In-Sights into Mobile Learning
An Exploration of Mobile Eye Tracking Methodology for Learning in Museums

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Overview
Mobile eye tracking provides insights into cognitive processing of visual information while a learner moves around. This chapter presents a case study in a small museum exhibition that was conducted to explore the suitability of mobile eye tracking for researching mobile learning. The study showed both potentials and limitations of mobile eye tracking methodology for research on mobile learning in general and in science exhibitions in particular: Mobile eye tracking provides rich, non-reactive data from the learner's perspective which can be further analysed qualitatively and quantitatively. Concerns were raised with respect to interrelations of object fixations and underlying cognitive processes. Limitations also include obtrusiveness, accuracy, selective sampling, ethical concerns, financial effort, and effort of data analysis. These limitations suggest that, to increase validity, eye tracking is best used in combination with other methods. Nonetheless, mobile eye tracking can be a powerful data collection method in research on mobile learning.

1. Mobile eye tracking

Why are eye movements interesting for mobile learning? Our eyesight is our most important sense: most daily tasks involve visual input, and people need to look at objects to acquire information about them. Eye movements are not only important for research on natural human behaviour but especially on mobile learning. We define *mobile learning* in the context of this chapter as learning by integrating information that is spatially distributed in natural environments and, therefore, requires movement of the learner. This book chapter deals with a special case of mobile learning, namely informal learning in science museums (see also Lelliott and Sharples in this book). Most information in exhibitions is represented visually as exhibits with corresponding text labels. The spatial distribution of exhibits requires that learners move around. We argue that methods to examine learning in these visually dominated and spatial environments should be chosen carefully in order to address the specifics of the setting, especially the high mobility of the learner. This paper discusses the suitability of tracking visitors' eye movements as a method to explore mobile learning in museums.

1.1 A short history of eye tracking

Research on eye movements dates back to the early 20th century. Historically, it focused on scene perception (see Henderson, 2007) and reading (see Rayner, 1998). Stationary eye trackers were used for the limited purpose of laboratory studies employing rather simple tasks requiring information processing. Only in recent years has the development of light-weight, mobile eye tracking technologies (Pelz et al., 2000) allowed the assessment of daily activities in a natural environment (e.g., Land & Hayhoe, 2001). This research has still, however, been limited to rather simple tasks.

1.2 How does mobile eye tracking work?

There are different designs of eye trackers and methods of analysis to determine the location of fixations. However, most mobile eye trackers use two cameras. One camera records one eye of the participant, on which three invisible (infrared) dots are projected, while the other camera records the scene from the subject's perspective. These two cameras must be calibrated to give accurate data about eye movements and fixations of each individual. Both images are saved as alternate frames using a video recorder. The most useful output format of mobile eye tracking data is a video that combines the scene view and the position of the fixation indicated with a marker (e.g., small red cross). It provides insight into the perspective of the participant and the point where his or her tracked eye is fixated at a certain moment. This video can be analyzed via conventional video-analysis software.
Fixations and saccades are the basic objects of the analysis of eye tracking data (Rayner, 1998). During fixations, eyes are focused on one location and visual information is obtained. Saccades are rapid eye movements between fixations when visual input is reduced or even totally suppressed.

2. Re-viewing the museum visitor's view - an explorative study

The aim of this study was mainly an exploratory one: We wanted to examine the potentials and limitations of mobile eye tracking for research on informal learning in museums. Mobile eye tracking allowed us to 're-view' the visitors' view – beyond observational or questionnaire methods. In this way, we hoped to literally 'see' what eye movements can tell us about exploration behaviour in exhibitions and information processing of exhibition content. To supplement our observations, we performed a literature review on mobile eye tracking. However, in the literature we only found mobile eye tracking studies which examine well-structured, temporally restricted tasks like making a sandwich, finding a specific door, or washing one's hands (e.g., Hayhoe & Ballard, 2005; Land & Hayhoe, 2001; Pelz et al., 2000; Turano, Geruschat, & Baker, 2003). Our study, in contrast, took place in a complex setting with a more open-ended task: the exploration of a science exhibition. This is an example of a setting in which informal learning is likely to take place. As the exhibition was designed to communicate the basic facts and figures, chances and risks, and areas and concrete applications of nanotechnology, we consider the exploration of the exhibition a learning task. However, as with many informal settings, the subjects had not been instructed 'to learn', nor were they provided with other concrete instructions concerning the exploration of the exhibition (like learning goals, time restrictions, predefined learning activities; see for example the chapter by Sharples in this book). Corresponding to the 'open' nature of this task, a broad range of visiting behaviour was found: for example, the duration of the visits ranged from 17 to 57 minutes.

