

Chapter 3

Eye Tracking and Eye-Based Human–Computer Interaction

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Abstract Eye tracking has a long history in medical and psychological research as a tool for recording and studying human visual behavior. Real-time gaze-based text entry can also be a powerful means of communication and control for people with physical disabilities. Following recent technological advances and the advent of affordable eye trackers, there is a growing interest in pervasive attention-aware systems and interfaces that have the potential to revolutionize mainstream human–technology interaction. In this chapter, we provide an introduction to the state-of-the-art in eye tracking technology and gaze estimation. We discuss challenges involved in using a perceptual organ, the eye, as an input modality. Examples of real life applications are reviewed, together with design solutions derived from research results. We also discuss how to match the user requirements and key features of different eye tracking systems to find the best system for each task and application.

Introduction

The eye has a lot of communicative power. Eye contact and gaze direction are central and very important cues in human communication, for example, in regulating interaction and turn taking, establishing socio-emotional connection, or indicating the target of our visual interest (Kleinke 1986). The eye has also been said to be a mirror to the soul or window into the brain (Brigham et al. 2001; Ellis et al. 1998). Gaze behavior reflects cognitive processes and can give hints of our thinking and intentions. We often look at things before acting on them (Land and Furneaux 1997).

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Eye tracking refers to the process of tracking eye movements or the absolute point of gaze (POG)—referring to the point the user’s gaze is focused at in the visual scene. Eye tracking is useful in a broad range of application areas, from psychological research and medical diagnostic to usability studies and interactive, gaze-controlled applications. This chapter is focused on the use of real-time data from human eye movements that can be exploited in the area of human-technology interaction. The aim is to provide a useful starting point for researchers, designers of interactive technology and assistive technology professionals wishing to gain deeper insight into gaze interaction.

Initially, eye movements were mainly studied by physiological introspection and observation. Basic eye movements were categorized and their duration estimated long before the eye tracking technology enabled precise measurement of eye movements. The first generation of eye tracking devices was highly invasive and uncomfortable. A breakthrough in eye tracking technology was the development of the first “non-invasive” eye tracking apparatus in the early 1900s (Wade and Tatler 2005), based on photography and light reflected from the cornea. It can be considered as the first ancestor of the current widely used video-based, corneal reflection eye tracking systems. The development of unobtrusive camera-based systems (Morimoto and Mimica 2005) and the increase of computing power enabled gathering of eye tracking data in real time, enabling the use of gaze as a control method for people with disabilities (Ten Kate et al. 1979; Friedman et al. 1982). Since then, eye tracking has been used in a wide range of application areas, some of which are reviewed later in this chapter.

Using the eye as an input method has benefits but also some considerable challenges. These challenges originate from eye physiology and from its perceptive nature. Below, we briefly introduce the basics of eye physiology and eye movements. The rest of the chapter concentrates on giving an overview of eye tracking technology and methods used to implement gaze interaction. We will also review related research and introduce example applications that should help the readers to understand the reasons behind the problem issues—and to design solutions that avoid the typical pitfalls. We will conclude this chapter with a summary and a discussion of potential future research directions for gaze-based interfaces.

Eye Physiology and Types of Eye Movement

To see an object in the real world, we have to fixate our gaze at it long enough for the brain’s visual system to perceive it. Fixations are often defined as pauses of at least 100 ms, typically between 200 and 600 ms. During any one fixation, we only see a fairly narrow area of the visual scene with high acuity. To perceive the visual scene accurately, we need to constantly scan it with rapid eye movement, so-called saccades. Saccades are quick, ballistic jumps of 2° or longer that take about 30–120 ms each (Jacob 1995). In addition to saccadic movements, the eyes can

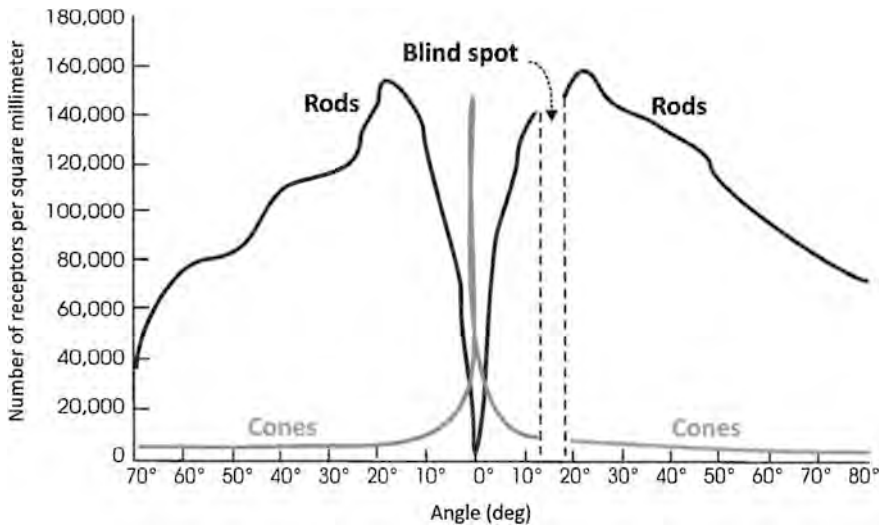


Fig. 3.1 Distribution of rods and cones on the retina (Adapted from Osterberg 1935)

smoothly follow a moving target; this is known as (smooth) pursuit movement. For more information about other types of eye movements and visual perception in general, see, for example, Mulvey (2012).

