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Cognitive issues of mobile map design and use

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ABSTRACT

Internet-connected mobile devices have changed how people access information. Like other information sources, maps have benefited from and been re-envisioned for mobile devices, and they are used in new contexts. However, these new contexts often generate additional cognitive load. We explored in depth two strategies designers could use to mitigate high cognitive loads associated with mobile map use: offloading cognition and reducing cognitive load by improved design to support the allocation of attention between the map and the environment. In reviewing these strategies, we considered their relevance to several mobile map use cases (navigation, individual and collaborative spatial decision making, information enrichment, and entertainment). Next, we identified recent progress in our understanding of how to measure cognitive load and map use context. Finally, we explored the wider implications of mobile maps for human behaviour and cognition. We identified two important cross-cutting research questions: 1) How can mobile maps be designed to reduce cognitive load by providing what is really needed by users to facilitate their cognitive processes?; 2) How can the intrinsic additional cognitive load created by the characteristics of mobile maps be managed and minimised by supporting the distribution of the user's attention between the map and environment?

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1. Introduction

Mobile telecommunications devices have made their way into the hands of most of the world's population in the almost fifty years since the world's first mass-produced mobile phone was put on the market by Motorola in 1973 (Farley 2005; Radicati 2021). The linking of the Internet to mobile devices fundamentally changed how people access information, unlocking it from

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storehouses of printed materials like libraries and putting access points in the palm of anyone holding a smartphone. Like other information sources, maps have also benefited from and been re-envisioned for internet-connected mobile devices. We can now use maps to support our everyday activities in ways that were unimaginable with paper maps – for example, providing real-time updates and design that adapts when their use context changes. However, these new use contexts also often generate additional cognitive load, by presenting distractions in noisy and highly dynamic environments. This increased cognitive load is exacerbated by the design constraints posed by the characteristics that make mobile devices portable (e.g. small screens). While some foundational work exists (e.g. Meng, Zipf, and Reichenbacher 2005; Reichenbacher 2004; Ruginski et al. 2022; Thrash et al. 2019), there are many dimensions of how people use mobile maps and how we can best design such maps that are un- or under-explored.

We understand 'mobile map' as an overarching term for any maps used on mobile devices for different purposes and in many geography-related tasks. While the use of mobile maps in wayfinding be their most common use, this is by far not their only application, and we deliberately do not limit our exploration of mobile maps to navigation and assistance systems. Nonetheless, we see our work as complementary to earlier position papers that focused more narrowly on navigation systems (Ruginski et al. 2022) and spatial learning (Thrash et al. 2019). Recent work following this line of research has explored many cognitive dimensions relevant for the design of future navigation systems (Cheng et al. 2023; Fabrikant 2023; Kapaj et al. 2024; Lanini-Maggi, Hilton, and Fabrikant 2023). In this contribution, we identify key dimensions of cognition and mobile map use that would benefit from a focused research effort. In our exploration of these dimensions, we begin with a hypothetical motivating example of mobile map use to which we refer throughout our discussion.

> Luke and Carol, a young couple, recently moved to a flat in *The City*. By now, they know their local neighborhood from grocery shopping and short strolls. Carol is also familiar with her route to her workplace in a downtown office. This morning though, on her way to the subway station, she receives a push notification on her smartphone, informing her about an incident on her subway line. She opens the app *moma*, a mobile mapping app she uses regularly. She starts to explore alternative trips by bus and tramway. Soon she has found an appropriate substitute itinerary, and *moma* is presenting the route to the stop where she needs to hop on the bus. In addition to route instructions offered by *moma*, Carol also checks her position on the map display to confirm she is still on track. After a short bus ride, she changes to the tramway, and 10 minutes later, *moma* alerts her that she needs to exit at the next stop. Just when Carol has almost made it to the office, her employer's *workharder* app sends her a message, saying that the office is locked down due to a fire service operation unrelated to the earlier subway incident. Carol is getting a bit stressed, because she does not know the surrounding area and must quickly reschedule a meeting with a client. What is more, she wonders when, where, and how she would hold a very

important team meeting. Chris, one of her team members, suggests to the team on the *workharder* chat channel to instead meet in a coffee shop. The team immediately starts to use the planning function on *workharder*. Carol now sees the positions of her team members, and jointly they identify a coffee shop that is located nearby and can be reached by all team members in a reasonable time. *workharder* guides Carol the 600 metres to the coffee shop. Carol and her team have one of their most productive meetings ever.

This series of dramatic events is unnoticed by Luke who has a relaxed drive to his workplace, located in the outskirts of *The City*. Because he is in such a good mood, Luke decides to drive a different route this morning and explore unfamiliar districts. The route is labelled as a 'scenic route' by *moma's* car navigation function. Luke wants to learn this new part of *The City* and regularly checks the map on the car navigation system. When arriving in his company's parking lot, he can still remember three major landmarks on his route: the *Ridge Bridge*, the green-yellow façade of a bank tower, and a big diamond-shaped crossing. At lunch break, a couple of colleagues invite Luke to play the much hyped *greenismean* game with them in a nearby park. The game is a collaborative AR game with the aim of catching grass monsters. Luke sees the locations, hiding spots, and movements of the virtual monsters superimposed on the visual scene displayed on his augmented reality glasses.

A bit exhausted, but very pleased, Luke returns to the office and has a bit more work to do. He does not mind too much, since it has started to rain heavily. Just when walking to the car he gets a first alert from *moma's* alerting function about severe storms and flash floods in *The City*. A quick glance on the warning map in *moma* tells him that things look still okay. However, while driving home he suddenly registers a blinking warning sign on *moma's* warning map about a situation on his route home. *moma* immediately presents him with a new alternative route home that is unaffected by the hazard, and Luke decides to take it. Since he has registered Carol as a family member with *moma's* alert function, he also receives a message that Carol is safe.

