. J. (2022). Entropy of city street networks linked to future spatial navigation ability. *Nature*, *604*(7904), 104–110. https://doi.org/10.1038/s41586-022-04486-7

Credé, S., Thrash, T., Hölscher, C., & Fabrikant, S. I. (2019). The acquisition of survey knowledge for local and global landmark configurations under time pressure. *Spatial Cognition & Computation*, *19*(3), 190–219. https://doi.org/10.1080/13875868.2019.1569016

Credé, S., Thrash, T., Hölscher, C., & Fabrikant, S. I. (2020). The advantage of globally visible landmarks for spatial learning. *Journal of Environmental Psychology*, *67*(October 2019), Article 101369. https://doi.org/10.1016/j.jenvp.2019.101369

Çöltekin, A., Bleisch, S., Andrienko, G., & Dykes, J. (2017). Persistent challenges in geovisualization – a community perspective. *International Journal of Cartography*, *3*(Suppl 1), 115–139. https://doi.org/10.1080/23729333.2017.1302910

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

Dehais, F., Lafont, A., Roy, R., & Fairclough, S. (2020). A neuroergonomics approach to mental workload, engagement and human performance. *Frontiers in Neuroscience*, *14*. https://doi.org/10.3389/fnins.2020.00268

Delaux, A., de Saint Aubert, J., Ramanoël, S., Bécu, M., Gehrke, L., Klug, M., Chavarriaga, R., Sahel, J., Gramann, K., & Arleo, A. (2021). Mobile brain/body imaging of landmark-based navigation with high-density EEG. *European Journal of Neuroscience*, *54*(12), 8256–8282. https://doi.org/10.1111/ejn.15190

Delikostidis, I., Fritze, H., Fechner, T., & Kray, C. (2015). *Bridging the Gap Between Field- and Lab-Based User Studies for Location-Based Services* (pp. 257–271).

Delikostidis, I., Fechner, T., Fritze, H., AbdelMouty, A. M., & Kray, C. (2013). Evaluating mobile applications in virtual environments. *International Journal of Mobile Human Computer Interaction*, *5*(4), 1–19. https://doi.org/10.4018/ijmhci.2013100101

Delikostidis, I., van Elzakker, C. P. J. M., & Kraak, M.-J. (2016). Overcoming challenges in developing more usable pedestrian navigation systems. *Cartography and Geographic Information Science*, *43*(3), 189–207. https://doi.org/10.1080/15230406.2015.1031180

Dey, A., Chatburn, A., & Billinghurst, M. (2019). *Exploration of an EEG-based cognitively adaptive training system in virtual reality*. 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) (pp. 220–226). https://doi.org/10.1109/VR.2019.8797840

Dickmann, F., Keil, J., Dickmann, P. L., & Edler, D. (2021). The impact of augmented reality techniques on cartographic visualization. *KN - Journal of Cartography and Geographic Information*, *71*(4), 285–295. https://doi.org/10.1007/s42489-021-00091-2

Dijkstra, J., de Vries, B., & Jessurun, J. (2014). Wayfinding search strategies and matching familiarity in the built environment through virtual navigation. *Transportation Research Procedia*, *2*, 141–148. https://doi.org/10.1016/j.trpro.2014.09.018

Fabrikant, S. I. (2022). Neuro-adaptive LBS: Towards human- and context-adaptive mobile geographic information displays (mGIDs) to support spatial learning for pedestrian navigation. In J. Krisp, & L. Meng (Eds.), *17th international conference on location based services (LBS 2022), Sep. 12-14* (pp. 48–58). Augsburg University.

Fabrikant, S. I., & Lobben, A. (2009). Introduction: Cognitive issues in geographic information visualization. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *44*(3), 139–143. https://doi.org/10.3138/carto.44.3.139

Fairclough, S. (2022). Designing human-computer interaction with neuroadaptive technology. In *Current research in neuroadaptive technology* (pp. 1–15). Elsevier. https://doi.org/10.1016/B978-0-12-821413-8.00006-3

Fairclough, S. (2023). Neuroadaptive technology and the self: A postphenomenological perspective. *Philosophy & Technology*, *36*(2), 30. https://doi.org/10.1007/s13347-023-00636-5