The size of the high-acuity field of vision, the fovea, subtends at an angle of about one degree from the eye. The diameter of this region corresponds to an area of about two degrees, which is about the size of a thumbnail when viewed with the arm extended (Duchowski and Vertegaal 2000). Everything inside the fovea can be perceived with high acuity but the acuity decreases rapidly towards the periphery of the eye. The cause for this can be seen by examining the physiology of the retina (see Fig. 3.1). The lens focuses the light coming from the pupil on the center of the retina. The fovea is packed with photoreceptive cells but the density of these cells decreases rapidly in the peripheral area. The fovea mainly contains cones, photoreceptive cells that are sensitive to color and provide acuity. In contrast, the peripheral area contains mostly rods, i.e. cells that are sensitive to light, shade and motion. The remaining peripheral vision provides cues about where to look next and also gives information on movement or changes in the scene in front of the viewer. For example, a sudden movement in the periphery can thus quickly attract the viewer’s attention (Hillstrom and Yantis 1994).

We only see a small fraction of the visual scene in front of us with high acuity at any point in time. The need to move our eyes toward the target is the basis for eye tracking: it is possible to deduce the gaze vector by observing the “line-of-sight”.

Eye Tracking Techniques

While a large number of different techniques to track eye movements have been investigated in the past, three eye tracking techniques have emerged as the predominant ones and are widely used in research and commercial applications today. These techniques are (1) videoculography (VOG), video based tracking using head-mounted or remote visible light video cameras, (2) video-based infrared (IR) pupil-corneal reflection (PCR), and (3) Electrooculography (EOG). While particularly the first two video-based techniques have a lot of properties in common, all techniques have application areas where they are most useful.

Video-based eye tracking relies on off-the-shelf components and video cameras and can therefore be used for developing “eye-aware” or attentive user interfaces that do not strictly require accurate point of gaze tracking (e.g. about 4° , Hansen and Pece 2005). In contrast, due to the additional information gained from the IR-induced corneal reflection, IR-PCR provides highly accurate point of gaze measurements of up to 0.5° of visual angle and has therefore emerged as the preferred technique for scientific domains, such as usability studies or gaze-based interaction, and commercial applications, such as in marketing research. Finally, EOG has been used for decades for ophthalmological studies as it allows for measuring relative movements of the eyes with high temporal accuracy. In addition to different application areas, each of these measurement techniques also has specific technical advantages and disadvantages that we will discuss in the following sections.

Video-Based Tracking

A video-based eye tracking system can be either used in a remote or head-mounted configuration. A typical setup consists of a video camera that records the movements of the eye(s) and a computer that saves and analyses the gaze data. In remote systems, the camera is typically based below the computer screen (Fig. 3.2) while in head-mounted systems, the camera is attached either on a frame of eyeglasses or in a separate “helmet”. Head-mounted systems often also include a scene camera for recording the user’s point of view, which can then be used to map the user’s gaze to the current visual scene.

The frame rate and resolution of the video camera have a significant effect on the accuracy of tracking; a low-cost web camera cannot compete with a high-end camera with high-resolution and high sample rate. The focal length of the lens, the angle, as well as the distance between the eye and the camera have an effect on the working distance and the quality of gaze tracking. With large zooming (large focal length), it is possible to get a close-up view of the eye but it narrows the working angle of the camera and requires the user to sit fairly still (unless the camera follows the user’s movements). In head-mounted systems, the camera is placed

Fig. 3.2 The eye tracker’s camera is placed under the monitor. Infrared light sources are located on each side of the camera. IR is used to illuminate the eye and its reflection on the cornea provides an additional reference point that improves accuracy when tracked together with the center of the pupil (© 2008, www.cogain.org. Used with permission)



near the eye, which means a bigger image of the eye and thus more pixels for tracking the eye. If a wide angle camera is used, it allows more freedom of movement of the user but also requires a high-resolution camera to maintain enough accuracy for tracking the pupil (Hansen and Majaranta 2012).

Since tracking is based on video images of the eye, it requires an unobstructed view of the eye. There are a number of issues that can affect the quality of tracking, such as varying light conditions, reflections of eyeglasses, droopy eyelids, squinting the eyes while smiling, or even heavy makeup (for more information and guidelines, see Goldberg and Wichansky 2003).

The video images are the basis for estimating the gaze position on the computer screen: the location of the eye(s) and the center of the pupil are detected. Changes in their position are tracked, analyzed and mapped to gaze coordinates. For a detailed survey of video-based techniques for eye and pupil detection and gaze position estimation, see Hansen and Ji (2009). If only the pupil center is used and no other reference points are available, the user must stay absolutely still for an accurate calculation of the gaze vector (the line of sight from the user’s eye to the point of view on the screen). Forcing the user to sit still may be uncomfortable, thus various methods for tracking and compensating the head movement have been

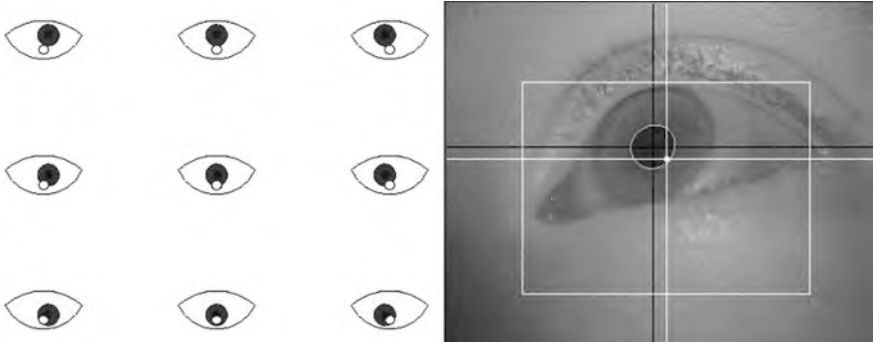


Fig. 3.3 The relationship between the pupil center and the corneal reflection when the user fixates on different locations on the screen (Adapted from Majoranta et al. 2009b)

implemented (e.g. Sugioka et al. 1996; Murphy-Chutorian and Trivedi 2009; Zhu and Ji 2005). Head tracking methods are also required for head-mounted systems, if one wishes to calculate the point of gaze in relation to the user’s eye and the environment (Rothkopf and Pelz 2004).

