Eye Tracking in Human-Computer Interaction and Usability Research: Current Status and Future Prospects

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ABSTRACT

Eye-movement tracking is a method that is increasingly being employed to study usability issues in HCI contexts. The objectives of the present chapter are threefold. First, we introduce the reader to the basics of eye-movement technology, and also present key aspects of practical guidance to those who might be interested in using eye tracking in HCI research, whether in usability-evaluation studies, or for capturing people's eye movements as an input mechanism to drive system interaction. Second, we examine various ways in which eye movements can be systematically measured to examine interface usability. We illustrate the advantages of a range of different eye-movement metrics with reference to state-of-the-art usability research. Third, we discuss the various opportunities for eye-movement studies in future HCI research, and detail some of the challenges that need to be overcome to enable effective application of the technique in studying the complexities of advanced interactive-system use.

INTRODUCTION

Eye tracking is a technique whereby an individual's eye movements are measured so that the researcher knows both where a person is looking at any given time and the sequence in which their eyes are shifting from one location to another. Tracking people's eye movements can help HCI researchers understand visual and display-based information processing and the factors that may impact upon the usability of system interfaces. In this way, eye-movement recordings can provide an objective source of interface-evaluation data that can inform the design of improved interfaces. Eye movements can also be captured and used as control signals to enable people to interact with interfaces directly without the need for mouse or keyboard input, which can be a major advantage for certain populations of users such as disabled individuals. We begin this chapter with an overview of eye-tacking technology, and progress toward a detailed discussion of the use of eye tracking in HCI and usability research. A key element of this discussion is to provide a practical guide to inform researchers of the various eye-movement measures that can be taken, and the way in which these metrics can address questions about system usability. We conclude by considering the future prospects for eye-tracking research in HCI and usability testing.

EYE-TRACKING TECHNOLOGY

The History of Eye Tracking
Many different methods have been used to track eye movements since the use of eye-tracking technology was first pioneered in reading research over 100 years ago (Rayner

& Pollatsek, 1989). Electro-oculographic techniques, for example, relied on electrodes mounted on the skin around the eye that could measure differences in electric potential so as to detect eye movements. Other historical methods required the wearing of large contact lenses that covered the cornea (the clear membrane covering the front of the eye) and sclera (the white of the eye that is seen from the outside), with a metal coil embedded around the edge of the lens; eye movements were then measured by fluctuations in an electromagnetic field when the metal coil moved along with the eyes (Duchowski, 2003). These methods proved quite invasive, and most modern eye-tracking systems now use video images of the eye to determine where a person is looking (i.e., their so-called “point-of-regard”). Many distinguishing features of the eye can be used to infer point-of-regard, such as corneal reflections (known as Purkinje images), the iris-sclera boundary, and the apparent pupil shape (Duchowski, 2003).

How Does an Eye Tracker Work?

Most commercial eye-tracking systems available today measure point-of-regard by the “corneal-reflection/pupil-centre” method (Goldberg & Wichansky, 2003). These kinds of trackers usually consist of a standard desktop computer with an infrared camera mounted beneath (or next to) a display monitor, with image processing software to locate and identify the features of the eye used for tracking. In operation, infrared light from an LED embedded in the infrared camera is first directed into the eye to create strong reflections in target eye features to make them easier to track (infrared light is used to avoid dazzling the user with visible light). The light enters the retina and a large proportion of it is reflected back, making the pupil appear as a bright, well defined disc (known as the “bright pupil” effect). The corneal reflection (or first Purkinje image) is also generated by the infrared light, appearing as a small, but sharp, glint (see Figure 1).

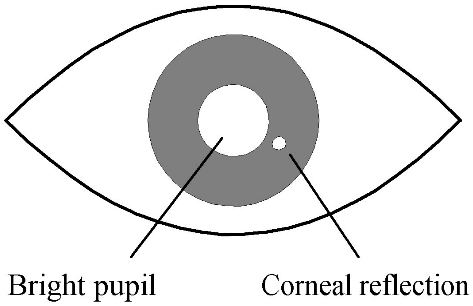

Figure 1. Corneal reflection and bright pupil as seen in the infrared camera image.

