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Neuro-adaptive LBS: Towards human- and context-adaptive mobile geographic information displays to support spatial learning for pedestrian navigation

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Summary: *Well-designed neuro-adaptive mobile geographic information displays (namGIDs) could improve the lives of millions who daily need to make time critical and societally relevant decisions on the go. However, what are the basic processes with which humans make movement decisions when guided by human- and context-adaptive namGIDs? We report on our ongoing empirical neuro-adaptive research program to answer this fundamental question, and present implemented methodological solutions of novel empirical evaluation methods, by critical examination of how perceptual, neuro-cognitive, psycho-physiological, and display design factors might influence decision making and spatial learning in pedestrian mobility across broad ranges of users and mobility contexts.*

Motivation

Every day, millions of mobile citizens of the evolving digital information society are making many spatio-temporal decisions indoors and outdoors, in familiar and unfamiliar environments, and especially while being on the move. Mobility decisions are often made in-situ, in context- and time-dependent situations, and influenced by smart mobile geographic information displays (mGIDs) (Ruginski et al. 2021, Bruegger et al. 2016, 2019). We define mGIDs here as any type of display that visualizes geographic information, including but not limited to paper maps, digital mobile map interfaces on navigation systems, extended mobile reality displays (AR/VR), etc. Increased reliance on assistive location-based mGIDs has already shown to influence our daily space-time behavior (Bruegger et al. 2016, 2019), and negatively impact our attentional and cognitive spatial abilities and resources (Sugimoto, et. al. 2021). Some even warn about technological infantilizing of society, as a result of over-dependence of personalized, user-assistive devices, including LBS, and respective mGIDs (Thrash et al. 2019). Even though extremely popular, and becoming ubiquitous, mGIDs can be still difficult to use successfully for people, and users of mobile maps may still have difficulties to understand the presented information (Ruginski et al. 2019). This is because current mGIDs are not adapted to human needs, do not yet automatically consider their individual variable prior knowledge, competences, skills, and training, and/or are not yet adapted to users available or changing perceptual, cognitive, and emotional resources and capacities for the mobility tasks at hand, and rapidly changing task and use contexts (Thrash et al. 2019). Human- and context-adaptive mobile map displays (Reichenbacher, 2001), should be cognitively supportive and perceptually salient (Brügger et al., 2019), to guide the mobile citizens safely to a desired destination; to support them in remembering the traversed environments should the device unexpectedly fail, and thus to generally improve mobile users' well-being and safety during use (Thrash et al, 2019, Bartling et al. 2021). This is important, because users of well-designed mGIDs will be more efficient in their decision making, as they need less time and fewer resources to solve the task at hand, and thus, they are then also more likely to be more effective (i.e., accurate) with made decisions and resulting mobility behavior (Thrash et al. 2019). In doing so, mobile citizens will feel confident, and in control with made decisions (Sugimoto et al. 2021).

Towards empirically validated, human- and context-adaptive mGIDs

Increasing empirical evidence suggests that any map display use performance can be predicted by varying individual differences in spatial abilities (Ruginski et al. 2019, Lanini-Maggi et al. 2021), emotional states of the map users (Frei et al. 2016, Credé et al. 2019a+b), and even by personality traits, such as anxiety (Çoltekin et al. 2017), for instance. Various researchers already provide empirical evidence that spatial knowledge and spatial learning deteriorates when people increasingly rely on non-user centered, chiefly technology-driven, location-based navigation assistance, because current LBS and mGIDs are not yet user-centered enough (Thrash et al. 2019, Bartling et al. 2021). It is still unclear whether this might occur as a result of split-attention and disengagement from the navigated environment, and/or from the wayfinding decision-making process, and/or what role the design of the mGID plays in this process (Ruginski et al. 2022). Technically driven LBS developments are still not informed enough by perceptual and cognitive theories, geographic information theory, and/or respective cartographic visualization principles, thus they are mostly not based on solid empirical evidence derived from user studies (Davies et al. 2015). Echoing Hegarty (2011) who suggests cognitive science as a translational perspective on visual display use, because it can bridge fundamental research in human/computer cognitive systems, and thus the design and evaluation of visual information displays, we argue for adaptive human-centered mGID research, to further inform the still mostly technology-driven LBS community, particularly when considering using mGIDs for navigation and wayfinding.