Infrared Pupil-Corneal Reflection Tracking

Systems only based on visible light and pupil center tracking tend to be inaccurate and sensitive to head movement. To address this problem, a reference point, a so called “corneal reflection” or glint, can be added. Such a reference point can be added by using an artificial infrared (IR) light source aimed on- or off-axis at the eye. An on-axis light source will result in a “bright pupil” effect, making it easier for the analysis software to recognize the pupil in the image. The effect is similar to the red-eye effect caused by flash in a photograph. The off-axis light results in “dark pupil” images. Both will help in keeping the eye area well lit but they do not disturb viewing or affect pupil dilation since IR light is invisible to the human eye (Duchowski 2003).

By measuring the corneal reflection(s) from the IR source relative to the center of the pupil, the system can compensate for inaccuracies and also allow for a limited degree of head movement. Gaze direction is then calculated by measuring the changing relationship between the moving pupil center of the eye and the corneal reflection (see Fig. 3.3). As the position of the corneal reflection remains roughly constant during eye movement, the reflection will remain static during rotation of the eye and changes in gaze direction, thus giving a basic eye and head position reference. In addition, it also provides a simple reference point to compare with the moving pupil, and thus enables calculation of the gaze vector (for a more detailed explanation, see Duchowski and Vertegaal 2000).

While IR illumination enables fairly accurate remote tracking of the user it does not work well in changing ambient light, such as in outdoors settings. There is an ongoing research that tries to solve this issue (see e.g. Kinsman and Pelz 2012; Bengochea et al. 2012). In addition, according to our personal experience, there seems to be a small number of people for whom, robust/accurate eye tracking does not seem to work even in laboratory settings. Electrooculography is not dependent or disturbed by lighting conditions and thus can replace VOG-based tracking in some of these situations and for some applications.

Electrooculography-Based Tracking

The human eye can be modeled as a dipole with its positive pole at the cornea and its negative pole at the retina. Assuming a stable cornea-retinal potential difference, the eye is the origin of a steady electric potential field. The electrical signal that can be measured from this field is called the electrooculogram (EOG). The signal is measured between two pairs of surface electrodes placed in periorbital positions around the eye (see Fig. 3.4) with respect to a reference electrode (typically placed on the forehead). If the eyes move from the center position towards one of these electrodes, the retina approaches this electrode, while the cornea approaches the opposing one. This change in dipole orientation causes a change in the electric potential field, which in turn can be measured to track eye movements. In contrast to video-based eye tracking, recorded eye movements are typically split into one horizontal and one vertical EOG signal component. This split reflects the discretisation given by the electrode setup.

One drawback of EOG compared to video-based tracking is the fact that EOG requires electrodes to be attached to the skin around the eyes. In addition, EOG provides lower spatial POG tracking accuracy and is therefore better suited for tracking relative eye movements. EOG signals are subject to signal noise and artifacts and prone to drifting, particularly if recorded in mobile settings. EOG signals—like other physiological signals—may be corrupted with noise from the residential power line, the measurement circuitry, electrodes, or other interfering physiological sources.

One advantage of EOG compared to video-based eye tracking is that changing lighting conditions have only little impact on EOG signals, a property that is particularly useful for mobile recordings in daily life settings. As light falling into the eyes is not required for the electric potential field to be established; EOG can also be measured in total darkness or when the eyes are closed. It is for this reason that EOG is a well-known measurement technique for recording eye movements during sleep, e.g. to identify REM phases (Smith et al. 1971) or diagnosing sleep disorders (Penzel et al. 2005). The second major advantage of EOG is that the signal processing is computationally light-weight and particularly does not require any complex video and image processing. Consequently, while EOG has traditionally been used in stationary settings (Hori et al. 2006; Borghetti et al. 2007), it can also

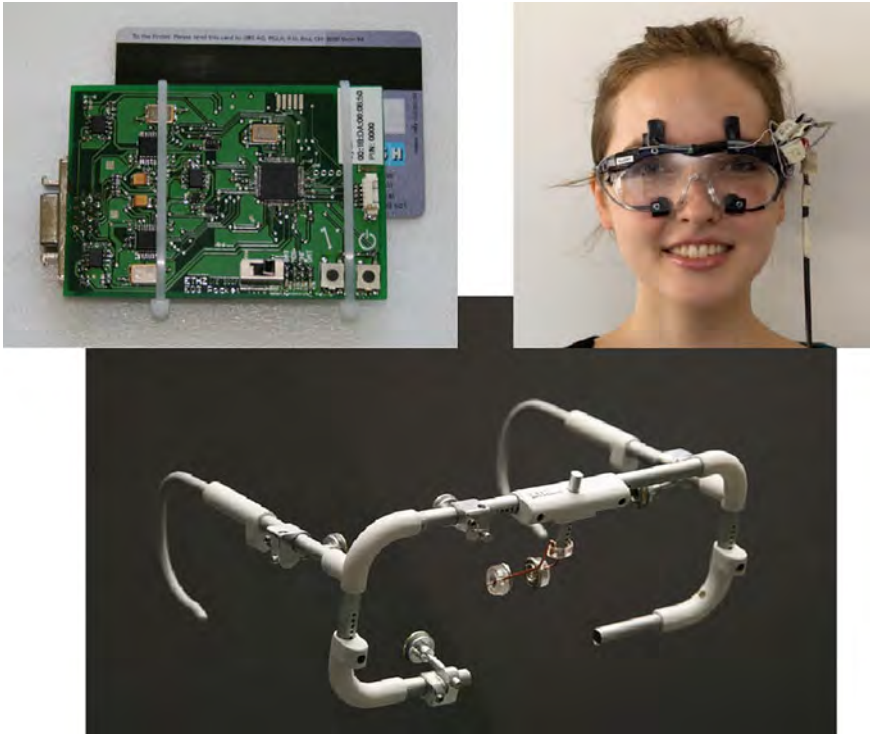


Fig. 3.4 Wearable EOG goggles (Bulling et al. 2008b, 2009b)