Once the image processing software has identified the centre of the pupil and the location of the corneal reflection, the vector between them is measured, and, with further trigonometric calculations, point-of-regard can be found. Although it is possible to determine approximate point-of-regard by the corneal reflection alone (as shown in Figure 2), by tracking both features eye movements can, critically, be disassociated from head movements (Duchowski, 2003**,** Jacob & Karn, 2003).

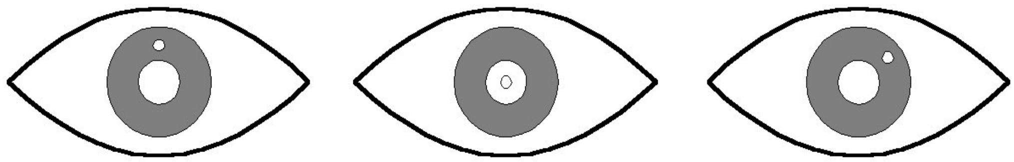

Figure 2. Corneal reflection position changing according to point of regard (cf. Redline & Lankford, 2001).

Video-based eye trackers need to be fine-tuned to the particularities of each person's eye movements by a "calibration" process. This calibration works by displaying a dot on the screen, and if the eye fixes for longer than a certain threshold time and within a certain area, the system records that pupil-centre/corneal-reflection relationship as corresponding to a specific x,y coordinate on the screen. This is repeated over a 9 to 13 point grid-pattern to gain an accurate calibration over the whole screen (Goldberg & Wichansky, 2003).

EYE TRACKING AS A RESEARCH AND USABILITY-EVALUATION TOOL

Why Study Eye Movements in HCI Research?

What a person is looking at is assumed to indicate the thought "on top of the stack" of cognitive processes (Just & Carpenter, 1976). This "eye-mind" hypothesis means that eye-movement recordings can provide a dynamic trace of where a person's *attention* is being directed in relation to a visual display. Measuring other aspects of eye movements, such as fixations (moments when the eyes are relatively stationary, taking in or "encoding" information), can also reveal the *amount* of processing being applied to objects at the point-of-regard. In practice, the process of inferring useful information from eye-movement recordings involves the HCI researcher defining "areas of interest" over certain parts of a display or interface under evaluation, and analysing the eye movements which fall within such areas. In this way, the visibility, meaningfulness and placement of specific interface elements can be objectively evaluated and the resulting findings can be used to improve the design of the interface (Goldberg & Kotval, 1999). For example, in a task scenario where participants are asked to search for an icon, longer-than-expected gaze on the icon before eventual selection would indicate that it lacks meaningfulness, and probably needs to be redesigned. A detailed description of eye-tracking metrics and their interpretation is provided in the following sections.

Previous Eye-Tracking Research

Mainstream psychological research has benefited from studying eye movements as they can provide an insight into problem solving, reasoning, mental imagery, and search strategies (e.g., Ball, Lucas, Miles, & Gale, 2003; Just & Carpenter, 1976; Yoon & Narayanan, 2004, Zelinsky & Sheinberg, 1995). Because eye movements provide a window onto so many aspects of cognition, there are also rich opportunities for the application of eye-movement analysis as a usability research tool in HCI and related disciplines such as human factors and cognitive ergonomics. Although eye-movement analysis is still very much in its infancy in HCI and usability research, issues that are being increasingly studied include the nature and efficacy of information search strategies on menu-based interfaces (e.g., Altonen, Hyrskykari, & Räihä, 1998; Byrne, Anderson, Douglas, & Matessa, 1999; Hendrickson, 1989), and the features of websites that correlate with effective usability (e.g., Cowen, Ball, & Delin, 2002; Goldberg, Stimson, Lewenstein, Scott, & Wichansky, 2002; Poole, Ball, & Philips, 2004). Eye trackers have, additionally, been used more broadly in applied human factors research to measure situation awareness in air-traffic-control training (Hauland, 2003), to evaluate the design of cockpit controls to reduce pilot error (Hanson, 2004), and to investigate and improve doctors' performance in medical procedures (Law, Atkins, Kirkpatrick, & Lomax, 2004; Mello-Thoms, Nodine, & Kundel, 2002). The commercial sector is also showing increased interest in the use of eye-tracking technology in areas such as market research, for example, to determine what advert designs attract the greatest attention (Lohse, 1997), and to determine if Internet users look at banner advertising on websites (Albert, 2002).

