Potentials of Eye-Movement Tracking in Adaptive Systems

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Abstract. Eye-movement tracking proved its potentials in many areas of human-computer interaction. Resting on a hypothesis that eye-direction and mind are linked, some of the HCI researchers have employed eye-movement trackers to investigate the visual attention focus of the participants completing their tasks. Others have used the eye-movement tracking in real-time applications, either as a direct interaction device or as an input to gaze-aware interfaces. Inspired by the previous HCI applications, we propose to utilize eye-movement trackers in adaptive systems research and development in two ways. First, the evaluations of adaptive systems could get an access to the information otherwise unavailable, as for instance to how the visual attention and cognitive processing are influenced by an adaptivity implemented into the evaluated system. Second, we propose to employ the eye-movement tracking technologies for a real-time registration of users' loci of visual attention, therefore increasing the awareness of the adaptive systems about their current users. We discuss possible potentials, difficulties and pitfalls of eye-movement tracking when applied to adaptive systems. We argue that a methodological framework of applying eye-tracking into adaptive systems shall be developed.

1 Introduction

In various areas, eye-movement tracking systems have provided researchers an access to underlying cognitive processing of users completing their tasks. Typical areas where eye-trackers have been successfully employed are studies of reading [13], scene perception, visual search, and eye-based interaction as for instance eye-typing [11]. Others have used eye-tracking in usability evaluations of computer interfaces [5]. For a recent survey of applications of eye-movement tracking, see [4].

Surprisingly little is known about how eye-movement patterns, and therefore also cognitive processes, are influenced when the environments exhibit some kind of adaptive behavior. Although eye-tracking technology has achieved a certain degree of maturity, its applications to the adaptivity research were rare. Evaluations of adaptive systems which would employ eye-movement tracking are indeed hard to find. Moreover, even though the gaze location recorded by eye-trackers has been used in real-time application, the aims were either to save the bandwidth of a channel through which a graphics is transferred or to enhance the interaction by direct manipulation of cursor through new gaze-modality. In the present paper, we propose to fill the gap of knowledge about the eye-movement patterns in adaptive systems by suggesting two possible directions for future research into 1) evaluation of adaptive systems with a help of eye-movement tracking and 2) using the gaze as a new adaptation source. However, we believe that neither of the proposed directions can be taken immediately, without developing a methodological framework sensitive to the specific area of adaptive systems.

In the rest of this section we briefly introduce eye-movement tracking as a powerful tool for investigating visual attention. In section 2 we propose how eye-tracking could be integrated into evaluation of adaptive systems. The possibilities of using real-time gaze direction as a new adaptation source are outlined in section 3. In section 4 we discuss some of the problems and pitfalls of the proposed approach, and we present our conclusions in section 5.

1.1 Eye-movement tracking

Eye-tracker is a device that registers the movements of eyes via processing of reflections from infrared light shone to eyes. Two types of eye-trackers exist, (1) a remote, table mounted version, making no contact with users, or (2) a head-mounted version with a see-through mirror. In addition to the measurements of the movements of the eyes, most of the current eye-trackers can also provide an estimate of pupil size, users' distance from the eye-camera, and validity codes indicating the presence of the eyes within the field of view. Current eye-trackers are relatively cheap and can deliver the gaze location precisely; the data are usually sampled at rates between 50-250Hz.

Eyes are never perfectly still. In general, two types of eye movements, saccades and fixations, are identified from the protocol recorded by the eye-tracker [14]. *Saccade* is rapid and ballistic eye-movement that serves for repositioning the eyes onto a new location. Human visual system does not extract any information during a saccade; a phenomenon known as saccadic suppression. Information from a stimulus is extracted only during fixation, when the image of the investigated object falls onto the fovea. *Fixation* is a relatively stable position of eye, lasting about 300ms. During fixation the information is extracted from the observed object. Because the retina needs to be continuously refreshed, even during a fixation eyes perform microscopic movements. Other types of eye movements exist, for instance microsaccades or pursuits; for the description of these, see [8].

Another division of eye-movements can be done in terms of how they are initiated and controlled. We recognize either voluntary eye-movements, as for instance when one wants to keep a certain object on the retina, or involuntary, reflexive eye-movements, such as changes in the pupil size or the microscopic movements serving to refresh the image on the retina.