The goal of this contribution is thus two-fold: 1) to present a cutting-edge research program aimed at the design and development of *neuro-adaptive mGIDs (namGIDs),* specifically used for pedestrian navigation, which is based on sound theoretical foundations, and 2) outline novel methodological approaches for use-inspired, empirical research at the nexus of serving human- and context-adaptive geographic information for pedestrian mobility. Our framework is especially targeted for this LBS and GIScience community, because it emphasizes empirical studies with human- and context-adaptive namGIDs in-situ, where navigation happens, but is still rarely considered to date. In doing so, we aim those namGIDs of the future will not only guide navigators efficiently, effectively, and safely to their desired destinations, but more importantly, engage them with the traversed environment to support spatial learning in unfamiliar environments, and to strengthen spatial knowledge of familiar environments. This is important to avoid earlier mentioned technological infantilizing of society due over-reliance on LBS and assistive GeoIT (Thrash et al. 2019). Our empirical research program is driven thus by the following fundamental research question:

How do we need to design human- and context-adaptive namGID displays that guide visual attention, mitigate cognitive load, and support spatial learning when wayfinders navigate in familiar and unfamiliar environments?

Before one can answer this complex question, one first needs fundamental insights into human decision making and spatial behavior with mGIDs (Brügger et al. 2016, 2019, Credé et al. 2019a+b, Ruginski et al. 2022). We thus delineate a three-pronged empirical research path (Fig. 1) to answer this research question which seems squarely relevant to this LBS community. As seen in Fig. 1 below, our approach includes three intertwined research foci and factors that we have already begun to study, 1) namGID display design, 2) the namGID users, and 3) their task- and context-dependent namGID use.

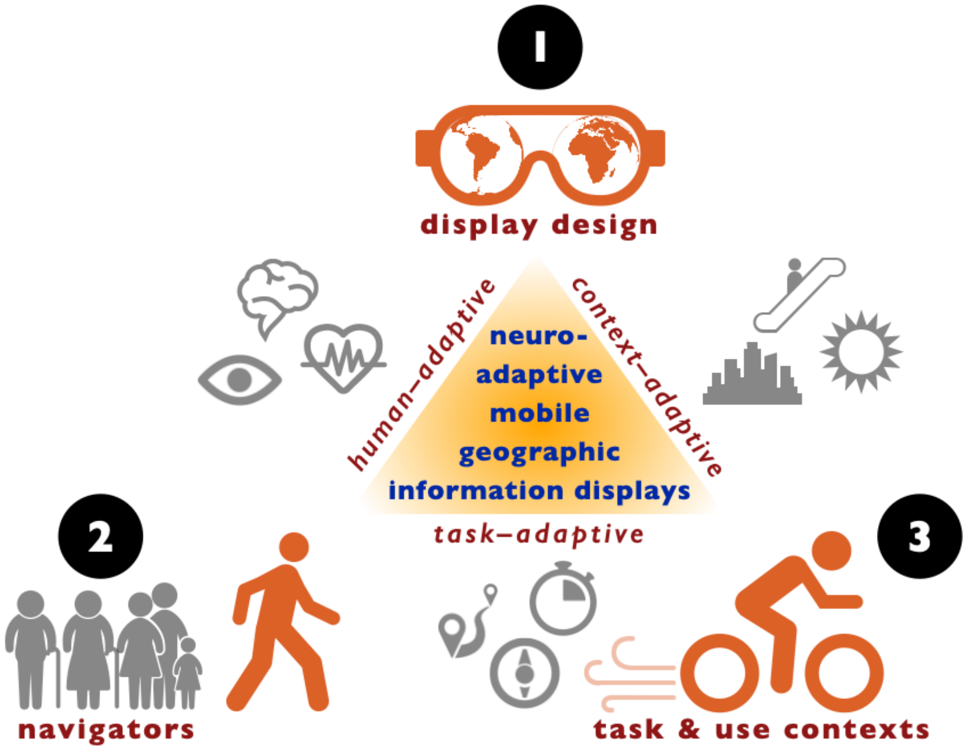

Fig. 1: Proposed three-pronged *neuro-adaptive mobile geographic information display (namGID)* research framework considering human-, task- and context-adaptive research dimensions.