2.1 Method

Setting. We had the opportunity to present a small exhibition about nanotechnology at our research institute. In this way, we ensured a fair amount of external and internal validity: The research setting was designed to be as close as possible to a 'normal' visit for participants and at the same time as controlled as possible to reduce the impact of interfering variables.

Technical equipment. For this study we used an ASL MobileEye eye tracker (see Figure 1).

[Insert figure 1 approximately here]

Sample. Two male adults and one female adult with normal vision were asked to explore the exhibition with an eye tracker.

Procedure. First, the purpose of the study and the function of the eye tracker were explained to the subjects. Then, the eye tracker was calibrated to a distance that visitors would normally keep while looking at exhibits (which varied interindividually and ranged between 30 and 60 cm). The study participants were instructed to explore the exhibition as they would normally do in a science museum. After exploration of the exhibition, a structured interview provided insight into visitors' subjective experiences and introspective thoughts on reasons for exploration behaviour and on cognitive processes. For example, the participants were encouraged to report on criteria and reasons for information selection (e.g., "Which exhibits were particularly interesting for you and why?") and their spatial orientation and sequence of exhibit exploration ("Did you explore the exhibits in a certain order or randomly?").

Analysis. Eye movement recordings were transformed to .avi-files and analyzed with the video analysis software Videograph©. Similarly to Turano et al. (2003), we did not analyze eye movements based on xy-coordinates (examining which points on a wall are fixated independent of their denotation), but based on elements and categories (examining which exhibits on a wall are fixated). For our purposes, fixations of similar elements or within the same object category were of higher interest than proximity of fixations. Also, elements and categories are more easily adjusted to background changes than xy-coordinates would be. This makes them better suited to analyze complex mobile eye movement recordings. The categories were developed according to information elements of the exhibition (see Figure 2). Each exhibit or text unit was an element. Elements were grouped in larger categories like "exhibits with corresponding labels" or "exhibits on the same concept."

[Insert figure 2 approximately here]

2.2 Exemplary results of the study

This exploratory study on mobile eye tracking provided information both about the way a visitor explores the exhibition and about the usefulness of this method for gaining insight into mobile, informal learning. The following exemplary results may illustrate the kind and quality of information that is obtained by means of mobile eye tracking.

Intra-individual analysis of each visitor's eye tracking recording revealed that exhibits belonging together conceptually are more likely to be fixated successively and also several times alternately (see Figure 2 for an example) than adjacent but unrelated exhibits. This may indicate that people integrate multiple information units into an underlying concept (Rayner, Rotello, Stewart, Keir, & Duffy, 2001) or at least that they do not process these information units independently from one another (Schwonke, Berthold, & Renkl, 2007). However, in one case, our post-visit interview revealed a different explanation for alternate fixation of objects: One participant stated that he was not comparing the content but the design of the exhibition elements. Both explanations of the participant's eye movements indicate that conceptually intertwined exhibits were processed together. However, eye movement recordings alone cannot reveal which information is being processed (in our case: semantic information or information about design) or what cognitive processes exactly are going on.

Analysis across all three participants showed that, overall, some exhibits were less likely to be explored than others. This might be due to limitations in exhibition design: research has shown that the probability of visual exploration depends on the visual salience of objects (e.g., Holsanova, Rahm, & Holmqvist, 2006). An alternative explanation is that these parts of the exhibition were attended to without direct fixations (Treisman, 2006).