Eye-Movement Metrics

The main measurements used in eye-tracking research are fixations (described previously) and "saccades", which are quick eye movements occurring between fixations. There are also a multitude of derived metrics that stem from these basic measures, including "gaze" and "scanpath" measurements. Pupil size and blink rate are also studied.

Fixations: Fixations can be interpreted quite differently depending on the context. In an encoding task (e.g., browsing a web page), higher *fixation frequency* on a particular area can be indicative of greater interest in the target, such as a photograph in a news report, or it can be a sign that the target is complex in some way and more difficult to encode (Jacob & Karn, 2003; Just & Carpenter, 1976). However, these interpretations may be reversed in a search task: A higher number of single fixations, or clusters of fixations, are often an index of greater uncertainty in recognising a target item (Jacob & Karn, 2003). The *duration* of a fixation is also linked to the processing-time applied to the object being fixated (Just & Carpenter, 1976). It is widely accepted that external representations associated with long fixations are not as meaningful to the user as those associated with short fixations (Goldberg & Kotval, 1999). Fixation-derived metrics are described in Table 1.

Eye-Movement Metric	**What it Measures**	**Reference**
Number of fixations overall	More overall fixations indicate less efficient search (perhaps due to sub-optimal layout of the interface).	Goldberg & Kotval (1999)
Fixations per area of interest	More fixations on a particular area indicate that it is more noticeable, or more important, to the viewer than other areas.	Poole et al. (2004)
Fixations per area of interest and	If areas of interest are comprised of text only, the mean number of fixations per area of interest	Poole et al. (2004)

adjusted for text length	should be divided by the mean number of words in the text. This is necessary to separate out: (i) a higher fixation count simply because there are more words to read, from (ii) a higher fixation count because an item is actually harder to recognise.	
Fixation duration	A longer fixation duration indicates difficulty in extracting information, or it means that the object is more engaging in some way.	Just & Carpenter (1976)
Gaze (also referred to as "dwell, fixation cluster" and "fixation cycle")	Gaze is usually the sum of all fixation durations within a prescribed area. It is best used to compare attention distributed between targets. It can also be used as a measure of anticipation in situation awareness if longer gazes fall on an area of interest before a possible event occurring.	Mello-Thoms et al. (2004); Hauland (2003)
Fixation spatial density	Fixations concentrated in a small area indicate focussed and efficient searching. Evenly spread fixations reflect widespread and inefficient search.	Cowen et al. (2002)
Repeat fixations (also called "post-target fixations")	Higher numbers of fixations off-target after the target has been fixated indicate that it lacks meaningfulness or visibility.	Goldberg & Kotval (1999)
Time to first fixation on-target	Faster times to first-fixation on an object or area mean that it has better attention-getting properties.	Byrne et al. (1999)
Percentage of participants fixating an area of interest	If a low proportion of participants is fixating an area that is important to the task, it may need to be highlighted or moved.	Albert (2002)
On-target (all target fixations)	Fixations on-target divided by total number of fixations. A lower ratio indicates lower search efficiency.	Goldberg & Kotval (1999)

Table 1. Fixation-derived metrics and how they can be interpreted in the context of interface design and usability evaluation. References are given to examples of studies that have used each metric.