be implemented as a low-power and fully embedded on-body system for mobile recordings in daily life settings (Manabe and Fukumoto 2006; Vehkaoja et al. 2005; Bulling et al. 2008b, 2009b). While state-of-the art video-based eye trackers require additional equipment for data recording and storage, such as laptops, and are limited to recording times of a few hours, EOG allows for long-term recordings, allowing capture of people’s everyday life (Bulling et al. 2012a, b).

Eye Tracker Calibration and Accuracy

Before a remote video-based eye tracking system can map gaze onto a screen, it must be calibrated to that screen for each user. This is usually done by showing a number of calibration points on the screen and asking the user to consecutively fixate at these points, one at a time. The relationship between the pupil position and the corneal reflections changes as a function of eye gaze direction (see Fig. 3.3). The images of the eye and thus its orientation in space are analyzed by the computer for each calibration point, and each image is associated with

corresponding screen coordinates. These main points are used to calculate any other point on-screen via interpolation of the data.

Gaze mapping is more challenging for mobile head-mounted eye trackers as, in contrast to remote eye trackers, the user and thus eye tracker cannot be assumed to be positioned in a fixed location or distance relative to the screen to which the tracker was initially calibrated. The system can be calibrated by asking the user to fixate at certain points in the environment (e.g. indicated by a laser pointer) and the system obtains the eye angle during each calibration point (Schneider et al. 2005). If a scene camera is used, it is possible to overlay the gaze point on top of the scene video for offline analysis. For real-time use, the most common solution to this problem is to place visual markers in the environment, calibrate the eye tracker relative to these markers, and to use computer vision techniques to detect and track them and map gaze accordingly in real time. The robustness of recognizing the markers can be improved by using reflective markers (Essig et al. 2012). Given that visual markers can only be tracked with a certain accuracy, gaze estimates obtained from head-mounted eye trackers are typically less accurate than those from remote systems. In addition, the eye glass frames or the helmet where the camera is attached may occasionally move, causing some drifting.

Calibration is a key factor defining the accuracy of any eye tracker. If the calibration is successful, the accuracy is typically about 0.5° of visual angle. This corresponds to about 15 pixels on a 17" display with the resolution of 1024×768 pixels, viewed from a distance of 70 cm. Even with successful calibration, the practical accuracy may be less due to drifting which will cause an offset between the measured point of gaze and the actual gaze point. Such drifting may be caused by changes in lighting and pupil size. In head mounted systems, it is also possible that the camera has moved along with the frames. Various methods have been implemented to prevent drifting (Hansen et al. 2010) or to cope with it (Stampe and Reingold 1995). If both eyes are tracked, it usually not only improves accuracy in general but also limits drifting. Since calibration takes time and may be seen as an obstacle for using eye tracking in everyday applications, techniques requiring only one calibration point, automatic calibration procedures, and “calibration-free” systems have been developed (see e.g. Nagamatsu et al. 2010).

Even if the eye tracker was perfectly accurate, it may still be impossible to know the exact pixel the user is focused on. This is because everything within the fovea is seen in detail and the user can move attention within this area without voluntarily moving her eyes. Besides, the eyes perform very small, rapid movements, so-called micro saccades, even during fixations to keep the nerve cells in the retina active and to correct slight drifting in focus. Thus, if the cursor of an “eye mouse” were to follow eye movements faithfully, the cursor movement would appear jerky and it would be difficult to concentrate on pointing (Jacob 1993). Therefore, the coordinates reported by the system are often “smoothed” by averaging data from several raw gaze points. This may have an effect on the responsiveness of the system, especially if the sample rate of the camera is low.

Eye-Based Interaction

While gaze may not be as accurate an input device as, for example, a manual mouse, if the target objects are large enough, gaze can be much faster at pointing (Sibert and Jacob 2000; Ware and Mikaelian 1987). Gaze not only shows where our current visual attention is directed at but it also often precedes action, meaning we look at things before acting on them. Thus, there is a lot of potential in using gaze in human-computer interfaces either as an input method or as an information source for proactive interfaces.

Using gaze as an input method can be problematic, since the same modality is used for both perception and control. The system needs to be able to distinguish casual viewing of an object from intentional control, in order to prevent the “Midas touch” problem where all items viewed are selected (Jacob 1991). Gaze is also easily distracted by movement in the peripheral vision, resulting in unwanted glances away from the object of interest. Eye movements are also largely unconscious and automatic. When necessary, however, one can control gaze at will, which makes voluntary eye control possible.

Implementation Issues

We will now discuss issues involved in implementing gaze-control in HCI and give practical hints on how to avoid typical caveats using the different eye tracking techniques. We will then review gaze-based applications and real life examples that demonstrate successful gaze interaction.