All participants first scanned each exhibition wall as a whole (the exhibition consisted of four exhibition walls arranged as a circle). They then began to explore single exhibits in their vicinity. Research suggests that the first process serves as initial selection of information and visual search – and is rather automated (Holmberg, 2004). During early processing stages, pictorial information or text is quickly skimmed and scanned, so that a viewer gets the gist of a scene very quickly (see for example Rayner, 1998, p. 398f.).

In a second step, late processing like reading text or exploring details of objects occurs. However, there are multiple exploration patterns for the same scene: in his review on eye tracking, Rayner (1998) states that exploration patterns are especially heterogeneous in scene perception. This is even more likely in our natural setting, as the circular arrangement of the exhibition elements did not trigger a certain exploration path but provided multiple entry points and exploration directions. An exhibition also easily allows for multiple changes between the exhibition elements.

2.3 Discussion of the study

Our results from three visitors' eye tracking data are difficult to generalize for three reasons. First, the sample size is small; further subjects are needed to allow generalization of our results. Second, the ill-structured task of visiting an exhibition resulted in highly diverse inter-individual behaviour, which is difficult to compare across subjects. To identify common patterns across subjects, more clearly defined tasks or at least reduction of the amount of data per visitor would be necessary. Third, data analysis was not based on a-priori hypotheses; we tried to find explanations for patterns a-posteriori. To validate the presented results from this study, further research has to be conducted with larger samples and pre-defined tasks.

Still, the results of this study provide a first insight into informal mobile learning in museums: We were able to identify common eye movement patterns, which allowed us to generate hypotheses about information processing in an exhibition (conceptually heterogeneous exhibits are fixated successively; an exhibition wall is first skimmed then explored in detail). These hypotheses can be tested in further studies. We also identified elements in the exhibition that are less likely to be explored. This result could be used to improve the design of exhibitions by changing salience, position, and information density of less popular exhibition elements.

3. Potentials and limitations of mobile eye tracking

Based on mobile eye tracking literature and our own exploratory study, we identified several potentials of mobile eye tracking for research on mobile, informal learning. Though the advantages of mobile eye tracking for examining mobile learning are more apparent and also very appealing, we would also like to allude to some limitations which might be easily overlooked or underestimated.

3.1 Potentials of mobile eye tracking

Data richness. Eye tracking provides rich, continuous data of natural viewing behaviour and – in the case of mobile eye tracking – also the context of this behaviour. In contrast to other tracking methods (e.g., logfile analyses, see for example Trinder, Roy, & Magill and Wali, Oliver, & Winters in this book), eye tracking can additionally provide insight into planning behaviour that requires visual input but does not result in easily observable action. For example, a visitor visually explores two different walls from a distance and then moves to one of them to explore it in detail. External observation (e.g., by video surveillance) can only show the visitor's actual movements towards one of the walls but not his or her prior visual exploration of *both* walls.

Data validity. Since the actual fixations are recorded objectively by means of a camera, the validity of mobile eye tracking is higher than the validity of external observation: External observation can only determine the direction in which a person turns his or her head and moves but not the point on which his or her eyes are fixated. Since eye tracking data is obtained from the acting subject's perspective, it reduces perspective errors as well.

In contrast to retrospective questionnaires/interviews, eye tracking gathers data *online*, that is, during actual behaviour. If one considers the amount, the immediacy, and the objectiveness of measurement – no error-prone memory or verbalization is needed (e.g., Nisbett & Wilson, 1977) – it becomes apparent that eye tracking can provide insights into unconscious information processing that lies beyond introspectively accessible processing (Pelz et al., 2000).

Mobile eye tracking by means of light-weight head-mounted cameras brings eye tracking out of the laboratory into the natural environment. Behaviour can be measured where it naturally occurs, providing data with high external validity.

Non-reactive measurement. Data-collecting methods like questionnaires and interviews are considered to be highly reactive (Fritsche & Linneweber, 2006). In contrast, eye movements are natural behaviour that can hardly be manipulated by the tracked subject, especially not over longer periods of continuous measurement. While participants might report in an interview that they *did not* see a particular piece of information, mobile eye tracking can reveal that they *did at least look at it* – even if they say otherwise for any reason or simply do not remember it.