After eventually returning to the office and spending a few hours at her desk, Carol decides to leave early today. Having two hours of unexpected leisure time at her disposal, she opts for exploring the market district, which she always had wanted to visit. Since she has only about two hours before she will meet Luke for a movie night, she wants to get an overview of what various places in the market district look like. She uses *moma's* explore function and can access live feeds from webcams, social media comments, and even live sound streams from local sensors. Also, she receives links to services available at the places that *moma* clearly marks as *service integrator products*, providing sources and operating principles of underlying recommender algorithms. While strolling through the market she notices a damaged bench at the roadside and reports the damage to the city council with *moma's* report function, which automatically registers her location in the report post.

What an eventful day! Luke has agreed to organize the movie night and checks *moma* for cinemas near Carol's current location that show the movie 'Victim of Geography', which they both want to watch. *moma's* planning function shows three cinemas that feature the movie, and that both he and Carol can get to before the movie starts. Since time is a bit short, Luke is grateful that the app is

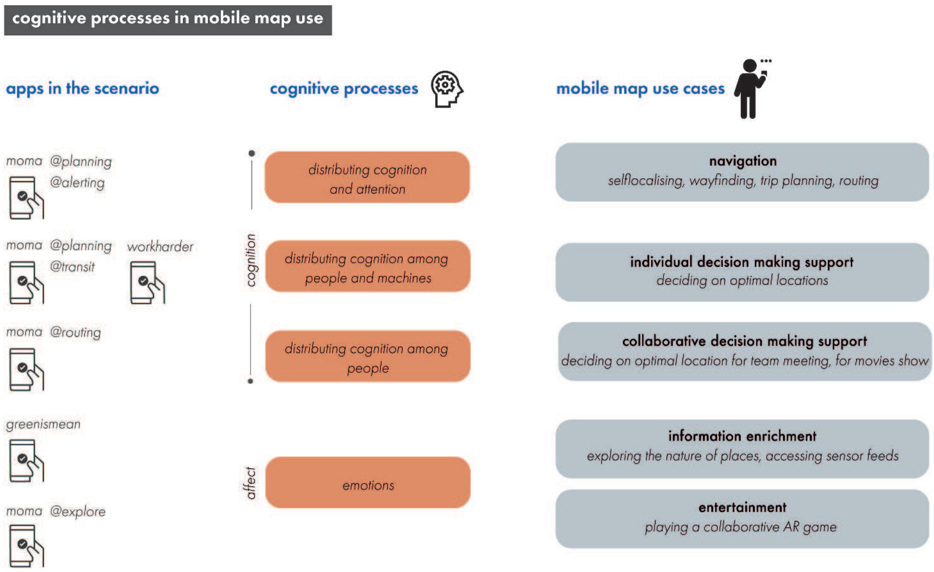

Figure 1. Schema of tasks and apps from the scenario and their linkages to cognitive processes and mobile use cases.

doing some of the multi-criteria analysis and shows only the most relevant information on the map. Eventually, Carol and Luke sit comfortably in their seats and learn about how one can become a victim of geography.

With this short example, we aim to demonstrate the need for studying humans in mobile map research. It illustrates the breadth and diversity of cognitive issues involved in mobile map design and mobile map use (Figure 1). Map use is triggered by information needs, activities, and goals. As we can see, Carol and Luke take different roles and act in various situations. They are *human sensors*, *information processors*, *spatio-temporal analysts and planners*, *spatial decision makers*, *collaborators*, and *game players*.

In some map use situations, mobile maps serve as an interface to an assistance system, such as when Carol needs to find a new location for a team meeting and then navigate to it. In other cases, mobile maps are used for tasks that are less goal-directed, such as when Luke plays a game, or when (not discussed in the motivating story above) a person might examine a map embedded within a news article while browsing the newspaper on their mobile device. Human cognitive limits and design constraints will share some similarities across these different situations.

In the following section we highlight cognitive processes that are particularly critical for the different mobile map use tasks described in the scenario and identify research challenges associated with understanding these processes. Section 3 presents use cases that demonstrate these cognitive issues at work with mobile maps. For simplicity, we focus deliberately on the most characteristic cognitive issues for each of the use cases, while acknowledging that real-world use cases involve multiple, entangled cognitive processes and that several of these run synchronously. In our review, we acknowledge the importance of, but do not focus explicitly on how individual differences between mobile map users also play a role in the successful use of mobile maps. In Section 4, we detail needs for research on the methods that can be employed for measuring and understanding cognition and behaviour. Finally, in Section 5, we reflect on research needs that relate to the existing and potential future impacts of mobile maps on individuals and society.

2. Cognition and mobile map use

Cognitive processes include 'attention, perception, reasoning, emoting, learning, synthesizing, rearrangement and manipulation of stored information, memory storage, retrieval, and metacognition' (Krch 2011, 627). Armitage et al. (2020) remark that humans often face hard limits regarding memory, attention, or perception when relying on internal cognitive processes alone. Digital devices seem to exacerbate this problem. The mere presence of a mobile device appears to deplete internal cognitive resources (Ward et al. 2017). Ilany-Tzur and Fink (2019) see mobile cognition as a 'distracted mindset', showing that on tasks that induce a high cognitive load, participants using desktop computers outperform those using mobile devices.

Cognitive load can increase due to changes in the environment, more dynamic stimuli, or greater demands from the activity, among other reasons. Mobile map users are typically engaged in one or more activities within which map use tasks are embedded. In mobile map use situations, demands on cognitive processes are often comparably higher than in stationary use cases because of the dynamism of the environment. These dynamically changing contexts offer additional challenges for designing mobile maps that are fit for purpose.

There are at least two options to mitigate these limitations and compensate for human cognitive constraints imposed by mobile use cases: 1) offloading cognition by distributing some of the load to other actors such as other people or machines; and 2) reducing cognitive load by improved design to support efficient and effective allocation of attention between the map and the environment. Each of these will be discussed in the next sections and opportunities for research and development will be highlighted.