Studies investigating the allocation of visual attention of users completing experimental tasks have confirmed a strong relation between the direction of gaze and focus of visual attention. Particularly, the link between eye fixations and cognitive processes has been investigated [10], [13]. From these and other studies a general assumption has been derived that eye and visual attention are tightly linked. It is believed that attention precedes the eyes so that after the information is extracted and current feature is processed, the attention is shifted to a new location and a saccade to the location is programmed and executed. Duration of a fixation has been shown to correlate with participants' difficultness to process the fixated object [5], indicating therefore the depth of the processing required to encode the information or the experience level [1]. Number of fixations, on the other hand, has been shown to reflect the importance of the interface object to the participants. Finally, the patterns of eye-movements, in terms of sequence of fixations and saccades to different object of a scene viewed, differ for the same scene when the task given to participants changes [15].

2 Eye-movement tracking and evaluation of adaptive systems

Eye-movement based evaluation of interaction is often conducted either in a retrospective way or it is based on some underlying cognitive model and hypothesis. A typical scenario includes experimental participants conducting their tasks while their eye-movements are measured. Experimenters manipulate with the features of the investigated task and then examine the eye-movements for significant patterns related to the manipulation.

Apart the domain of studies using eye-movement patterns, it is often the case that an evaluation of benefits of new techniques concentrates on measures of performance, completion time, frequency of errors, or preference. However, as the adaptive technologies aim to support users in carrying on their tasks, for instance during learning, we shall pay attention to how the underlying cognitive processing is influenced by the adaptivity.

It has been previously suggested that an evaluation of adaptivity shall be conducted at two distinct phases, recognized as interaction assessment and adaptation decision making [3]. Considering the former, eye-movement tracking itself is the source of rich interaction information and provides data with a high level of detail. In the latter phase, eye-trackers could be used to quantify whether the decision of the adaptive system were visually attended by the users.

In the following, we illustrate how the evaluation of adaptive systems could benefit from employing the eye-movement tracking. Two main approaches to adaptation, namely the adaptive navigation support and the adaptive presentation technologies, can be identified in current adaptive systems [2]. By involving the adaptive navigation support, the directions a user can take during learning are limited and proposed, or guidance is given to better support the learning process. In adaptive presentation of content, the materials shown to the user are modified to better suit the user according to the user model built. In any case, the user model is built and updated, as accurately as possible, so the adaptive engine can act upon it and provide the users the most relevant information to support achieving their goals.

2.1 Evaluating adaptive presentation of content

Some adaptive systems make the decision of what content shall be displayed to users, based on knowledge the user acquired during a previous interaction with the tool. For instance, the adaptation mechanism of a tool aiding the understanding of mathematical expression evaluation decides whether certain parts of an expression are understood well enough, so some other parts can be displayed with a focus. We propose that eye-movement tracking could help to estimate automatically the focus of attention on certain elements of such an expression. That means a study would compare the patterns of eye-movements on the elements or operations that are recognized by the adaptive engine to be already comprehended to those fixations falling on the elements that are thought to be not yet fully understood. The difference in the eye-movement patterns shall then indicate whether the decisions of adaptive algorithm indeed correlate with interests of users, and with problematic and less familiar parts the users were attending.

2.2 Evaluating adaptive navigation support

The decision made by the adaptive navigation support can be investigated using eye-movement tracking. Typically, some links are hidden when the adaptive system comes to a decision that the user is not ready to follow the links. On the other hand, some links are generated and/or annotated dynamically when the adaptive component decides that the user might benefit from the information behind the links. Two systems could be compared (with and without adaptive component), in terms of whether the annotation is attended by the users, or whether the presence of additional links creates a confusion or disturbance to otherwise unaltered cognitive processing. Clearly, eye-movement tracking can be employed in such studies; comparison of two or more adaptive systems or adaptive vs. non-adaptive system comparison with respect to the eye-movement data can be conducted. For example, eye-movement trackers allow for a measurement of cognitive workload, through the dilatations of the pupil [12]. These dilatations happen involuntary, and therefore provide an objective measure of users' cognitive processing and changes in the mental workload during competition of a task [6].

Previous eye-tracking research established and applied numerous eye-movement metrics (for an overview see [4]); however, not all of them may directly apply to adaptive system evaluation. Therefore, studies of interaction with adaptive systems and comparative studies with/without adaptive features have to be conducted in order to establish a body of knowledge about typical eye-movement patterns produced during the interaction and during the adaptation decision making. With conjunction with other data collected during the interaction, eye-movement tracking can then deliver a powerful tool for evaluators of adaptive systems.