Equipped with empirically studied vision principles and supported by cognitive science theories, borrowed from psychology and cognitive neuro-science (Davies et al. 2015, Thrash et al. 2019, Ruginski 2022), we draw upon novel data-analytics-driven and human sensing-based, ambulatory assessment techniques, tested by first empirical studies with users in the lab using virtual reality (VR, Fig. 2: Cheng, et al. 2020/21, 2021, 2022); in remote online settings (Fig. 4: Lanz 2021), and more importantly, in-situ in the messy real world outdoors (Fig. 5: Kapaj et al. 2020/21, 2021, 2022). For the purpose of gaining a deeper understanding of how humans make mobility decisions with smart assistive navigation devices, and how mGIDs affects individual and group mobility behavior and spatial learning, we have started to deploy a novel mGID evaluation approach based on real-time in-situ, ambulatory user neuro-cognitive sensing and assessment. This, with the aim to upscale from today's small-scale behavioral lab studies (i.e., in VR or indoors, etc.) with few participants (e.g., Credé et al. 2019a+b) to tomorrow's large in-situ, crowd sourced data analytics (Spiers et al. 2021, Coutrot et al. 2022) in the messy real world. This allows for empirically studying space-time decision-making, learning, and behavior with human- and context-adaptive mGIDs for broad ranges of indoor and outdoor uses and contexts. Given the recent global pandemic developments and respective difficulties to run studies with participants on-site in enclosed research laboratories, we have also started to apply remote, online user testing technologies including remote video-based emotion sensing methods (Fig. 4).

With this empirical and fundamental long-term research program on namGIDs, we aim to enrich ongoing LBS activities on the currently still weakly-defined linkages between the corners in Fig. 1, that is, ***human-adaptive*** (Fig. 1: Axis 1–2), ***task-adaptive*** (Fig. 1: Axis 2–3), and ***context-adaptive*** (Fig. 1: Axis 1–3) namGID design for space-time decision making and mobility behavior support. Next, we highlight ongoing methodological advancements, and briefly review first empirically supported insights related to human and context adaptive mGIDs, with the aim to design and implement *neuro-adaptive mGIDs (namGIDs)* of the future.

Deploying Ambulatory Human-Sensing and First Empirical Results

Previously employed empirical methods typically used in highly controlled research laboratories have either not at all, and/or are only slowly adapted to today's rapidly evolving geographic information technology (GIT), either increasingly used in movement, or with globally crowd-sourced paradigms (Coutrot et al. 2022). Empirical methods thus should increasingly support complex, real-time, and dynamic decision-making in the real world, in virtual worlds, and in digitally augmented reality. Next, we further detail our adopted empirical approach coupling controlled lab studies in VR, with remote online web-based studies, and those carried out in-situ in the real world (Fig. 1: Axis 1–3).

Lab-based navigation study set up: In-house built VR and remote online web-based human-sensing settings to study pedestrian navigation

To increase ecological validity of navigation studies, we have built a room-sized cave automatic virtual environment (CAVE[1]) equipped with in-situ human sensing technology to study human- and context-adaptive mGID use, as shown in Fig. 2 below.