Statistical analysis. Similar to other tracking methods, data from eye tracking is highly structured and allows for further statistical analysis. Relevant data that can be extracted from the raw data are, for example, fixation durations, saccade length and degree, occurrences of specific events, holding power of exhibits or navigation sequences (to determine scan patterns, see for example Henderson, 2003). Eye tracking can also reveal interesting details about information processing: for example, which information has been missed, which information is fixated longer than other information, what gaze patterns occurred overall, or what differences in gaze patterns across participants and/or experimental groups exist.

3.2 Limitations of mobile eye tracking

Covert attention and mental spotlight. The first and most important limitation is the limited interpretation of a location of a fixation with respect to attention processes. Treisman (2006, p. 4) stated that “the window of attention set by the parietal scan can take on different apertures, to encompass anything from a finely localized object to a global view of the surrounding scene”. Therefore, eye tracking in fact delivers accurate data about eye fixations, but this data does not always lead to correct conclusions regarding the focus of attention. For informal learning in museums, this means while a participant’s eye is fixating a specific exhibit, he may actually be attending to the whole exhibition wall without devoting attention to the fixated exhibit itself, or he may be thinking about something completely different while his gaze still lingers on that specific exhibit.

Limited conclusions about cognitive processing. A related problem is the limited validity of the interpretation of eye movements. “Whereas a given cognitive event might reliably lead to a particular fixation, the fixation itself does not uniquely specify the cognitive event” (Hayhoe & Ballard, 2005, p. 190). Interpretations of eye tracking data are often based on assumptions and heuristics about underlying cognitive processes. We may have an objective recording of a person’s eye movements, but the cognitive processes that take place in the meanwhile are subject to interpretation.

One problem here is that eye movements are determined by two processes, namely bottom-up, stimulus-led processes triggered by salience of stimuli and top-down, cognitively-led processes based on prior knowledge and goals of the subject (Henderson, 2003). Whereas the influence of bottom-up processes can be modelled (Turano et al., 2003), data on a person’s reasons for specific behaviour cannot be obtained by eye tracking. Cognitive processes cannot be observed directly through eye movements. Such top-down processes might be modelled more easily for clearly defined tasks, but only with great difficulty for open tasks like those involved in mobile, informal learning.

The example from our explorative study – when our interpretation of a participant’s eye movement was proven to be incorrect by the interview – illustrates the limited validity of conclusions from eye tracking data on underlying cognitive processes.

Obtrusiveness of measurement. In contrast to static eye tracking embedded into computer monitors, a mobile eye tracker is obtrusive for both the subject wearing the camera(s) and his or her environment: Participants wearing goggles know that their gazes are tracked, and the unfamiliar feeling may bother them. Other people can clearly see the eye tracker and, thus, they might interact differently with the person wearing it. This holds especially for informal settings like museums, which are highly social settings (Gammon, 2004). While this was not relevant for our study, since we allowed only one visitor in the exhibition at each time, this might be a major problem in more natural settings.

Selective sampling. Mobile eye tracking devices are difficult to calibrate for persons with glasses or corneal irregularity. Therefore, usually only people with normal vision are invited to participate in eye tracking studies. This might impair the generalization of results from eye tracking: If visual impairment is correlated with other relevant variables, this restriction leads to a biased sample.

Limited temporal and spatial accuracy. The temporal resolution depends on the recording of eye tracking images. A 50 Hz PAL DVCR tape in a mobile recorder saves two camera images by alternating frames. This results in a resolution of 25 Hz. Given that short fixations of about 33 ms were observed (Pelz et al., 2000), this means that some fixations can easily be missed.

Eye tracking works best if the system is calibrated to a specific fixation distance. Yet fixation distance is not constant in mobile settings but rather changing constantly. As a consequence, spatial accuracy of mobile eye tracking systems is worse than that of stationary systems. We tried to reduce this problem by calibrating the device at a distance the participants would typically keep to an exhibit wall. However, in other settings with an even wider range of fixation distances (e.g., a museum with large rooms and exhibits with a broad range of sizes) this limitation becomes a problem for mobile eye tracking.