3 Real-time gaze registration and adaptive systems

Knowledge level, learning style, preferences, goals, user and usage (interaction) data, are all typical sources of adaptation [2]. We believe, however, that the collection of users' actions cannot be complete without the awareness of what features of the interface were visually attended, what strategies the users exhibited, and what cognitive efforts they had to exert while completing their tasks. Considering the eye-movement tracking as a source of adaptation, the tool provides instant information about the location of user's visual attention. Presumably, the object under one's visual investigation is most of the time also located on the top of his/her cognitive processing stack. Therefore, knowledge about the location of the gaze in time and space helps us in understanding what features of the interface were of interest to the user, in what order, when, and how long the user needed to attend each of the objects.

Considering again the example of an adaptive tool for expression evaluation learning, the user modeling mechanisms of the tool could be enriched by knowing what parts of an actual expression caused users the greatest problems, measured, for instance, as the number of fixations paid to a certain element of the expression. Further, if some component of a complex expression was not attended at all during the learning process and the knowledge level related to the component indicates it shall be still processed before continuing, the tool can immediately act upon this information and ask the user whether he/she wishes to overcome the problem.

We see a great potential of using eye-movement tracking as a real-time adaptation source. However, similarly as in the previous section concerning the evaluation of adaptation systems, we believe that a thorough investigation of what type and patterns of eye-movements could be used and how they can be used has to be carried out first. We suggest that the eye-trackers shall be used first for evaluating the outcomes of adaptivity to create a set of measures appropriate for a specific application domain. Once the metrics are developed, it shall be possible to employ the real-time gaze collection and use the gaze data and inferred cognitive processing as a new source of adaptation.

4 Difficulties and pitfalls of eye-movement tracking

Although eye-movement tracking provides information which is inaccessible via other measurements, its application also involves certain difficulties that have to be taken into consideration prior the technique is applied. Although a number of issues exist, we briefly introduce here the most significant problems that hinder the widespread of eye-trackers.

4.1 Methodological issues

First and foremost, the methodological issues of proper analysis and interpretation of eye-movement data seriously influence the outcome. Given the typical sampling rate of 50Hz, a 10 minutes recording generates as much as 1.5 Mbytes of eye-movement data to be analyzed. Although the methods for an automatic eye-movement data extraction (in terms of fixations and saccades identification) have been developed [e.g. 14], there is no standard way of interpreting the protocols and establishing their relation to the investigated task.

Eye movements are both voluntary and unconscious, although we usually execute them automatically. When fixations are used as means for selecting/controlling objects in an interface and for information acquisition, another methodological consideration arises, known as Midas touch [7]: the interface cannot certainly determine whether a fixation at an interaction widget is meant to issue a command or to purely extract information. Avoiding the Midas touch remains one of the greatest challenges in the eye tracking research.

4.2 Technological issues

The eye-movement data often contain a great deal of noise. The noise can be attributed to participants moving excessively their heads, wearing glasses, blinking, or to other factors, such as drift and inaccurate calibration. These all cause the eye-trackers to fail to obtain a video-image of the eye(s) and as a result not to report any eye-movement data for some time.

Another problem can be seen in the accuracy of the present eye-tracking systems. Most of the technologies can achieve the accuracy between 1 to 2 degrees of visual angle (the size of thumb-nail at about 90 cm distance), which is not enough considering the resolution of current displays. Therefore, it is hard to investigate how the visual attention is allocated to the small areas like a single line and words in this paragraph. However, both the previous problems are technological issues that can be solved in the next versions of currently available eye-trackers. A limitation in accuracy will, nevertheless, persist, due to the size of human fovea.

5 Conclusion

The aim of this paper was to raise a discussion and interest about an intersection of areas of eye-movement tracking research and adaptive systems evaluation and development. Although the ideas presented in this paper are not necessarily novel, we still believe that their consideration contributes to a more holistic approach to adaptive systems evaluation. We presented two of possible directions for future research.

First, we suggested employing visual attention tracking as one of the methodologies for evaluating adaptive systems. As the eye-tracking can be conducted without any interventions to users and their tasks, it is a powerful tool to investigate the patterns of visual attention and therefore related cognitive processing influenced by adaptive mechanisms.

Second, we proposed to use the gaze direction for building gaze-aware adaptive environments, where the eye-movement patterns are used as a new adaptation source. Adaptive systems could become aware of the intentions and attention of their users to different parts of the interface. The process of modeling the users could benefit from such information to create more accurate user models.

We call for developing of the methodology enabling adaptive system research to fully utilize the potentials of eye-tracking. By doing so, the pitfalls and problems related to application of eye-movement tracking could be reduced. As we expect the price of the eye-tracking equipment to drop and making thus the technology available to a wider public, the eye-trackers will become a standard and common part of personal computers and other ordinary video-based systems. General-purpose adaptive systems could make a great use of the technology.

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