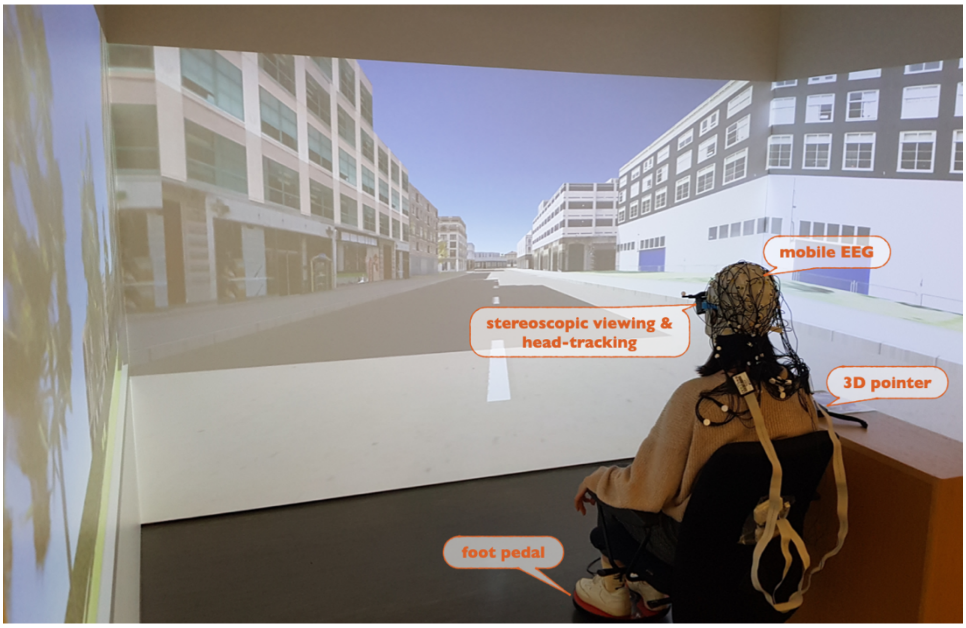

Fig. 2: The three-sided CAVE setup: A test participant is performing a navigation and wayfinding task in a virtual urban environment. Movement through the environment in VR is provided with a foot pedal, and other interaction is handled with a 3D pointing device. Cognitive load of a participant is measured in real-time with mEEG during the navigation experiment [image source: Alex Sofios].

We leverage neuro-physiological data collection methods, coupled with respective data-driven analysis approaches for controlled laboratory studies in VR (Figs. 2+3), remote online (Fig. 4), and in-situ outdoors (Fig. 5) to gain further insights along research axis 1–2 in Fig. 1. The collected human sensor data also comprises of psycho-physiological data streams

[1] On the Web at https://www.geo.uzh.ch/en/units/giva/services/cave-automatic-virtual-environment.html

including galvanic skin responses (GSR: Frei et al. 2016, Credé et al. 2019a+b, Lanini-Maggi, 2021, 2020/1), and online facial electromyography (EMG: Lanz 2021) to measure users' affect and emotion online (Fig. 4) and in-situ (Fig. 5). We also employ in-situ mobile eye tracking (Fig. 5) to study users' visual attention using mGIDs (Kapaj 2020/1, 2021, 2022). As a unique novel contribution to the geographic information science (GIScience) community, including cartography, LBS, and cognate fields, we present here for the first-time *mobile Electro Encephalography (mEEG)* to study navigators' spatial learning by means of cognitive load when using mGIDs in the lab (Cheng et al. 2020/1, 2021, 2022) and in-situ outdoors (Kapaj 2020/1, 2021, 2022). A closer description of our developed lab set up, deployed hardware, and software including respective technical information is available online[2].

In their VR-based user studies, Cheng and colleagues (2020/1, 2021, 2022) suggest that the number of landmarks shown on a mGID influences wayfinders' spatial learning, and the cognitive processing of shown information on the mGID has an impact on wayfinders' cognitive load during navigation measured by mEEG. We thus contend that namGIDs need not only be designed to assist navigators to reach a destination swiftly and safely, but they should also support wayfinders' spatial learning outcomes. This is particularly necessary should assistive navigation devices mal function, fail altogether, or if they would be unable to geolocate in real time during navigation. The ongoing user studies on how landmarks influence cognitive load during navigation directly informs the development of a future neuroadaptive navigation system that changes to individuals' cognitive load in real-time during navigation, and in doing so, also would support pedestrians' spatial learning of the traversed environment. Cheng and colleagues' goal is to develop a neuroadaptive navigation system where relevant environmental features—for example the number of 3D landmarks shown on 2D mGIDs—will be adapted to individuals' cognitive load in real-time, as they are measured by mEEG during navigation (see Fig. 2 above, and 3+5 below).