<u>Saccades:</u> No encoding takes place during saccades, so they cannot tell us anything about the complexity or salience of an object in the interface. However, regressive saccades (i.e., backtracking eye-movements) *can* act as a measure of processing difficulty during encoding (Rayner & Pollatsek, 1989). Although most regressive saccades (or "regressions") are very small, only skipping back two or three letters in reading tasks, much larger phrase-length regressions can represent confusion in higher-level processing of the text (Rayner & Pollatsek, 1989). Regressions could equally be used as a measure of recognition value, in that there should be an inverse relationship between the number of regressions and the salience of the phrase. Saccade-derived metrics are described in Table 2.

Eye-Movement Metric	**What it Measures**	**Reference**
Number of saccades	More saccades indicate more searching.	Goldberg & Kotval (1999)
Saccade amplitude	Larger saccades indicate more meaningful cues, as attention is drawn from a distance.	Goldberg et al. (2002)
Regressive saccades (regressions)	Regressions indicate the presence of less meaningful cues.	Sibert et al. (2000)
Saccades revealing marked directional shifts	Any saccade larger than 90 degrees from the saccade that preceded it shows a rapid change in direction. This could mean that the user's goals have changed or the interface layout does not match the user's expectations.	Cowen et al. (2002)

Table 2. Saccade-derived metrics and how they can be interpreted in the context of interface design and usability evaluation. References are given to examples of studies that have used each metric.

Scanpaths: A scanpath describes a complete saccade-fixate-saccade sequence. In a search task, an optimal scan path is viewed as being a straight line to a desired target, with relatively short fixation duration at the target (Goldberg & Kotval, 1999). Scanpaths can be analysed quantitatively with the derived measures described in Table 3.

Eye-Movement Metric	**What it Measures**	**Reference**
Scanpath duration	A longer-lasting scanpath indicates less efficient scanning.	Goldberg & Kotval (1999)
Scanpath length	A longer scanpath indicates less efficient searching (perhaps due to a sub-optimal layout).	Goldberg et al. (2002)
Spatial density	Smaller spatial density indicates more direct search.	Goldberg & Kotval (1999)
Transition matrix	The transition matrix reveals search order in terms of transitions from one area to another. Scanpaths	Goldberg & Kotval (1999);

	with an identical spatial density and convex hull area can have completely different transition values – one is efficient and direct whilst the other goes back and forth between areas, indicating uncertainty.	Hendrickson, (1989)
Scanpath regularity	Once "cyclic scanning behaviour" is defined, deviation from a "normal" scanpath can indicate search problems due to lack of user training or bad interface layout.	Goldberg & Kotval (1999)
Spatial coverage calculated with convex hull area	Scanpath length plus convex hull area define scanning in a localised or larger area.	Goldberg & Kotval (1999)
Scanpath direction	This can determine a participant's search strategy with menus, lists and other interface elements (e.g. top-down vs. bottom-up scanpaths). 'Sweep" denotes a scanpath progressing in the same direction.	Altonen et al. (1998)
Saccade/fixation ratio	This compares time spent searching (saccades) to time spent processing (fixating). A higher ratio indicates more processing or less searching.	Goldberg & Kotval (1999)

Table 3. Scanpath-derived metrics and how they can be interpreted in the context of interface design and usability evaluation. References are given to examples of studies that used each metric.

Blink rate and pupil size: Blink rate and pupil size can be used as an index of cognitive workload. A lower blink rate is assumed to indicate a higher workload, and a higher blink rate may indicate fatigue (Bruneau, Sasse, & McCarthy, 2002; Brookings, Wilson, & Swain, 1996). Larger pupils may also indicate more cognitive effort (Marshall, 2000; Pomplun & Sunkara, 2003). However, pupil size and blink rate can be determined by many other factors, such as ambient light levels, so are open to contamination (Goldberg & Wichansky, 2003). For these reasons, pupil size and blink rate are less often used in eye tracking research.