2.1. Cognitive offloading by distributing cognition among people and machines

Cognitive load (CL) is the total mental effort or resources being used in working memory (Kirschner et al. 2018; Paas, Renkl, and Sweller 2003; Paas and Van Merriënboer 1993; Sweller, Van Merrienboer, and Paas 1998). Cognitive load theory differentiates between three types of cognitive load: intrinsic, extraneous, and germane (Sweller, Van Merrienboer, and Paas 1998). Intrinsic CL refers to the inherent level of difficulty of the information presented. Extraneous CL is influenced by the way the information is presented. Finally, germane CL denotes the creating and using of schemata, i.e. patterns of information processing, structuring, organising, and sense-making. CL is often rather high in mobile map use cases, and can come from several sources, including the complexity of the mapped features or dynamic context changes (intrinsic CL) or the design of the map (extraneous CL) (Bunch and Lloyd 2006; Paas, Renkl, and Sweller 2003; Sweller, Van Merrienboer, and Paas 1998). It is difficult to attribute cognitive load to its source, but total cognitive load in a map use situation can be measured (Kirschner 2002). For discussion of methods to measure cognitive load see Section 4.1.

External cognition is not a new concept (Scaife and Rogers 1996) and has been described by Clark and Chalmers (1998) as the extended mind. As is any map, mobile maps are a cognitive artefact, an external spatial representation in visual form. A key affordance of external representations is cognitive offloading, i.e. the externalisation of cognitive processes (Hu, Luo, and Fleming 2019). They reduce the cognitive demands on memory and thus save internal cognitive resources (Risko and Gilbert 2016). As such, they allow us to surpass limits of working memory and handle more information than would be otherwise be possible (Grinschgl, Meyerhoff, and Papenmeier 2020). When designing mobile maps, we may also seek to achieve a shift from the cognitive to the perceptual system, favouring recognition over recall. This echoes the idea of knowledge-in-the-head versus knowledge-in-the-world (Norman 2013; Risko and Dunn 2015).

Related to external cognition is *distributed cognition* which '[. . .] extends the reach of what is considered cognitive beyond the individual to encompass interactions between people and with resources and materials in the environment' (Hollan, Hutchins, and Kirsh 2000, 175; Rogers and Ellis 1994). Cognition could be distributed to other people or to machines and thereby shared, offloading some of the cognitive effort for an individual map user. Each of these solutions comes with additional design challenges which could be supported by research.

Distributing cognition among multiple people increases the total cognitive resource that is available for solving a geographical problem. But collective performance is not simply the sum of individual performances and is also influenced by social interactions within the group (Hutchins 1995). As social creatures, people take cues from other people, whether implicitly or explicitly. Previous studies show that social influences constrain individual behaviour (Hutchins 1995). Implicit cues might be relevant when an individual's behaviours and decision making are influenced by the presence of other people, whether physical or virtual. For example, map use can be impacted if a map stress or anxiety levels increase because they feel other drivers getting impatient as they struggle to locate themselves on a map while blocking traffic during rush hour. Virtual presence of others can also impact map use behaviours. For example, a public transport user may decide to instead take a taxi if they can see on the map that their train is overcrowded. The development of new technologies, e.g. mixed reality and eye-tracking, offers us good opportunities to study group social interactions and their relationship to mobile maps (Moussaïd et al. 2018; Zhao et al. 2020).

Explicit social cues, such as those that are observable in situations of collaborative decision making, might stem from real-time communication and shared map context. In mobile map use cases that require collaboration (e.g. disaster response, social wayfinding, gaming, collaborative route planning), drawing on the group's knowledge is important, but this can be hindered if the mobile map does not support communication and shared map context and minimise social cues that can lead to some group members being unable to contribute their knowledge. The *workharder* app's shared map context allowed Carol's team members to collectively identify a coffee shop for their meeting; without knowing everyone's location, this task would have been much harder. Some examples of explicit social cues include the *social influence effect*, which undermines group diversity, and the *confidence effect*, which makes individuals overly confident (Lorenz et al. 2011). To avoid such effects, Woolley et al. (2010) proposed to distribute conversational turn-taking equally in a group. To support collaborative use of mobile maps, it would be fruitful to further investigate group social interactions, in terms of the impacts of group size and familiarity among group members on shaping social interactions, and how individual decision making is influenced by group dynamics.

Sharing or distributing parts of cognition between humans and machines (i.e. any kind of computing device, software service, software agent, or robot) also offers great potential for amplifying and extending human cognition (Clark and Chalmers 1998). For example, rather than having to sort through all the possible new routings to get to work when her subway line is disrupted, Carol can quickly look at the map to select an appropriate substitute from a few that the app displays. However, for distributing cognition to machines to be beneficial, several questions and challenges need to be addressed.

LBS and mobile map apps already show a remarkable amount of automation. Leaning on the well-established classification of automation levels of driving[1] we can distinguish (0) no automation, (1) assistance, (2) partial automation, (3) conditional automation, (4) high automation, and

(5) full automation. For levels 0–2, the human monitors system and environment; for levels 3–5, the system monitors the environment. In the context of mobile maps, Reichenbacher (2004) used a different conceptualisation based on human-computer interface research, discriminating non-adaptive, static systems from adaptive systems. Despite the several taxonomies used, we can differentiate at least five levels of automation in LBS and mobile map apps: no automation; simple automation in the form of automated positioning, e.g. by GNSS; assistance, e.g. through route instructions; advanced automation: e.g. automatic collection of information from different data sources & integration of information in the mobile map; and high automation employing artificial intelligence (AI) and deep learning techniques, e.g. adaptive map interface behaviour.

Shneiderman (2020) conceptualised a human-centred AI and proposed a two-dimensional framework for categorising automated human-machine systems, with levels of human control and computer automation being the two dimensions. The main questions involved in automation are trust, control, transparency, and accountability. The field of ethical AI has gained a lot of attention in the last couple of years, particularly advocating for algorithm transparency and mitigation of algorithmic biases. The *moma @explore* app that Carol used to explore the market district communicated what criteria it used to recommend different features of interest, making the algorithm more transparent.