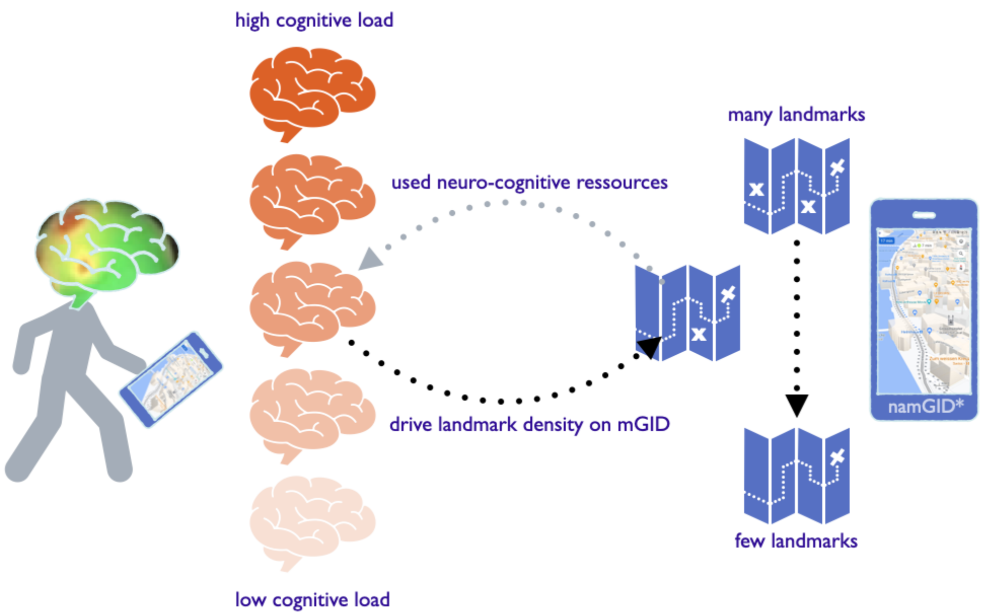

Fig. 3: Human- and context dependent neuroadaptation: The density of landmarks shown on a namGID is adapted to individuals' cognitive load during navigation to improve wayfinders' spatial learning (based on Cheng, 2019). [*map source: https://www.google.com/maps].

As shown in Fig. 3 above, once the cognitive load of an individual navigator has reached a given saturation point, the density of the landmarks on the display is reduced until more cognitive resources are available for a user to handle a greater number of landmarks shown

[2] On the web at: https://www.geo.uzh.ch/en/units/giva/services.html (accessed June 2022).

on the namGID. Which threshold to use, and how to adapt it to individuals is still an open empirical research question. The goal of a neuroadaptive navigation assistance is to optimally support navigators' spatial learning dependent on available cognitive and perceptual resources in real-time, and to orient navigators' attention back to the environment rather than rely solely on the assistive map display, as explained in the introduction. Next, we turn to how map users' affective states can influence the processing of geographic information, and thus how human- and context-adaptive mGIDs for pedestrian mobility need to consider wayfinders' emotion and affect during navigation.

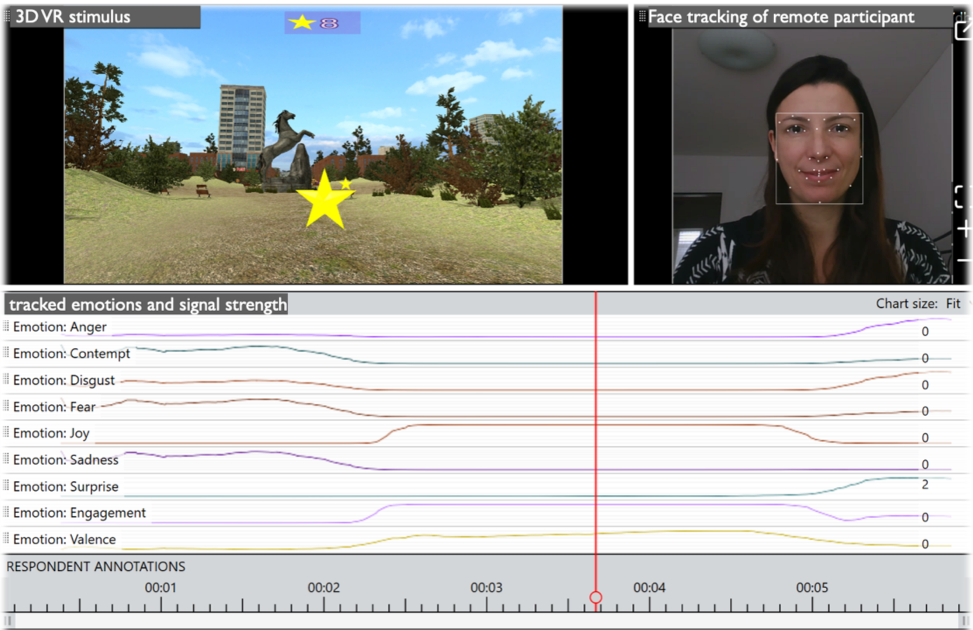

Fig. 4: Assessing a navigator's emotional states including their eye movements in a web-browser, in real-time, during a wayfinding task in a gamified VR setting deployed remotely online [image source: Sara Lanini Maggi].