Accuracy and Responsiveness

There are several ways to cope with the spatial inaccuracy of the measured point of gaze. Increasing the size of the targets makes them easier to hit by gaze. The drawback of increasing the target size is that fewer objects fit on the screen at any time. This increases the need to organize them hierarchically in menus and sub-menus, which, in turn, slows down interaction. Other methods include for example dynamic zooming and fish-eye lenses (Ashmore et al. 2005; Bates and Istance 2002). It is also possible to combine gaze with other modalities. For example, the user can look at the target item and confirm the desired object by speech (Miniotos et al. 2006), touch input (Stellmach and Dachsel 2012), or head movement (Špakov and Majoranta 2012).

If the eye is used as a replacement for the mouse cursor, poor calibration means the cursor may not be located exactly at the point of the user’s focus, but offset by a few pixels. In addition, the constant movement of the eye may make it hard to hit

a target with the eye. Eyes not only move during saccades but they also make small movements during a fixation. The jittery movement of the cursor may distract concentration as the user’s attention is drawn by the movement in the parafoveal vision. If the user tries to look at the cursor, he may end up chasing it as the cursor is always a few pixels away from the point they are looking at (Jacob 1995). Experienced users may learn either to ignore the cursor or to take advantage of the visual feedback provided by the cursor in order to compensate for any slight calibration errors by adjusting their gaze point accordingly to bring the cursor onto an object. Nevertheless, it is useful to smooth the cursor movement. A stable cursor is more comfortable to use and it is easier to keep it long enough upon a target for it to be selected. The level of the smoothing should be adjusted to suit the application, because extensive smoothing may slow down the responsiveness of the cursor too much for tasks requiring fast-paced actions (e.g. action games).

A video-based system places the cursor at the point of the user’s gaze. However, since the EOG potential is proportional to the angle of the eye in the head, an EOG-based mouse pointer is moved by changing the angle of the eyes in the head. This means the user can move the mouse cursor by moving the eyes, the head, or both. Thus, even if EOG as such may not be as accurate as VOG-based tracking methods, it allows head movements to be used for fine-tuning the position of the cursor.

Midas Touch

Coping with the Midas touch problem is maybe the most prominent challenge of gaze interaction. Various methods have been implemented and tested over the years (Velichkovsky et al. 1997). An easy way to prevent unintentional selections is to combine gaze pointing with an additional modality. This can be a spoken confirmation, a separate manual switch, a blink, a wink, a sip, a puff, a wrinkling, or any muscle activity available to the user (Skovsgaard et al. 2012).

For systems based solely on gaze-control, the most common method for preventing erroneous activations is to introduce a brief delay, a so-called “dwell time”, to differentiate viewing and gaze-control. The duration should match the specific requirements of the task and the user. Expert eye typists require only a very short dwell time duration (e.g. 300 ms) while novices may prefer longer dwell time durations (e.g. 1000 ms) that give them more time to think, react and cancel the action (Majaranta 2012). A long continuous dwelling (fixation) can be uncomfortable and tiring to the eyes. On the other hand, the possibility to adjust dwell time supports efficient learning of the gaze-controlled interface and increases user satisfaction (Majaranta et al. 2009a).

Other ways to implement eye-based selection include, for example, specially designed selection areas and gaze gestures. Ohno (1998) divided the menu objects into two areas: command name and selection area (located side by side on each menu item). This enabled the user to glance through the items by reading their

labels (command name) and select the desired item by moving the gaze to the selection area. In gesture based systems, the user initiates commands by making a sequence of “eye strokes” (Drewes and Schmidt 2007). Such gaze gestures can either be made by looking at certain areas on or off-the screen (Isokoski 2000; Wobbrock et al. 2008), or by making relative eye strokes without focusing on any specific target. The latter is useful especially in EOG-based systems where the user may execute commands simply by moving eyes up-down or left-right (Bulling et al. 2008a, b). Gestures are also useful in low-cost systems as they do not require accurate calibration (Huckauf and Urbina 2008). Simple gestures up, down, left or right can be used as a joystick, for example, to remotely control a toy car by gaze (Fig. 3.5).

Using gaze-initiated selection, corresponding feedback must be provided by the application. When manually pressing a button, the user makes the selection and physically executes it. In comparison, when using dwell time, the user only initiates the action; the system executes it after a predefined interval. Appropriate feedback plays an essential role in gaze-based interfaces; the user must be given clear indication of the status of the system: is the tracker following the gaze accurately, has the system recognized the target the user is looking at (feedback on focus), and has the system selected the intended object (feedback on selection).

It is also important to note that the user cannot simultaneously control an object and view the effects of the action, unless the effect appears on the object itself. For example, if the user is entering text by gaze, he or she cannot see the text appear in the text input field while simultaneously selecting a letter by “eye pressing” a key on an on-screen keyboard. Majoranta et al. (2006) showed that proper feedback significantly reduces errors and increase interaction speed in gaze-based text entry. For example, a simple animated feedback of the progression of the dwell time helped novices to maintain their gaze on the target for the full duration required for the item to be selected, thus reducing errors caused by premature exits. Successful feedback was also reflected in the gaze behavior and user satisfaction; as the users became more confident they no longer felt the need to repeatedly swap their gaze between the keyboard and the input field.

As discussed above, the calibration offset and the constant cursor movement may distract attention. Thus, it is often useful to give the visual feedback on the target item itself. If the item is highlighted on focus, the system appears as accurate and responsive to the user. It may also be useful to design the gaze-reactive button so that the user will look at the center of it, which will help in preventing errors and maintaining good accuracy. If the calibration is off by a few pixels, a look near the edge of the button may result in an error (e.g. a button adjacent to the target may get selected instead). If the user will always look at the center of the successfully selected button, this may also act as a checkpoint for dynamic re-calibration.