Fairclough, S., & Zander, T. (2022). *Current research in neuroadaptive technology*. Elsevier. https://doi.org/10.1016/C2019-0-02735-5

Gale, N., Golledge, R. G., Halperin, W. C., & Couclelis, H. (1990). Exploring spatial familiarity. *The Professional Geographer*, *42*(3), 299–313. https://doi.org/10.1111/j.0033-0124.1990.00299.x

Gardony, A. L., Brunyé, T. T., & Taylor, H. A. (2015). Navigational aids and spatial memory impairment: The role of divided attention. *Spatial Cognition & Computation*, *15*(4), 246–284. https://doi.org/10.1080/13875868.2015.1059432

Gokl, L., Mc Cutchan, M., Mazurkiewicz, B., Fogliaroni, P., & Giannopoulos, I. (2019). Towards urban environment familiarity prediction. *Advances in Cartography and GIScience of the ICA*, *2*, 1–8. https://doi.org/10.5194/ica-adv-2-5-2019

Griffin, A. L., & Fabrikant, S. I. (2012). More maps, more users, more devices means more cartographic challenges. *Cartographic Journal*, *49*(4), 298–301. https://doi.org/10.1179/0008704112Z.00000000049

Griffin, A. L., White, T., Fish, C., Tomio, B., Huang, H., Sluter, C. R., Bravo, J. V. M., Fabrikant, S. I., Bleisch, S., Yamada, M., & Picanço, P. (2017). Designing across map use contexts: A research agenda. *International Journal of Cartography*, *3*(Suppl 1), 90–114. https://doi.org/10.1080/23729333.2017.1315988

Hettinger, L. J., Branco, P., Encarnacao, L. M., & Bonato, P. (2003). Neuroadaptive technologies: Applying neuroergonomics to the design of advanced interfaces. *Theoretical Issues in Ergonomics Science*, *4*(1–2), 220–237. https://doi.org/10.1080/1463922021000020918

Hilton, C., Kapaj, A., & Fabrikant, S. I. (2023). Landmark sequence learning from real-world route navigation and the impact of navigation Aid visualisation style. *Journal of Cognition*, *6*(1), https://doi.org/10.5334/joc.307

Huang, H., Gartner, G., Krisp, J. M., Raubal, M., & van de Weghe, N. (2018). Location based services: Ongoing evolution and research agenda. *Journal of Location Based Services*, *12*(2), 63–93. https://doi.org/10.1080/17489725.2018.1508763

Ishikawa, T. (2020). *Human spatial cognition and experience: Mind in the world, world in the mind*. Routledge.

Ishikawa, T., Fujiwara, H., Imai, O., & Okabe, A. (2008). Wayfinding with a GPS-based mobile navigation system: A comparison with maps and direct experience. *Journal of Environmental Psychology*, *28*(1), 74–82. https://doi.org/10.1016/j.jenvp.2007.09.002

Ishikawa, T., & Newcombe, N. S. (2021). Why spatial is special in education, learning, and everyday activities. *Cognitive Research: Principles and Implications*, *6*(1), 20. https://doi.org/10.1186/s41235-021-00274-5

Jerald, J. (2015). *The VR book*. Association for Computing Machinery. https://doi.org/10.1145/2792790

Kapaj, A., Lanini-Maggi, S., Hilton, C., Cheng, B., & Fabrikant, S. I. (2023). How does the design of landmarks on a mobile map influence wayfinding experts' spatial learning during a real-world navigation task? *Cartography and Geographic Information Science*, *50*(2), 197–213. https://doi.org/10.1080/15230406.2023.2183525

Kapaj, A., Lin, E., & Lanini-Maggi, S. (2022). The effect of abstract vs. Realistic 3D visualization on landmark and route knowledge acquisition. In T. Ishikawa, S. I. Fabrikant, & S. Winter (Eds.), *COSIT 2022:*

15th conference on spatial information theory. Leibniz international proceedings in informatics (LIPIcs), volume 240. https://doi.org/10.4230/LIPIcs.COSIT.2022.15

Lin, A. Y., Kuehl, K., Schöning, J., & Hecht, B. (2017). *Understanding "Death by GPS"*. Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (pp. 1154–1166). https://doi.org/10.1145/3025453.3025737