Lanini-Maggi et al. (2021) coupled EEG, eye tracking in-situ and self-reports to assess decision-making performance in an emotionally laden moving object tracking task. By means of stationary gaze entropy these authors were able to predict decision accuracy and completion time across task and context-based expertise groups. They find that moving object tracking performance increases with superior spatial ability, and when users show positive affect (i.e., engagement), extracted both, from neural measurements, and self-reports. Task domain experts are less influenced by display design choices compared to task novices. In essence, authors suggest that neural and behavioral data can be beneficially complemented to interpret and understand collected eye tracking data. In a lab-based wayfinding study with pedestrian navigation experts to study how navigational instructions in the form of emotional storytelling affect spatial memory and map use Lanini-Maggi et al. 2020/1 indicate that showing the first person-view of a navigator while moving through an urban landscape is looked at significantly more often than the dynamically synchronized orthographic cartographic map, and this viewing behavior is even stronger when instructions are emotionally laden. While above studies were executed in a controlled lab environment, we now turn to outdoor navigation studies using human-sensing methodology in-situ.

In-situ-based human-sensing studies in the real world to study pedestrian navigation

With the empirical research methodology laid out above, we can now track users' cognitive load with mEEG also in the un-controlled outdoors (Kapaj and colleagues 2020/1, 2021, 2022) as shown in Fig. 5 below. This includes the real-time monitoring of navigators' display interactions using display touch analyses, coupled with mobile eye tracking (mET) to study navigators' viewing behaviors in-situ (Kapaj 2020/1, 2021, 2022). Of course, this methodology can also be deployed indoors, if so desired (e.g., see Fig. 2 above).

Fig. 5: Real-time ambulatory assessment of a navigator's visual attention (mET) and cognitive load (mEEG) in during a mGID assisted wayfinding task outdoors [image source: Armand Kapaj].

Similarly, one can assess navigators' emotion and affect together with their eye-movements indoors and outdoors with facial video recordings, either in-situ or remotely (Lanz, 2021). This is done using vision-based classification of affective states in participants' faces using online EMG (Fig. 4) or arousal measurement with GSR (Lanini-Maggi et al. 2021[3], Credé et al. 2019a+b), while users solve tasks in the lab and/or outdoors. Based on decision-making theories and design principles, areas of interests (AOIs) are placed at relevant locations on a mGIDs of the employed smart-assistive device. The AOIs could be thematically relevant (high/low uncertainty, emotional triggers, etc.) and/or perceptually salient (cartographically enhanced) areas (Kapaj et al. 2020/1, 2021, 2022), and users' eye movements and affective states are tracked with reference to these AOIs (Lanini-Maggi et al. 2021). We apply different design solutions based on empirically validated design theory (Kapaj et al. 2020/21, 2022), and compare these to users' task performance and affective states (Lanini-Maggi et al. 2020/1, 2021). Depending on the cognitive states (i.e., cognitive load recorded by mEEG) or affective states (i.e., using GSR or EMG) of the user, changes in the VR scene and/or namGID can be triggered for real-time audiovisual feedback during decision-making in mobile situations (Fig. 6). For example, Kapaj and colleagues (2020/1, 2021, 2022) are able to show that changing the display style of task-relevant landmarks from abstract 2D footprints to highly realistic 3D symbols on the location-based mGID does not affect expert navigators' cognitive load, but modifies their viewing behavior, in detrimental ways for spatial learning (Ruginski et al. 2022), that is, away from the traversed environment towards the assistive mGID. Affect and emotion also play a role in pedestrian navigation. For example, Lanz (2021) can demonstrate that people watching a 3D video online of a walk-through in a virtual urban park at night in first-person view, feel more relaxed after the walk when the park is lit with blue color highlights compared to the traditional white environmental lighting.