Fig. 3.5 The toy car (described in Fejtová et al. 2009) is controlled by relative eye movements that act like a joystick to move the car forward or backward, or turn it *left* or *right* (© 2006, www.cogain.org. Used with permission)



Gaze Interaction Applications

Information from eye movements and gaze direction can be utilized on various levels in a wide variety of applications. Some applications require the user to move her eyes voluntarily while other systems monitor the eye movements subtly in the background and require no special effort from the user.

Fairclough (2011) suggested a four-group classification to describe the different kinds of physiological computing system. The categories start from the overt, intentional systems (such as conventional input devices) and end with the covert, unintentional systems (e.g. ambulatory monitoring). Each individual system can be placed on this continuum and some systems may also be hybrids that contain features from different categories. A similar continuum can also be used to describe different types of gaze-based systems, starting from applications where the intention is the driving force, requiring full, overt, conscious attention from the user (see Fig. 3.6). In the middle, we have attentive applications that somehow react to the user's behavior but do not require any explicit control from the user. An advanced form of this are adaptive applications that learn the user's behavior

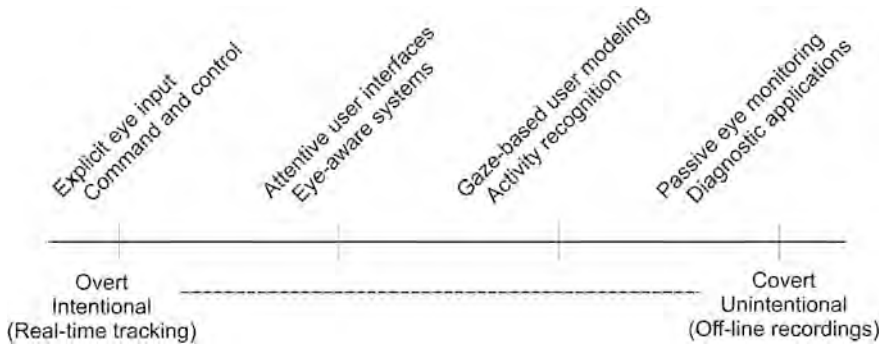


Fig. 3.6 Continuum of eye tracking applications from intentional to unintentional systems

patterns and are able to model the user’s behavior. In the other end, we have systems that passively monitor their eye behavior, requiring no conscious input from the user whose behavior is monitored and analyzed. In the following section, we provide examples of representative applications for each category.

- (1) *Explicit eye input* is utilized in applications that implement gaze-based command and control. Here, people use voluntary eye movements and consciously control their gaze direction, for example, to communicate or control a computer. Gaze-based control is especially useful for people with severe disabilities for whom eyes may be the only or—due to developments in technology—a reckonable option to interact with the world (Bates et al. 2006; Donegan et al. 2009).

In its simplest form, the eye can be used as a switch. For example, the user may blink once or twice, or use simple vertical or horizontal eye movements as an indication of agreement or disagreement (obtainable even with a low-cost web camera based tracker). The most common way to implement gaze-based control is to use the eye’s capability to point at the desired target (requiring a more accurate tracker). Mouse emulation, combined with different techniques and gaze-friendly tools for dragging, double-click, screen magnification etc. make it possible to control practically any graphical interface based on windows, icons, menus, and pointer devices (WIMP). It should be noted, though, that gaze control of WIMP is noticeably slower and more error prone than control by conventional mouse and keyboard (e.g. gaze typing reaches about 20 wpm which is far from the 80 wpm by a touch typist, see Majoranta et al. 2009a). However, with special techniques such as zooming to overcome the inaccuracy problems, gaze becomes comparable with other special access methods such as head pointing where head movement is used to control the cursor movement (Bates and Istance 2002; Hansen et al. 2004; Porta et al. 2010). Other example applications include gaze-based text entry, web browsing, gaze-controlled games, music, etc. (see e.g. (Majoranta and Riih  2002;

Castellina and Corno 2007; Isokoski et al. 2009; Vickers et al. 2010). For a review of different techniques and applications for gaze-based computer control, see (Skovsgaard et al. 2012).

Some applications, such as eye drawing or steering of a wheelchair with the eyes, are not best suited for a simple point-and-select interface. For example, drawing a smooth curve is not possible with fixations and saccades but would require smooth pursuit type of eye movement. Such continuous smooth movement is not easy for the human eyes but require a target to follow or some other visual guidance (e.g. the after image effect, see Lorenceau 2012). Similarly, in steering tasks or navigation in e.g. virtual worlds require special techniques that take into account the special characteristics of eye input (Bates et al. 2008; Hansen et al. 2008).

Most current assistive gaze-controlled systems utilize video and infrared based eye trackers. However, a lot of research has been conducted on EOG-based systems and some of them are currently in real use by people with disabilities (see EagleEyes, www.eagleeyes.org). Patmore et al. (1998) developed an EOG-based system intended to provide a pointing device for people with physical disabilities. Basic eye movement characteristics detected from EOG signals, such as saccades, fixations, blinks and deliberate movement patterns, have been used for hands-free operation of stationary human-computer (Ding et al. 2005; Kherlopian et al. 2006) and human-robot (Kim et al. 2001; Chen and Newman 2004) command interfaces. As part of a hospital alarm system, EOG-based switches provided immobile patients with a safe and reliable way of signaling an alarm (Venkataramanan et al. 2005).

Bulling et al. (2008b, 2009a) investigated EOG-based interaction with a desktop using eye gestures, sequences of consecutive relative eye movements. Since EOG measures relative eye movements, it is especially useful for mobile settings, e.g. for assistive robots (Wijesoma et al. 2005) and as a control for an electric wheelchair (Barea et al. 2002; Philips et al. 2007). These systems are intended to be used by physically disabled people who have extremely limited peripheral mobility but still retain eye motor coordination. Mizuno et al. (2003) used basic characteristics of eye motion to operate a wearable computer system for medical caregivers.