Automation comes with many benefits, such as efficiency or reduction of human errors, but also presents challenges that were nicely summarised as *ironies of automation* (Bainbridge 1983). The irony refers to the fact that human operators degrade in their capabilities (i.e. skills and knowledge) to take over a task if the machine fails. Endsley (2017, 5) states that 'as more autonomy is added to a system, and its reliability and robustness increase, the lower the situation awareness of human operators and the less likely that they will be able to take over manual control when needed'. This is echoed by Brügger et al. (2019), who found that while automated navigation assistance benefits navigation performance, it seems to have a negative impact on attention paid to the environment, on spatial knowledge acquisition, and on memory. This has potential negative effects on long-term memory and knowledge acquisition, which we discuss further in Section 5.2.

Despite the clear benefits of cognitive offloading in mobile map use situations, users still need to align the map representations with both their internal representations and the environment itself, which is cognitively demanding, and may cause problems with attention allocation. We discuss this problem in the next section.

Opportunity 1: Reducing the cognitive load of mobile map use

(1.1) How much do we need to understand about the source of the cognitive load (intrinsic, extrinsic, germane) to determine how mobile maps can be designed to minimise cognitive load?
(1.2) What are the important social cues that should be accounted for when designing for collaborative mobile map use?
(1.3) Which tasks can and should be distributed between humans and machines, i.e. which tasks profit most?
(1.4) How can we clearly communicate to the user what the machine is doing when we outsource cognitive processing to a machine?
(1.5) How do we decide how much context should be shared between humans or between humans and machines for mobile map use?

2.2. Distributing attention between mobile maps and the environment

Map use involves both sensory-driven, perceptual bottom-up, and concept-driven, top-down cognitive processes. While this is common to the use of any map, mobile map use cases pose a particular challenge to distributing attentional resources, since the attention is divided between display, the environment, and the task or activity being pursued.

Typically, attention is divided into five types: focused, sustained, selective, alternating, and divided (Commodari 2017; Sohlberg and Mateer 1987). Of these, focused, selective, and divided are most important for mobile map design. *Focused attention* is 'the ability to respond discretely to specific visual, auditory, or tactile stimuli' (Sohlberg and Mateer 1987, 361). *Selective attention* can be defined as 'the ability to maintain a cognitive set which requires activation and inhibition of responses dependent upon discrimination of stimuli' while *divided attention* refers to 'the ability to simultaneously respond to multiple tasks' (Sohlberg and Mateer 1987, 361). Although distracting stimuli from the environment can also have impacts on reading paper maps, we see the problem of attention as aggravated with mobile maps since their smaller size results in having more (distracting) environmental stimuli in the field of view of the map reader.

Although attention allocation depends on several factors and can be supported through smart interaction styles developed in other fields, such as HCI, we focus here on the role of map design for attention shifts. In mobile map use contexts, the number of distracting environmental stimuli might be rather large, and they compete with the mobile map display for the user's attention. To enable effective and efficient map use, map design should favour selective and focused attention. Because divided attention may have negative impacts on task performance, it should be limited to matching map content and the environment where needed. In our scenario, because *moma @explore* was designed well, Luke was able to pay enough attention to the environment to notice and remember some of the most important environmental features on his route through a new neighbourhood, supporting his spatial knowledge acquisition.

Swienty et al. (2008) proposed an adaptive design approach to deliberately guide users' attention towards relevant information on the map display. However, many questions related to attention allocation with mobile maps are under-explored, such as task dependency, environment (indoor vs. outdoor), frame of reference (egocentric vs. allocentric), modalities, among others.

Opportunity 2: Supporting effective attention distribution

(2.1) How much attention needs to be focused on the environment versus the map to support successful mobile map use?
(2.2) What design elements support a mobile map user's ability to effectively distribute attention between the map and the wider environment?

2.3. Emotions

No matter where cognitive processes reside, they are linked with emotions (Andrade and Ariely 2009). Studying the emotions of mobile map users may provide important insights into how mobile map users experience mobile maps. For example, people in a positive affective state appear to have a wider focus of attention than those in a negative affective state (Jeon, Walker, and Yim 2014). It is not hard to imagine that mobile map users in a negative affective state while trying to find their way to a new destination might get 'lost in the map' when trying to locate themselves in space and on the map because they focus too much on the map and not enough on their surrounding environment. Because of the connection between emotions and cognitive processes, knowledge of emotions, whatever their source, is likely to be important for mobile map designers. However, how this knowledge informs mobile map design may differ depending on the emotion's source.

People have emotions as part of their everyday lives. These emotions may stem from their interactions with their environment (i.e. their external surroundings) or their internal state. The use of a mobile map can itself have impacts on a person's emotional state, such as when Luke returned to the office after playing *greenismean* feeling a bit tired but very satisfied. Moreover, because of their mobility, mobile map use often occurs across different environments and contexts, producing an entanglement of influences on the user's emotional state (Caquard and Griffin 2018; Peterle 2018). It is an open question whether a mobile map should react in any way to some of these other sources of the user's emotions, using approaches proposed in affective computing (Calvo et al. 2015).

Human-computer interaction studies have underlined the importance of learning about emotions that stem from the design of an interactive tool (Saariluoma and Jokinen 2014). Norman (2004) proposed different levels at which emotion might factor into the user experience with a design: the visceral (e.g. the appearance of the product), the behavioural (e.g. emotions derived from the use of the product), and reflective (e.g. remembering past use of the product or imagining future use of the product). Disambiguating at which of these levels an emotion is generated would be necessary to improving the design of any product and is a key challenge for studying the role of emotions in shaping mobile map user experiences.

Opportunity 3: Delineating impacts of emotions on mobile map cognition

(3.1) How can we understand what emotions are being generated by a mobile map's use rather than other sources?
(3.2) To what extent should mobile maps adapt to changes in the emotional states of mobile map users?

3. Use cases of mobile map use tasks

In this section we will exemplify mobile map use tasks and show how the cognitive processes identified in section 2 are relevant in specific use cases.

3.1. Navigation

Mobile maps facilitate navigation in different contexts (e.g. familiar or unfamiliar, indoor or outdoor environments). Navigation is a cognitively demanding process (especially in unfamiliar environments) because navigators need to accomplish a series of tasks such as self-localisation, spatial orientation, map-environment matching, route planning and memorisation, route control, and destination confirmation. Existing mobile map designs have some features to reduce this high cognitive load, for example, the blue dot that shows the map user's position in the environment, which assists with self-localisation.