Technical Issues in Eye-Tracking Research

Experimenters looking to conduct their own eye-tracking research should bear in mind the limits of the technology and how these limits impact the data that they will want to collect. For example, they should ensure that if they are interested in analysing fixations, that the equipment is optimised to detect fixations (Karn, Goldberg, McConkie, Rojna, Salvucci, Senders, Vertegaal, & Wooding, 2000). The minimum time for a fixation is also highly significant. Interpretations of cognitive processing can vary dramatically according to the time set to detect a fixation in the eye-tracking system. Researchers are advised to set the lower threshold to at least 100ms (Inhoff & Radach, 1998).

Researchers have to work with limits of accuracy and resolution. A sampling rate of 60hz is good enough for usability studies, but inadequate for reading research, which requires sampling rates of around 500hz or more (Rayner & Pollatsek, 1989). It is also imperative to define areas of interest that are large enough to capture all relevant eye movements. Even the best eye trackers available are only accurate to within one degree of actual point-of-regard (Byrne et al., 1999). Attention can also be directed up to one degree away from measured point-of-regard without moving the eyes (Jacob & Karn, 2003).

Eye trackers are quite sensitive instruments and can have difficulty tracking participants who have eye-wear that interrupts the normal path of a reflection, such as hard contact lenses, bifocal and trifocal glasses, and glasses with super-condensed lenses. There may also be problems tracking people with very large pupils or "lazy eye", such that their eyelid obscures part of the pupil and makes it difficult to identify. Once a person is successfully calibrated, the calibration procedure should than be repeated at regular intervals during a test session to maintain an accurate point-of-regard measurement.

There are large differences in eye movements between participants on identical tasks, so it is prudent to use a within-participants design in order to make valid performance comparisons (Goldberg & Wichansky, 2003). Participants should also have well-defined tasks to carry out (Just & Carpenter, 1976) so that their eye movements can be properly attributed to actual cognitive processing. Visual distractions (e.g., colourful or moving objects around the screen or in the testing environment) should also be eliminated, as these will inevitably contaminate the eye-movement data (Goldberg & Wichansky, 2003). Lastly, eye tracking generates huge amounts of data, so it is essential to perform filtering and analysis automatically, not only to save time, but also to minimise chances of introducing errors through manual data processing.

EYE TRACKING AS AN INPUT DEVICE

Eye movements can be measured and used to enable an individual actually to interact with an interface. Users could position a cursor by simply looking at where they want it to go, or "click" an icon by gazing at it for a certain amount of time or by blinking. The first obvious application of this capability is for disabled users who cannot make use of their hands to control a mouse or keyboard (Jacob & Karn, 2003). However, intention can often be hard to interpret; many eye movements are involuntary, leading to a certain "Midas Touch" (see Jacob & Karn, 2003), in that you cannot look at anything without immediately activating some part of the interface. One solution to this problem is to use eye movements in combination with other input devices to make intentions clear. Speech commands can add extra context to users' intentions when eye movements may be vague, and vice versa (Kaur et al., 2003).

Virtual reality environments can also be controlled by the use of eye movements. The large three-dimensional spaces that users operate in often contain far-away objects that have to be manipulated. Eye movements seem to be the ideal tool in such a context, as moving the eyes to span long distances requires little effort compared with other control methods (Jacob & Karn, 2003). Eye movement interaction can also be used in a subtler way, for example, to trigger context-sensitive help as soon as a user becomes confused (e.g., performs too many regressions) while reading text (Sibert et al., 2000). Other researchers (e.g., Ramloll, Trepagnier, Sebrechts, & Finkelmeyer, 2004) have used gaze-based interaction to help autistic children learn social skills by rewarding them when they maintain eye contact while communicating.