A current trend in gaze-controlled applications seems to be to move gaze interaction away from the desktop environment, to support environmental control by gaze, mobile applications and gaze-based mobility, and control of physical objects and human-robot interaction (e.g. Corno et al. 2010; Dybdal et al. 2012; Fejtová et al. 2009; Mohammad et al. 2010).

- (2) *Attentive user interfaces* can be considered as non-command interfaces (Nielsen 1993) where the user is not expected to change his or her gaze behavior to give explicit commands. Instead, the information of the user's natural eye movements is used subtly in the background. In its simplest form, an attentive interface may implement a "gaze-contingent display" that shows a higher resolution image on the area the user is focusing on

while maintaining a lower resolution in the periphery in order to save bandwidth (Duchowski et al. 2004). Another example is given by Vesterby et al. (2005) who experimented with gaze-guided viewing of interactive movies where the plot of the movie changes according to the viewer's visual interest. The movie contained scenes where the narrative would branch based on the level of visual interest paid by the viewers on the key objects in the movie. The choice did not require any special effort from the viewer as it was based on their viewing behavior. If the user is explicitly required to give commands and if gaze-reactive areas are emphasized by explicit feedback, it might disturb the immersion and the viewer might lose track of the story line.

There is a thin line between attentive interfaces and explicit gaze input. An attentive system may assist the user's conventional manual interactions. For example, information from the eye movements may be used to automatize part of the task. For example, the eyes are used to set the focus (e.g. on viewed window/dialog) while manual input is used to select the focused item (Fono and Vertegaal 2005). Some systems constantly monitor the user's natural gaze behavior and may assist for example by automatically fetching information so that it can be shown immediately as the user moves her gaze to the information window (Jacob 1991; Hyrskykari et al. 2000). If the user knows her gaze is being tracked, she may also learn to adapt her gaze behavior in order to take better benefit of the gaze-aware features of the system (Hyrskykari et al. 2003). For example, a gaze-aware reading assistant provides automatic translations for foreign words and phrases when it detects deviations in reading behavior. The reader may also explicitly trigger the translation by staring at the difficult word (Fig. 3.7). An attentive system may be gaze-aware or eye-aware. For some applications, simply detecting the presence of the eye(s) may be useful, without knowledge of the gaze direction. Eye-contact detection is useful for example in home appliances which know they are being attended to. For example, an attentive TV knows when it is looked at and could pause the movie if the viewer turns her gaze away. Another example is a multimodal "look-to-talk" application that reacts to spoken commands only when the user is visually attending it (Shell et al. 2004). As the application reacts to the user's natural behavior by explicit commands, it is important to provide enough information of the system state so that the user does not lose control and is able to react to potential problems caused by the inaccuracy of gaze. It has been argued (e.g. by Jacob 1993), that the eye, as a perceptual organ, is best suited for interaction as an additional input. It is thus unlikely that systems based solely on gaze input would attract wider audiences. However, attentive applications that incorporate eye input into the interface in a natural way, have a lot of potential for mainstream applications that may help able-bodied and disabled users alike. For a review and more information about attentive applications, see Rähkä et al. (2011) or Istance and Hyrskykari (2012).

computer interaction is to move beyond such purely descriptive analyses of a small set of specific eye movement characteristics toward developing holistic computational models of a user's visual behavior. These models typically rely on computational methods from machine learning and pattern recognition (Kandemir and Kaski 2012). The key goal of these efforts is to gain a better understanding of and to be able to perform automatic predictions about user behavior. For example, Bulling et al. demonstrated for the first time that a variety of visual and non-visual human activities, such as reading (Bulling et al. 2008a, 2012b) or common office activities (Bulling et al. 2009c, 2011b), could be spotted and recognized automatically by analyzing features based solely on eye movement patterns— independent of any information on gaze.

As evidenced by research in experimental psychology, visual behavior is closely linked to a number of cognitive processes of visual perception (Rayner 1995). In the first study of its kind, Bulling et al. (2011a, b) demonstrated that they could automatically recognise visual memory recall from eye movements by predicting whether people were looking at familiar or unfamiliar pictures. Using a support vector machine classifier and person-independent classifier training they achieved a top recognition performance of 84.3 %. In another study, Tesselndorf et al. (2011) showed that high cognitive load during concentrated work could be recognized from visual behavior with up to 86 % accuracy. Finally, Bednarik et al. (2012) investigated automatic detection of intention from eye movements. However, Greene et al. (2012) were not able to automatically recognize the task that elicited specific visual behaviors using linear classifiers.

- (4) *Passive eye monitoring* is useful for diagnostic applications in which the user's visual behavior is only recorded and stored for later offline processing and analysis with no immediate reaction or effect on the user's interaction with the world (Duchowski 2002). While passive eye monitoring has traditionally been conducted in laboratory settings a current trend is to move out from the laboratory and to study people in their natural, everyday settings. For example, Bulling et al. (2013) proposed and implemented passive long-term eye movement monitoring as a means for computing systems to better understand the situation of the user. Their system allowed to automatically detect high-level behavioral cues, such as being socially or physically active, being inside or outside a building or doing concentrated work. This information could, for example, be used for automatic annotation and filtering in life logging applications. More information of passive eye monitoring and its applications can be found in Hammoud (2008).