To further reduce the cognitive load of navigation, alternatives to current designs can be envisioned. For example, instead of turn-by-turn instructions, navigation apps might provide landmark-based routes, which reduce the amount of attention that needs to be allocated to the map and assists an unfamiliar user with map-environment matching and route control. In addition, landmark-based routes can help reduce the problem of decreased spatial knowledge acquisition that is associated with turn-by-turn instructions (Wunderlich, Grieger, and Gramann 2022). Good design can reduce the cognitive load for map users who are already familiar with an area but who need supplementary detailed information to make navigation choices (e.g. traffic or weather conditions, such as those experienced by Carol and Luke in our scenario on their way to and from work) (Liao et al. 2022; Zhou, Weibel, and Huang 2022; Zhu et al. 2022). Various aspects of mobile navigation services have been explored, e.g. planning routes based on user affective responses and history locations (Huang and Gartner 2012; Huang et al. 2014; Quercia, Schifanella, and Aiello 2014), communicating landmark information according to users' familiarity with the environment (Zhou, Weibel, and Huang 2022), and providing adaptive map content based on users' visual behaviour and tasks at hand (Giannopoulos, Kiefer, and Raubal 2015; Liao et al. 2019).

Navigation has long been studied as an individual activity, even though it has seldom been a solitary process without any influence by others (Bae and Montello 2019; Dalton, Hölscher, and Montello 2019), such as in the example of the team jointly identifying a nearby coffee shop in our scenario. Informed by the cognitive research in Section 2.1, corresponding features to better support social wayfinding and collective LBS should be provided when designing navigation services.

Opportunity 4: Making map-assisted navigation easier

(4.1) Which navigation sub-processes (e.g. self-localisation, map-environment matching, etc.) induce the highest cognitive load for map users who have different levels of familiarity with the environment?

(4.2) How is the map user's attention distributed differently when the mobile map offers different kinds of support (e.g. self-localization, orientation) for understanding the relationship between the map user and the environment?

3.2. Individual spatial decision-making

GIS-based spatial decision support systems (SDSS) have long been exploited to support complex, multi-criteria and subjective decision making by facilitating human-machine dialogue and providing modelled assistance to reduce decision dimensions (Andrienko et al. 2007; Jankowski, Andrienko, and Andrienko 2001; Karnatak et al. 2007). In contrast, mobile maps often over-simplify the spatial decision-making process by presenting a location- and context-based optimal decision synthesised by computer models, such as the alternative route presented to Luke on his way home from work when his typical route is affected by the storm. Such simplification is understandable due to the physical constraints of mobile devices and applications, but whether it provides effective decision support is unclear. Modelling decisions without integrating users' subjective knowledge and preferences may not always be favourable. Furthermore, even if more than one viable option is provided to users, simple decision suggestions may not be trusted by users. For complicated and significant decisions such as disaster evacuation, research shows that many people need to make their own assessment of risk and assess the necessity and efficacy of evacuation prior to complying with the evacuation order suggested for their location (Cao, Boruff, and McNeill 2017). However, over-presentation of professional explanatory information, such as hazard development delineation (Cao, Boruff, and McNeill 2017; Thompson, Lindsay, and Leonard 2017), uncertainty information (Kübler, Richter, and Fabrikant 2020), and realistic hillshade images (Wilkening and Fabrikant 2011) is undesirable, as it may unnecessarily increase the cognitive load of decision makers and cause confusion. Mobile-map-based SDSS users need to be able to communicate effectively with the machine that presents the decision options, yet, the sophisticated multi-panel interface designs typically employed by desktop- and web-based SDSS cannot be implemented on mobile devices due to display size constraints. It is thus especially important to adopt a human-centred, iterative and agile methodology (Roth 2013) to design effective mobile SDSS. Rules of thumb for designing effective interactions can be borrowed from the mobile GIS literature (e.g. Binti Ayob, Hussin, and Dahlan 2009; Haimes, Baba, and Medley 2015; Meng, Zipf, and Reichenbacher 2005; Vincent et al. 2019).

Opportunity 5: Clear human-machine communication about decision information

- *(5.1) How much explanatory information needs to be provided by mobile-map-based SDSS to satisfy users' needs for understanding and trusting the simplified decision options the machine proposes?*
- *(5.2) How can a mobile-map-based SDSS support easy, effective, and consistent human-machine dialogue and interaction?*

3.3. Collaborative spatial decision-making

Mobile maps can support collaborative spatial decision-making in various applications, e.g. field data collection (Pisařovic et al. 2017; Whitlock, Wu, and Szafir 2019), travel planning (Chang et al. 2019), education (Šašinka et al. 2019), emergency response and disaster management (Cai 2005; MacEachren et al. 2005). On the one hand, to support collaborative spatial decision-making, research on mobile maps needs to consider similar issues as does collaborative GIS: real-time data integration and synchronisation, concurrent control, group collaborative awareness, negotiation and conflict management (Andrienko et al. 2007; MacEachren 2001; Pisařovic et al. 2017; Sun and Li 2016). On the other hand, the limitations of the mobile device and the use context pose specific challenges. Mobile use context concerns for collaborative spatial decision-making include privacy and attention and cognition distribution between the device, the environment, and the group. Thus, instead of the comprehensive group collaborative awareness (i.e. the context of each group member being shared to everyone else: what you see is what I see) preferred in collaborative GIS, mobile maps may benefit from a simplified group awareness. This awareness could even be dynamically changeable, depending on the needs of the group – finding a jointly accessible coffee shop for an unplanned meeting, as in our scenario, would require team members to share their location among the group. In addition, different technology configurations allow different levels of communication, coordination, and conflict management (Arciniegas, Janssen, and Rietveld 2013), which vary among different applications. Compared to a couple collaboratively deciding on a cinema location in our example scenario, the stakeholders from different domains involved in spatial planning may need more communication and coordination encouraged by mobile maps.

Opportunity 6: Adaptive collaboration support for spatial decision-making with mobile maps

(6.1) How can we identify communication and coordination requirements for different applications of mobile map-based collaborative spatial decision support?