Some techniques alter a display depending on the point of regard. Some large-display systems, such as flight simulators (e.g., Levoy & Whitaker, 1990; Tong & Fisher, 1984) channel image processing resources to display higher quality or higher resolution images only within the range of highest visual acuity (i.e., the fovea) and decrease image processing in the visual range where detail cannot be resolved (the parafovea). Other systems (e.g., Triesch, Sullivan, Hayhoe, & Ballard, 2002) take advantage of the visual suppression during saccades to update graphical displays without the user noticing. Yet another rather novel use is tracking the point-of-regard during video-conferencing, and warping the image of the eyes so that they maintain eye contact with other participants in the meeting (Jerald & Daily, 2002).

FUTURE TRENDS IN EYE TRACKING

Future developments in eye tracking should centre on standardising what eye-movement metrics are used, how they are referred to, and how they should be interpreted in the context of interface design (cf. Cowen et al., 2002). For example, no standard yet exists for the minimum duration of a fixation (Inhoff & Radach, 1998), yet small differences in duration thresholds can make it hard to compare studies on an even footing (Goldberg & Wichansky, 2003). Eye-tracking technology also needs to be improved to increase the validity and reliability of the recorded data. The robustness and accuracy of data capture needs to be increased, so that point-of-regard measurement stays accurate without the need for frequent re-calibration. Data-collection, -filtering and -analysis software should be streamlined so that they can work together without user intervention. The intrusiveness of equipment should be decreased to make users feel more comfortable, perhaps through the development of smaller and lighter head-mounted trackers. Finally, eye-tracking systems need to become cheaper in order to make them a viable usability tool for smaller commercial agencies and research labs (Jacob & Karn, 2003). Once eye tracking achieves these improvements in technology, methodology, and cost, it can take its place as part of a standard HCI toolkit.

CONCLUSION

Our contention is that eye-movement tracking represents an important, objective technique that can afford useful advantages for the in-depth analysis of interface usability. Eye-tracking studies in HCI are beginning to burgeon, and the technique seems set to become an established addition to the current battery of usability-testing methods employed by commercial and academic HCI researchers. This continued growth in the use of the method in HCI studies looks likely to continue as the technology becomes increasingly more affordable, less invasive, and easier to use. The future seems rich for eye tracking and HCI.

GLOSSARY

Eye tracker: Device used to determine point-of-regard and to measure eye movements such as fixations, saccades, and regressions. Works by tracking the position of various distinguishing features of the eye, such as reflections of infrared light off the cornea, the boundary between the iris and sclera, or apparent pupil shape.

Eye tracking: A technique whereby an individual's eye movements are measured so that the researcher knows where a person is looking at any given time, and how their eyes are moving from one location to another.

Eye-mind hypothesis: The principle at the origin of most eye tracking research. Assumes that what a person is looking at indicates what they are currently thinking about or attending to. Recording eye-movements can, therefore, provide a dynamic trace of where a person's attention is being directed in relation to a visual display such as a system interface.

Fixation: The moment when the eyes are relatively stationary, taking in or "encoding" information. Fixations last for 218 milliseconds on average, with a range of 66 to 416 milliseconds.

Gaze: An eye tracking metric, usually the sum of all fixation durations within a prescribed area. Also called "dwell", "fixation cluster", or "fixation cycle".

Point-of-regard: Point in space where a person is looking. Usually used in eye tracking research to reveal where visual attention is directed.

Regression: A regressive saccade. A saccade that moves back in the direction of text that has already been read.

Area of interest: An area of interest is an analysis method used in eye tracking. Researchers define areas of interest over certain parts of a display or interface under evaluation, and analyse only the eye movements that fall within such areas.

Saccade: An eye movement occurring between fixations, typically lasting for 20 to 35 milliseconds. The purpose of most saccades is to move the eyes to the next viewing position. Visual processing is automatically suppressed during saccades to avoid blurring of the visual image.

Scanpath: An eye-tracking metric, usually a complete sequence of fixations and interconnecting saccades.

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