Lovelace, K. L., Hegarty, M., & Montello, D. R. (1999). *Elements of good route directions in familiar and unfamiliar environments* (pp. 65–82). https://doi.org/10.1007/3-540-48384-5_5

Manrique-Sancho, M.-T., Avelar, S., Iturrioz-Aguirre, T., & Manso-Callejo, M-Á. (2018). Using the spatial knowledge of Map users to personalize city maps: A case study with tourists in Madrid, Spain. *ISPRS International Journal of Geo-Information*, *7*(8), Article 332. https://doi.org/10.3390/ijgi7080332

Mavros, P., Wälti, M. J., Nazemi, M., Ong, C. H., & Hölscher, C. (2022). A mobile EEG study on the psychophysiological effects of walking and crowding in indoor and outdoor urban environments. *Scientific Reports*, *12*(1), Article 18476. https://doi.org/10.1038/s41598-022-20649-y

Merriman, N. A., Ondřej, J., Roudaia, E., O'Sullivan, C., & Newell, F. N. (2016). Familiar environments enhance object and spatial memory in both younger and older adults. *Experimental Brain Research*, *234*(6), 1555–1574. https://doi.org/10.1007/s00221-016-4557-0

Michael, K., & Michael, M. G. (2011). The social and behavioural implications of location-based services. *Journal of Location Based Services*, *5*(3–4), 121–137. https://doi.org/10.1080/17489725.2011.642820

Münzer, S., Zimmer, H. D., & Baus, J. (2012). Navigation assistance: A trade-off between wayfinding support and configural learning support. *Journal of Experimental Psychology: Applied*, *18*(1), 18–37. https://doi.org/10.1037/a0026553

Narzt, W., Pomberger, G., Ferscha, A., Kolb, D., Müller, R., Wieghardt, J., Hörtner, H., & Lindinger, C. (2006). Augmented reality navigation systems. *Universal Access in the Information Society*, *4*(3), 177–187. https://doi.org/10.1007/s10209-005-0017-5

Nivala, A.-M., & Sarjakoski, T. L. (2007). User aspects of adaptive visualization for mobile maps. *Cartography and Geographic Information Science*, *34*(4), 275–284. https://doi.org/10.1559/152304007782382954

Quesnot, T., & Roche, S. (2015). *Quantifying the significance of semantic landmarks in familiar and unfamiliar environments* (pp. 468–489). https://doi.org/10.1007/978-3-319-23374-1_22

Reichenbacher, T. (2001). Adaptive concepts for a mobile cartography. *Journal of Geographical Sciences*, *11*(S1), 43–53. https://doi.org/10.1007/BF02837443

Reichenbacher, T., Aliakbarian, M., Ghosh, A., & Fabrikant, S. I. (2022). Tappigraphy: Continuous ambulatory assessment and analysis of in-situ map app use behaviour. *Journal of Location Based Services*, *16*(3), 181–207. https://doi.org/10.1080/17489725.2022.2105410

Ricker, B., & Roth, R. (2018). Mobile maps and responsive design. *Geographic Information Science & Technology Body of Knowledge*, *2018*(Q2). https://doi.org/10.22224/gistbok/2018.2.5

Robinson, A. C., Kettunen, P., Delazari, L., & Çöltekin, A. (2023). New directions for the state of the art and science in cartography. *International Journal of Cartography*, *9*(2), 143–149. https://doi.org/10.1080/23729333.2023.2216334

Rohs, M., Schöning, J., Raubal, M., Essl, G., & Krüger, A. (2007). *Map navigation with mobile devices*. Proceedings of the Ninth International Conference on Multimodal Interfaces – ICMI '07 (p. 146) .https://doi.org/10.1145/1322192.1322219

Roth, R. (2017). User interface and user experience (UI/UX) design. *Geographic Information Science & Technology Body of Knowledge*, *2017*(Q2). https://doi.org/10.22224/gistbok/2017.2.5

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

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

Savino, G.-L., Emanuel, N., Kowalzik, S., Kroll, F., Lange, M. C., Laudan, M., Leder, R., Liang, Z., Markhabayeva, D., Schmeißer, M., Schütz, N., Stellmacher, C., Xu, Z., Bub, K., Kluss, T., Maldonado, J., Kruijff, E., & Schöning, J. (2019). *Comparing pedestrian navigation methods in* *virtual reality and real life*. 2019 International Conference on Multimodal Interaction (pp. 16–25). https://doi.org/10.1145/3340555.3353741