[3] See technology used on the web at: https://www.geo.uzh.ch/en/units/giva/services/mobile-EDA-facial-emotions.html (accessed June 2022)

Discussion

First encouraging empirical results collected in the lab and in the world suggest that human- and context-adaptive mGIDs, and especially, neuroadaptation for LBS, have an exciting future. One can imagine various display adaptations based on cognitive load assessed in real-time, for example, changes in: display immersion (monoscopic vs. stereoscopic views), map abstraction levels (2D vs. 3D landmarks), levels of system automation (GPS on vs. off) (Brügger, et al. 2019), adaptations to the neuro-adaptive mobile maps based on eye movements (Kapaj et al. 2020/1, 2021, 2022), or a user's state of affect and arousal (Credé et al. 2019a+b), etc. For example, based on decision makers' route choices and their measured affective state, the VR display can be made to blink to alert the user, or to make decision-irrelevant information visually less salient (Fabrikant et al. 2010). We have already built a first neuro-adaptive navigation game for head-mounted (HMD) VR and tested it at a science fair at the University of Zurich in 2021 with the general public (Fig. 6). In a Pokémon GO inspired urban navigation scenario, pedestrian navigators need to collect stars (Fig. 6.1) or other items including lost keys during a wayfinding task. Landmarks are visualized along the route (Fig. 6.5) and symbols not only represent feature locations in the world (Fig. 6.2) but also on the mGID of the navigation device (Fig. 6.3). Navigators see their cognitive load visualized in the scene while they are playing the game. This is achieved with a dynamically changing fill-level of an empty black brain outline symbol in the middle of their vision field (Fig. 6.4), dependent on their current cognitive load (i.e., magenta fill level of the brain symbol), and measured in real-time with mEEG. We have also developed a version of the game where a pumping heart symbol changes dynamically, based on navigators' arousal state, captured with a smart watch that records a navigator's GSR in real-time[4]. The purity of the recorded mEEG signal (i.e., cognitive load accuracy) is still influenced by interferences from the infra-red signal of the HMD head-tracking, and its controller to manipulate the movement and the map display (Fig. 6.3), which should be systematically studied before more empirical research can be carried out.

Fig. 6: *Neuro-adaptive mGID* in a gamified navigation setting: The world a test participant is experiencing wearing the HMD VR over an EEG cap is projected onto a large, screen-based CAVE VR system[5]. [image source: Bingjie Cheng]. There are still some cognitive resources left (4) for the player.

Conclusions and Outlook

In summary, our empirical agenda-setting research program on neuro-adaptive LBS, that is, human- and context-adaptive namGIDs for pedestrian navigation, is aimed at future location-based namGID developers to provide them with empirically validated design guidelines. This is to assure that their namGID designs work as intended, and if they do, we

[4] See technology used on the web at: https://www.geo.uzh.ch/en/units/giva/services/mobile-EDA-facial-emotions.html (accessed June 2022)
[5] See technology used on the web at: https://www.geo.uzh.ch/en/units/giva/services/virtual-reality-HMD.html (accessed June 2022)

know *why, how, when,* for *which* kinds of users, and in which *use contexts* (Griffin et al. 2012, Bartling et al. 2021). It is especially critical in an age of increasing personalization and customer-based segmentation to be able to model and predict success of namGID use at fine grained granularity of use and levels of detail of users. Navigators must be confident that their spatial learning and decision making is not impacted by uncontrolled properties of the namGID, or limited by their own background, training, competences, skills and abilities, which might even hinder to apprehend the desired information rapidly, and to make well-informed, accurate, and timely decisions in dynamically evolving contexts. Future research could be oriented to scale up proposed empirical methods initially developed under the controlled lab paradigm in behavioral science (e.g., using mET, mEEG, mEMG, mGSR, etc.) to a new mobile, crowd-sourced, human sensor science in the real world, capitalizing on own well-established geospatial visual analytics approaches, including emerging geospatial artificial intelligence experiences, coupled with GIS. For this, we have started to collect users' smartphone tapping behaviors coupled with GPS fixes, ambient light, and accelerometer data fully remotely and in the wild, without any contact with the tracked users, except for their initial agreement of informed consent (Reichenbacher et al., 2022). In doing so, it is especially critical to consider not only ethical research methods and careful human participants research reviews, but also privacy concerns of users, and their collected data, which has yet to be fully addressed by this research community.

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