Laborious data analysis. With a stationary eye tracker and a given background (e.g., a website), software for automatic data analysis is available. However, in mobile eye tracking, automatic analysis is limited: the background changes constantly and the participants' behaviour and eye movements are very inter-individually variable. Therefore, each eye tracking recording has to be analyzed manually. To automate the process, software would be necessary that can recognize the elements on the video frame and combine this information with eye tracking data. As far as we know, there is currently no software capable of doing so. Thus, many studies use only short tasks where inter-individual similar eye movements can be expected (e.g., Land & Hayhoe, 2001), which unfortunately limits the generalization of eye tracking data to more complex (learning) tasks.

Price. Mobile eye trackers are expensive; for example, the version used in our study costs about 24000 € . The price of the equipment limits the number of simultaneous measurements within dyads or groups that could be useful in order to explore collaborative learning and social engagement. However, instructions on how to build mobile eye trackers using off-the-shelf components at a cost of about 350 USD have been presented recently (see for example Li & Parkhurst, 2006).

Ethical concerns. As eye tracking also gathers data about unconscious or uncontrolled eye movements, participants have no control about the information they reveal during eye tracking. Even if they have previously agreed to the study, participants might be embarrassed by a confrontation with their eye tracking videos. The videos might reveal information they would rather have kept private.

We propose the following procedure to meet these ethical concerns: Study participants should be briefed which data will be gathered and how it will be analyzed, and be informed about the general purpose of the eye tracking study prior to data collection (e.g., via a sample video). When participants are confronted with their video feed during data analysis, only the interviewing researcher should be with them. Before publication of image or video files for any audience, participants must be asked for permission. Regarding the privacy of the people who are recorded on the eye tracking video, the same conditions as in photography should be applied.

4. Conclusions

Given the described limitations, eye tracking should be combined with other methods to increase the validity of interpretations. Such triangulation is recommended for other data gathering methods – see for example the chapters by Lelliott; Sharples; and Wali et al. in this book. Conclusions from eye movements about underlying cognitive processes are error-prone (Hayhoe & Ballard, 2005). To reduce interpretation bias, clear a-priori hypotheses about cognitive processes and their influence on eye movements are indispensable. Interview and questionnaire data about a person's interests and prior knowledge can be used to examine hypotheses with the data at hand, like in the exploratory study presented. A combination of eye tracking with Personal Meaning Mapping (see Lelliott in this book) could be interesting for the purpose of explaining changes between PM-maps before and after a museum visit. An alternative is to confront visitors with their own eye movement record after the visit and ask them to think aloud.

An important question is whether data should be analyzed intra- or inter-individually. As eye tracking data are very rich, large samples are rarely used (for an exception, see Wooding, 2002), while the degree to which results from small samples can be generalized is limited. Especially in the context of complex, ill-defined problems (like visiting an exhibition), comparisons across subjects are restricted because of highly inter-individually variable behaviour. To be able to generalize results, pre-defined tasks should be used. Still, exploratory case studies – like the one presented here – can provide important insights into how information is processed and how informal learning happens on the move.

Further technical development of mobile eye tracking devices will probably eliminate some of the technical and pragmatic constraints of mobile eye tracking (e.g., fixation distance, costs, temporal and spatial accuracy). Development of software that supports automated analysis of real-world-videos with changing angles, views, distances, and objects is needed to reduce the complexity of the analysis of eye tracking data.

Despite some limitations, mobile eye tracking is a powerful data collection method in mobile learning research. Previous research has used mobile eye tracking to study behavioural planning, coordination of vision and action, and visual search (Hayhoe & Ballard, 2005; Land & Hayhoe, 2001; Pelz et al., 2000; Turano et al., 2003). The study presented here is the first to address information processing within the context of mobile learning by means of mobile eye tracking. In our exploratory study, we gained valuable in-sights into the information processing performed by museum visitors. Although the presented interpretations of our results need further validation, we would have hardly gained these findings otherwise. For this reason, we would like to encourage further research on mobile learning using mobile eye tracking.

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