Savino, G.-L., Sturdee, M., Rundé, S., Lohmeier, C., Hecht, B., Prandi, C., Nunes, N. J., & Schöning, J. (2021). Maprecorder: Analysing real-world usage of mobile map applications. *Behaviour & Information Technology*, *40*(7), 646–662. https://doi.org/10.1080/0144929X.2020.1714733

Savino, G.-L., von Sawitzky, T., Matviienko, A., Sturdee, M., Woźniak, P. W., Löchtefeld, M., Kun, A. L., Riener, A., & Häkkilä, J. (2021). *Cycling@CHI: Towards a research agenda for HCI in the bike lane*. Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems (pp. 1–5). https://doi.org/10.1145/3411763.3441316

Sitaram, R., Ros, T., Stoeckel, L., Haller, S., Scharnowski, F., Lewis-Peacock, J., Weiskopf, N., Blefari, M. L., Rana, M., Oblak, E., Birbaumer, N., & Sulzer, J. (2017). Closed-loop brain training: The science of neurofeedback. In *Nature reviews neuroscience (Vol. 18, issue 2)* (pp. 86–100). Nature Publishing Group. https://doi.org/10.1038/nrn.2016.164

Starrett, M. J., McAvan, A. S., Huffman, D. J., Stokes, J. D., Kyle, C. T., Smuda, D. N., Kolarik, B. S., Laczko, J., & Ekstrom, A. D. (2021). Landmarks: A solution for spatial navigation and memory experiments in virtual reality. *Behavior Research Methods*, *53*(3), 1046–1059. https://doi.org/10.3758/s13428-020-01481-6

Sugimoto, M., Kusumi, T., Nagata, N., & Ishikawa, T. (2022). Online mobile map effect: How smartphone map use impairs spatial memory. *Spatial Cognition & Computation*, *22*(1–2), 161–183. https://doi.org/10.1080/13875868.2021.1969401

Thrash, T., Fabrikant, S. I., Brügger, A., Do, C. T., Huang, H., Richter, K. F., Lanini-Maggi, S., Bertel, S., Credé, S., Gartner, G., & Münzer, S. (2019). *The future of geographic information displays from giscience, cartographic, and cognitive science perspectives*. 14th International Conference on Spatial Information Theory, Vol. 142 (pp. 19:1–19:11). https://doi.org/10.4230/LIPIcs.COSIT.2019.19

Uttal, D. H., & Cohen, C. A. (2012). *Spatial thinking and STEM education* (pp. 147–181). https://doi.org/10.1016/B978-0-12-394293-7.00004-2

Van Elzakker, C. P. J. M., & Delikostidis, I. (2014). User-centered design of mobile geo-applications. In *Handbook of research on mobile software engineering* (pp. 234–248). IGI Global. https://doi.org/10.4018/978-1-61520-655-1.ch014

Wascher, E., Reiser, J., Rinkenauer, G., Larrá, M., Dreger, F. A., Schneider, D., Karthaus, M., Getzmann, S., Gutberlet, M., & Arnau, S. (2023). Neuroergonomics on the go: An evaluation of the potential of mobile EEG for workplace assessment and design. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *65*(1), 86–106. https://doi.org/10.1177/00187208211007707

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

Wunderlich, A., & Gramann, K. (2021). Eye movement-related brain potentials during assisted navigation in real-world environments. *European Journal of Neuroscience*, *54*(12), 8336–8354. https://doi.org/10.1111/ejn.15095

Zhao, H., Frese, L., Venzin, C., Kaszás, D., Weibel, R. P., Hölscher, C., Schinazi, V. R., & Thrash, T. (2023). The time course of spatial knowledge acquisition for different digital navigation aids. *Computers, Environment and Urban Systems*, *103*, Article 101992. https://doi.org/10.1016/j.compenvurbsys.2023.101992

Zhu, L., Shen, J., Zhou, J., Stachoň, Z., Hong, S., & Wang, X. (2022). Personalized landmark adaptive visualization method for pedestrian navigation maps: Considering user familiarity. *Transactions in GIS*, *26*(2), 669–690. https://doi.org/10.1111/tgis.12877