(6.2) What is a good method for communicating context to facilitate collaborative decision making with mobile maps?

3.4. Information enrichment

Mobile maps can provide enriched information about a place, for example, through serious games (Pánek et al. 2018), guided tours of the landscape (Roth et al. 2018), or by highlighting 'invisible' features in the landscape via augmented reality (Loeffler et al. 2021). Information can be provided actively or passively, commonly termed as pull and push services, respectively, with push services being more common. The passive push mode is triggered by the device and environmental sensors, such as the information provided to Luke on the scenic route he took to work as he explored a new part of the city.

Passive notifications can be offered too frequently or may be ill-timed. This may end up overloading the user with information and constituting a distraction rather than a benefit, as any mobile phone user who has dismissed notifications on their phone can attest. But mobile maps offer the affordances of direct manipulation of and interaction with geospatial information. In active pull mode, mobile users are gathering and pulling information on their own initiative. The mobile map can then serve as an interface to information that offers the user a more comprehensive picture of their surroundings and a deeper understanding of a place, including its 'sense of place'. In contrast to the passive mode, where the information is almost solely about the current location and its near surroundings, in active mode users may also look for more distant places, for instance when exploring new environments or planning activities (Crease and Reichenbacher 2013), such as Carol's exploration of the market district in our scenario. Such behaviour is echoed by Savino et al., (2021, 657), who state that 'People like to explore maps, either through necessity or curiosity' and 'that mobile map applications are no longer just used to get from A to B but also serve as an important source of information beyond that'.

Opportunity 7: Providing the right amount of the right information for the activity at the right time

(7.1) How can mobile map interfaces support users to gain a sense-of-place and integrate sensed and gathered information about a place?
(7.2) What information should an automated map service push to which mobile map users, and in what form, where and when should it be pushed?

3.5. Entertainment

Location-based games are forms of entertainment in which the player's location has a central role in how the game unfolds. Maps underlie many of these games, for example, in determining where a player meets another nonplayer character, as in Pokemon Go. Although location-based games existed before internet-connected, GPS-enabled mobile devices could be found in most people's pockets, smartphones have brought location-based games to a much larger audience. In comparison to maps that are found in analogue board games, console-based or computer-based games, mobile maps in location-based games make the player's engagement with the (real-world) environment more explicit, showing their position in the world as a part of the game (Lammes and Wilmott 2018). Successful game designs work to create specific emotional experiences in their players (Isbister 2016). In location-based games, if the game is well designed, these emotions can extend to the locations in which the games play out (Oleksy and Wnuk 2017). For example, Coulton et al. (2017) argue that a design needs to manage the distribution of players' attention to facilitate 'heads up' movement through space rather than 'heads down' absorption in the screen. The augmented reality glasses Luke used when he played *greenismean* provided one way to facilitate 'heads up' movement. Multiplayer location-based games might also benefit from being able to communicate the emotional states of other game players. Other location-based products and services use a gamification approach to increase user engagement with a place, both for leisure purposes such as in tourist visits (Garcia et al. 2019) or for education (Pánek et al. 2018). They can also be designed to encourage behaviour changes, such as increasing physical activity (Intawong and Puritat 2021) or influence transportation route or mode decisions (Guo et al. 2022). For example, fitness apps may allow users to compete to cycle the longest distance or climb the most steps.

Opportunity 8: Understand how to use emotions to improve experiences with mobile maps

(8.1) *What are the benefits and disadvantages of communicating other mobile map users' emotional states in mobile maps?*
(8.2) *Which emotions are most likely to lead to success when location-based services employ gamification to achieve their aims?*

4. Methods for understanding human cognitive processes in mobile map use

The previous section highlighted how designing maps for different mobile map use tasks needs to consider human cognitive processes and their limits, for example, by decreasing the cognitive load that arises from mobile map use, helping to support an activity-appropriate allocation of the user's attention, and accounting for the user's emotional state. It also highlighted the role of context in shaping what map design features will be needed for successful mobile map use. The importance of reducing cognitive load for successful mobile map use makes its measurement a valuable part of the evaluation of the success of any mobile map design. Design features that can achieve this aim, such as distributing some of that load to other people or machines, requires context sharing, and, in many cases, context sensing. Context is furthermore important in that it influences the methods we can use to successfully measure human cognitive processes and mobile map use behaviours. This section reviews recent progress in our understanding of how to measure cognitive load and map use context. It also highlights research opportunities that will advance our knowledge of how to use these methods to understand how users experience mobile maps.

4.1. Measuring cognitive load

Cognitive load can be measured in different ways, including through subjective reports (e.g. the NASA-TLX instrument (Paas 1992)), measures of behaviour (e.g. pausing when walking along a route because it's too hard while walking to match the map with the environment), and psychophysiological measures (e.g. EEG, pupillometry using eye-tracking, heart rate). Each of these measurement methods has pros and cons, and recent reviews have explored many relevant general considerations when choosing a methodology for measuring cognitive load (Schmälzle and Grall 2020; Skulmowski and Rey 2017). For example, self-reports can be affected by numerous biases (e.g. social desirability bias) and their provision can interrupt and alter cognitive processes and change behaviours, while many psychophysiological methods can capture experience unobtrusively and without interrupting cognitive processes.

Here, we focus on the methodological considerations that are most relevant to mobile map use contexts. Mobile map use frequently takes place outdoors. Thus, a key consideration for designing mobile map use experiments is how changes in the environment (e.g. changing illumination levels, times of peak traffic, the environment changing more quickly than the map can be updated, etc.) might affect the measurement of cognitive load as well as attribution of the source of the cognitive load.

Eye-tracking can detect changes in pupil dilation. Pupil dilation happens unconsciously, and it is a highly useful and rich source of information on cognitive load, where higher load is associated with pupil dilation and lags in eye blinks (Kiefer et al. 2016; König et al. 2016; Krejtz et al. 2018). Pupillometry, however, is also affected by illumination changes, which are both dynamic and uncontrolled in outdoor environments, and can therefore confound relationships between pupil diameter and cognitive load. Pupillometry may be more usable as a measure of cognitive load in mobile map use experiments conducted in virtual environments where such factors can be controlled, making valid ambulatory measurement of cognitive load possible (Bækgaard, Jalaliniya, and Hansen 2019).