Conclusion and Future Directions

Eye tracking is no longer a niche technology used by specialized research laboratories or a few select user groups but actively exploited in a wide variety of disciplines and application areas. When choosing an eye tracking system, one should pay attention to the hardware's gaze tracking features as well as the accompanying software and additional accessories. Many eye tracking manufacturers provide different models targeted at different purposes. The systems may use the same basic technical principles of operation, but what makes a certain system suitable for a specific purpose are the applications (software) that utilize the raw eye data, e.g. software for recording and analyzing the gaze path, or assistive software that allow the eye to be used as an substitute for the mouse.

Issues to consider from the technical part that affect the suitability of the system for a specific purpose include: spatial and temporal resolution (accuracy), camera angle, freedom of head movements, tolerance to ambient light, tolerance to eye glasses and contact lenses, possibility to track only one or two eyes.

As shown above, video-based eye tracking, especially if implemented as a remote tracker, provides a fairly comfortable non-invasive (contact-free) option for the users. Systems that combine the video with infrared (i.e. track both the pupil and the IR corneal reflection) also provide reasonable freedom of head movement without sacrificing the accuracy too much. However, those systems, especially IR-PCR, are very sensitive to ambient light and changes in the light levels and only provide limited temporal accuracy and recording time. EOG-based eye trackers are not sensitive to lighting conditions. The downside is that EOG can be considered invasive and may be seen as impractical for everyday use, because it require electrodes to be placed around the eye to measure the skin's electrical potential differences. Since EOG is based on the changes in the electrical potential, it can also track all types of eye movements and blinks; this is an option for those for whom VOG-based calibration fails. EOG also continues tracking eye movements even if the user squints or closes the eyes for example during laughing.

There are also differences in the data produced by each of the trackers. Since an EOG-based system provides information on relative eye movements, it is especially useful in situations where only changes in the gaze direction are required (e.g. gaze gestures, navigation and steering tasks, or research on saccades and smooth pursuit). However, VOG based systems may work better if an exact point of gaze is important (e.g. point-and-select tasks).

For some tasks, a combination of EOG and VOG might provide the best results. Apart from a few exceptions (e.g. Du et al. 2012) their combined use has not been applied much. We believe there might be high potential in using a method that combines the best features of each technology, especially for passive eye monitoring and clinical studies conducted in challenging outdoor environments.

Depending on the context and the target environment, one should also consider issues such as the portability, support for wireless use, battery life and modularity of the tracker. The eye tracking device (camera) can be embedded into the edge of the

computer monitor or be shipped as a separate unit which can be attached to any laptop or other device, or it can be head-worn. Some manufacturers also sell eye tracking modules and tailored solutions that can be integrated into the customer's devices.

From the human factors point of view, the system's invasiveness, ease of use, setup time and available customer support are important issues. For a disabled person, an eye control system is a way of communicating and interacting with the world and may be used extensively in varying conditions. Thus, reliability, robustness, safety, and mounting issues must be carefully taken into account, in addition to ease of use and general usability. In addition, one should be able to tailor the system to match each user's abilities, needs and challenges induced by disease (Donegan et al. 2009). With increased availability, reliability and usability of the state-of-the-art trackers, the focus on gaze assistive technology research is slowly moving from technical challenges toward the human point of view, presenting a need to also study user experience (Mele and Federici 2012).

A current trend in both eye tracking research and application development is the move away from the laboratory to more natural mobile settings both indoors and outdoors (Bulling and Gellersen 2010). It is for this reason that there is a high demand for systems that can operate in varying mobile contexts. In addition to improved VOG and EOG based techniques, also novel eye tracking approaches are under investigation. Future eye tracking systems may be based on technology and sensory systems that mimic the biological sensing and eye structure. For example, the so-called "silicon retina" shows high potential for high speed eye tracking that can provide robust measurements also in ambient light conditions (Liu and Delbuck 2010). The pixels in the silicon retina are able to asynchronously respond to relative changes in intensity. This enables fast and robust detection of movement and tracking of object in varying light conditions where traditional video and IR based eye tracking typically fail.

In addition to gaze direction and eye movement patterns, also other eye-related measurements such as the pupil size and even microsaccades can contribute to the interpretation of the user's emotional and cognitive state. Gaze behavior can also be combined with other measurements from the user's face and body, enabling multimodal physiological computing. Gaze-based user modeling may offer a step toward truly intelligent interfaces that are able to facilitate the user in a smart way that complements the user's natural behavior.

Advances in the technology open new areas for eye tracking, widening the scope of gaze-based applications. Current hot topics include all kinds of mobile applications and pervasive systems where the user's visual behavior and attention is tracked and used for eye-based interaction everywhere and at any time, also called pervasive eye tracking and pervasive eye-based human-computer interaction (Bulling et al. 2010, 2012a, b; Zhang et al. 2013; Vidal et al. 2013). Other emerging areas include, for example, automotive industry (drowsiness, attention alarms, safety), attentive navigation and location awareness, information retrieval and enhanced visual search, human-robot interaction, attentive intelligent tutoring systems (e.g. Jokinen and Majoranta 2013; Nakano et al. 2012; Zhang et al. 2012). For people with special needs, mobile eye tracking may give more freedom by

wheelchair control, tele-presence and tele-operation of technology (Wästlund et al. 2010; Alapetite et al. 2012).

Eye tracking is becoming an increasingly interesting option even in traditional computing. Major technology companies and the gaming industry are starting to show growing interest in embedding eye tracking in their future products, such as laptops and tablets (Tobii 2011; Fujitsu 2012). Vision based technologies are already widely used in the gaming field, enabling players to use gestures and full body movement to control the games, and eye tracking is envisioned to be part of future gaming (Larsen 2012). The hype on smart glasses (such as the Google Glass) indicates that it is only a matter of time, when the first eye-controlled consumer product will enter the market. Wider use would mean lower costs. Thus, a breakthrough in one field can give a boost also to other areas of eye tracking.

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