Electroencephalography (EEG) is a non-invasive neuroimaging method that measures the electrical activity of the human brain (in the range of a few microvolts) using electrodes with amplifiers to enhance the signal placed on the scalp (Srinivasan and Nunez 2012). This allows the assessment of covert, non-directly observable behaviour, such as perceptual, cognitive, and affective processes. Brain activity can be measured during task performance without interrupting test participants and EEG is thus a highly effective method for measuring participants' ongoing cognitive load during the tasks, since real-time analysis of brain activity signals can show distinct changes in frequency bands that indicate increased cognitive load. For mobile map use studies, the emergence of mobile EEG (Makeig et al. 2009; Mavros, Austwick, and Smith 2016) offers great potential in conducting ambulatory experiments (e.g. participants walking indoors/outdoors). Nevertheless, up to now, only a few such studies have been undertaken, either in the lab through virtual environments (Cheng et al. 2023) or in field environments (Hilton, Kapaj, and Fabrikant 2024; Kapaj et al. 2023, 2024).

Changes in physiological signals can frequently be caused by multiple cognitive processes as well as by physical activity, meaning that disentangling the meaning of an individual signal can be difficult or impossible, especially in less controlled settings such as real-world environments (Lohani, Payne, and Strayer 2019). Measuring and combining several signals may be helpful in this regard. This brings its own challenges, however, including the need to sync signals with each other and the fact that different measures are sensable at varying temporal resolutions. Early cartographic work investigated some of these challenges of multi-method measurement of cognitive load (eye tracking and EEG) during a 2D map search task (Keskin and Ooms 2018).

More research is needed to determine which measures of cognitive load might be most validly measured in different experimental contexts (e.g. laboratory, virtual environments, or real-world environments). Putting participants in real-world environments can enable researchers to (1) investigate and understand human behaviour under the full complexity of its use context; (2) reveal how user behaviour in real environments differs from that in lab environments; and (3) validate whether results from lab-based studies can be generalised to real environments, and if yes, to what extent (Dong, Liao, et al. 2020). In contrast, laboratory environments provide the capacity for greater experimental control. Virtual environments, as a kind of half-way space between the laboratory and the real world, may be helpful for helping to understand how much of the cognitive load experienced by mobile map users comes from the environment or from the map. However, more needs to be understood about when to choose a particular environment for a study. A possible direction towards building this knowledge is to compare how people behave in different experimental settings, such as wayfinding in a virtual environment and in the real world (Dong et al. 2022) or performing map-reading tasks in a virtual environment and in a desktop environment (Dong, Yang, et al. 2020).

Opportunity 9: Determine how and where it is best to measure mobile map-use-related cognitive load.

(9.1) With what methodologies and devices can we best measure the cognitive load associated with mobile map use?
(9.2) What are the best ways to integrate multiple measurements of cognitive load in different mobile map use situations?
(9.3) What criteria might be helpful for deciding whether an experiment is best performed in the lab, in virtual environments, or in real-world environments?

4.2. Measuring map use context and understanding its impact on behaviour

Conducting user studies in a real-world environment can be challenging because the real-world environment is dynamic (Delikostidis, van Elzakker, and Kraak 2015; Dong, Liao, et al. 2020; Koletsis et al. 2017). Thus, participants are exposed to diverse visual stimuli, making it difficult to compare the data from different participant groups if changes in the context go unmeasured. Modern mobile devices are equipped with multiple sensors that can be used to measure elements of map use context (i.e. the user, environment, activity). These sensors include cameras, GNSS receivers, accelerometers, heartbeat sensors, Lidar sensors, temperature sensors, and ambient light sensors, among others.

Some methods are particularly helpful for understanding the user in context. Eye-tracking, for example, can be used for studying gaze behaviour and indicating cognitive load, but can also contribute to characterising context. It can be used to provide insights into where people look in their environment when they need to find their way or make spatial decisions as well as about where and how people look at mobile maps. Ideally, both gaze types are collected in conjunction to better understand the interplay of mobile map use with the environment. In recent years several studies were conducted in the field, examining wayfinding, spatial cognition, and mobile map usability (e.g. Brügger, Richter, and Fabrikant 2019; Giannopoulos, Kiefer, and Raubal 2013; Kiefer, Giannopoulos, and Raubal 2014; Liao et al. 2019). Kiefer et al. (2014) studied the process of matching content represented in mobile maps with its referent in the environment. Using mobile eye-tracking allowed them to conclude that participants were focusing on relevant features in the map and the environment during a self-localisation task. Moreover, a sequence analysis of gaze paths revealed that successful participants were more frequently switching their attention between the map and the environment, demonstrating the importance of understanding how attention distribution and cognitive load are related. In a usability study, de Cock et al. (2021) compared adapted and non-adapted indoor route guidance systems using mobile eye-tracking. They found that the people using the adapted system spent more time looking at the environment, less time looking at the mobile device, and made fewer navigational errors. Measuring behaviour in context can help us to understand more about when and how particular designs reduce cognitive load.

Opportunity 10: Identify how to measure and control context for understanding mobile map use cognition and behaviour.

(10.1) *What aspects of map use context need to be measured to disentangle sources of cognitive load that derive from the map's design versus the map use environment?*
(10.2) *To what extent can a virtual environment simulate the context of the real-world environment for studying different uses of mobile maps (e.g. self-localisation, spatial orientating, map-environment matching, distributed collaborative decision making, etc.)?*

5. Impacts on individuals and society

In this final section, we examine some of the wider implications of mobile maps for human behaviour and cognition. Some of these issues, such as ethical issues like algorithmic bias or the degradation of our spatial abilities when we rely too much on navigation guidance, arise when we implement design features that aim to reduce the cognitive load of map users, such as distributing some of the cognitive load of a map use situation to machines and the algorithms that run them. Others, such as changing behaviours and patterns of visual attention, are a result of social interactions being mediated through screens when we distribute cognitive load to other people.

5.1. Ethical issues of mobile map use

A major impact on users of mobile maps is the infringement of their privacy (see Huang et al. 2024). However, privacy is not the only ethical issue that surfaces from mobile map use. As increasing amounts of cognition get distributed to machines, questions arise about algorithmic bias, responsibility, and agency (Lally 2022). Mobile mapping applications reduce cognitive load by suggesting routes for getting from one location to another. For what qualities should the defaults controlling these routing algorithms be optimised (Fuest and Sester 2019)? The quickest route? The route that will generate the least pollution or traffic? An individually optimal route or a socially optimal route (Miller 2020)? Researchers are beginning to explore how the optimisation basis and/or the resulting routes should be transparently communicated to users (Fuest et al. 2021). At what point should users trust or rely entirely on automated tools, given that they can be influenced by commercial relationships between mapmakers and other businesses (e.g. Dalton and Thatcher 2019), or spoofed, as in the example of an artist who created a traffic jam that rerouted vehicles by dragging a waggon filled with smartphones through the streets of Berlin (Weckert and Ahlert 2020)? Or the example of autonomous vehicles, which use mobile maps to position and move the vehicle in space? In autonomous vehicles, navigation decision-making is distributed to the vehicle, though perhaps with some level of human oversight of the vehicle's operation. If an accident occurs, who is held responsible (Copp, Cabell, and Kemmelmeier 2021)? Hind (2019) argues that autonomous vehicles will in fact intensify the skill level needed by humans to supervise the car's navigation, with the implication that humans will retain some responsibility for the car's movements.

Opportunity 11: Outline the ethical implications for mobile map use of reducing cognitive load by distributing cognition to machines.

(11.1) What are the ethical implications (e.g. who is in control of an automated process) of distributing cognition between mobile map users and machines and of allowing decision-making by machines?

5.2. Short-term and long-term cognitive impacts of mobile map use

While there are manifold benefits of mobile technology, mobile maps, LBS, and navigation tools for modern societies, the use of mobile maps has also negative impacts on our behaviour and cognitive abilities. Two areas of potential concern are the abilities needed for spatial knowledge acquisition and changing behaviours related to life being increasingly mediated through screens.

There is now a good level of evidence that a high degree of reliance on navigation assistance has impacts on our brains. Based on empirical research, several researchers found evidence that automated positioning has negative impacts on the establishment of mental spatial representations and the acquisition of spatial knowledge (Brügger, Richter, and Fabrikant 2019; Burnett and Lee 2005; Münzer et al. 2006; Ruginski et al. 2019). Greater degrees of automation let the user pay less attention to the environment and there is less (immediate) need to form spatial knowledge. Ruginski et al. (2019) showed that long-term GPS use negatively impacts environmental learning through decreased spatial transformation abilities, in particular mental rotation abilities and perspective-taking. Most likely the reason for the decrease of mental transformation abilities is the reduced attention to or encoding of one's environment (Ruginski et al. 2019). However, Ishikawa's (2019) analysis did not show a direct link between the use of navigation systems and deterioration of spatial abilities measured by psychometric tests, though it did show a link to decreased navigation and wayfinding performance. Previous studies suggest higher engagement with the environment can help to mitigate some of these negative effects (Waters and Winter 2011), and several researchers suggest there is a need to find a balance between system automation and user engagement, i.e. to animate users to actively engage with their environment (Brügger, Richter, and Fabrikant 2018, 2019; Thrash et al. 2019). All these changes are important to understand because the neural mechanisms that underpin spatial navigation are also deployed in many other cognitive processes, so degradation of spatial navigation capabilities may have wide-ranging impacts on other aspects of our lives (Bellmund et al. 2018).

Research has also found that the use of mixed reality devices affects people's social behaviour in daily life (Göbel, Kwok, and Rudi 2019), by altering to what they are directing their attention. For example, immersion in a virtual world can decrease social engagement in the physical world; interacting with an 'intelligent' machine may damage our fundamental cognitive ability to distinguish between virtual and real objects (Çöltekin et al. 2020). Wearing mixed reality devices such as head-mounted-displays (HMDs) may also affect social interactions such as eye contact with other people. There is also a risk that we have difficulty building mutual trust if we rely so heavily on machines (Kobayashi et al. 2016).

Opportunity 12: Design mobile maps to minimise the potential for long-term negative individual and social cognitive consequences

(12.1) What mobile map designs support the development and maintenance of spatial abilities?

(12.1) Longitudinal studies of how mobile maps change our cognitive habits would clarify the long-term impacts of new mapping technologies.

6. Conclusion

In this article we have reviewed recent research that is relevant to understanding how cognitive processes shape the successful use of mobile maps. We have outlined the central importance of appropriate levels of cognitive load in supporting a positive user experience with mobile maps, and examined ways in which this load might be reduced for the map user.

We are left, however, with many questions that are unanswered and that deserve research attention. Of these, we would like to highlight two, along with the research opportunities we have identified as related to these questions:

(1) How can mobile maps be designed to reduce cognitive load by providing what is really needed by users to facilitate their cognitive processes? (Opportunities 1.1, 1.3)
   (a) What is the right amount of information that needs to be provided? (Opportunities 1.5, 5.1, 6.2)
   (b) What is the right level of assistance that is needed from other people or machines? (Opportunities 1.2, 1.3, 6.1, 11.1)
   (c) When should that assistance be provided? (Opportunity 7.2)
   (d) How much awareness of this assistance is needed by the user? (Opportunity 1.4)

(2) How can the intrinsic additional cognitive load created by the characteristics of mobile maps (e.g. small screen size, dynamic data and use contexts) be managed and minimised by supporting the distribution of the user's attention between the map and environment (Opportunities 2.1, 2.2, 4.2)?

Building the community's knowledge in these areas will help mobile map designers to create mobile maps that help people make spatial decisions and solve problems using the connected device they carry in their pockets.

Note

1. https://www.sae.org/news/2019/01/sae-updates-j3016-automated-driving-graphic.

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