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Methodology report

Jens Alfredson, Staffan Nählinder, Martin Castor

Measuring eye movements in applied psychological research – five different techniques – five different approaches

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Report title

Measuring eye movements in applied psychological research – five different techniques – five different approaches

Abstract (not more than 200 words)

This report briefly describes five eye movement measurement techniques, “GazeTracker”, “EOG”, “Jazz”, “Smart Eye” and “Video based”, with which the authors have experience of data collection in applied military settings. The advantages and disadvantages of the different techniques are discussed and examples of their uses are presented. Also, lessons learned from using these techniques in research are presented.

Keywords

eye movements, psychophysiological measures, EOG, EPOG

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Mätning av ögonrörelser för tillämpad psykologisk forskning – fem olika tekniker – fem olika ansatser

Sammanfattning (högst 200 ord)

Rapporten beskriver översiktligt fem tekniker för mätning av ögonrörelser, ”GazeTracker”, ”EOG”, ”Jazz”, ”Smart Eye”, och ”Videobaserad” som författarna har praktiska erfarenheter av att använda för datainsamling i tillämpade militära miljöer. Teknikernas fördelar respektive nackdelar diskuteras och exempel på deras användning presenteras. Praktiska erfarenheter från datainsamling med teknikerna redovisas också.

Nyckelord

ögonrörelser, psykofysiologisk mätning, EOG, EPOG

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1 Introduction

A pilot flying an aircraft sometimes experiences situations that are difficult to manage due to limitations of mental resources, but the pilot must still be able to handle complex tasks in these stressful situations. Future aircraft systems may include support systems that capable of real-time adaptation to the pilot's current needs and possibilities, i.e. adaptive aiding or adaptive automation. A candidate source of information to provide those systems with real-time data about the pilot's mental state is through the study of the pilot's eyes. The eyes do not only show where the pilot is looking but they also reflect aspects of the pilot's state of mind, such as the current mental workload. Many feel this intuitively feasible, since in our everyday lives we can look people in the eyes and feel that we learn about their "mental state". We can tell if he or she is angry, sad or tired simply by looking at the person's eyes. Measures of eye movements and eye point of gaze can also provide valuable information to a design process of a display or the placing of displays.

This report briefly describes five eye-measuring techniques. Their advantages and disadvantages are discussed and examples of their uses are presented.

1.1 Background

In both civil and military aviation, the level of automation has increased in recent years. The aircraft systems become more and more complex, which increase the demands on the pilots handling the systems. Much of the automation efforts have been aimed at increasing performance of the aircraft. However, the focus has mainly been externally directed towards the performance of subsystems in the aircraft system, and not so much on automation for the purpose of aiding the pilot handling the system. Multi sensor systems effectively scanning the surrounding environment for data have been developed together with advanced computational systems for extracting information. However, current aircraft systems lack an equivalent system for keeping track of what happens inside the cockpit, that is, information about the status of the pilot. With sensors directed towards the pilot an adaptive system might be created that focuses on the current needs and limitations of the pilot, as suggested in Alfredson & Nählinder (2002). Information from several psycho-physiological measures may be incorporated in such a system. For instance, measures of heart-rate and heart-rate variability have been shown to be useful indices of "pilot mental workload" (e. g. Mulder et al., 1985 and Svensson et al., 1997). Many other candidate measurement methods that have been used in the research community are described in the GARTEUR Handbook of mental workload measurement (Castor et al, 2003). Measures of the eye and its activities have successfully been used to assess mental workload (e. g. May et al., 1990 and Svensson et al., 1999). Since flying an aircraft is a visually demanding task, measures of the eye are very relevant to include in a pilot monitoring system.

1.2 Purpose

It is believed that the eyes and eye-movements can tell us some things about the human mind. When looking at a stranger for the first time, it is possible to see whether he or she is frightened, sad, tired etcetera simply by looking at the persons eyes.

In the research field of Mental Workload, measures of eye movements are often used as factors that statistically correlate with the latent concept of Mental Workload. That is, by studying eye movements, scientists believe they can (at least to some degree) predict Mental Workload.

The aim of this report is to highlight some techniques for measuring eye movements and report on some of their characteristics.

2 Theory

A pilot uses both foveal vision and peripheral vision to gather visual information. With the foveal vision, which is about two degrees of visual angle, the pilot can perceive details at a certain point, the eye point of gaze (EPOG). The movements of the eye that maintain fixations are called fixational eye movements. To make the image of constantly moving objects staying in the fovea, pursuit movements are made by the eye. Movements of the eye that are jumping from one point to the other are called saccadic movements. Vestibuloocular eye movements are compensating for the movements of the own head. The optokinetic eye movements are used when a large part of the visual field is rotating. Finally, the vergence or disjunctive eye movements are used, for example, to follow a target that is appearing closer or further away, by moving the eyes in opposite directions of one another.

The time that the eye is not moving, but staying in the same position, is called fixation time and amounts to approximately 90% of the total time (Duchowski, 2003). Fixation times are used to evaluate computer displays or other interfaces. However, it is not always obvious how to interpret the meaning of a long fixation time. For example, important information can make the pilot fixate at the information for a long time, as well as badly displayed and confusing information can lead to long fixations. However, by comparing the fixation times to other data it can sometimes be possible to draw valuable conclusions from the eye movement data.

Because the movements of the eye can follow a moving object, it is possible to follow a motionless image upon the retina, but still perceive the object to be in motion, which is explained from an evolutionary approach by Walls (1962). This allows us to keep an object fixed on the retina, which is necessary to be able to see the details in a moving object. In a cockpit, moving objects can appear in the outside view as well as inside the cockpit. Because of the dynamic nature of some of the displays in a military aircraft, moving objects will be quite frequent in some of the displays.

For a pilot it is not enough to follow an object with his/her gaze and to have good resolution image of that single object. Information has to be searched for. The search time is very much dependent on the number of elements to search (Mocharnuk, 1978).

When searching for a target the pilot uses visual scan patterns and these patterns can carry a lot of information about the interaction between the pilot and displays. Often individual differences appear when scan patterns are registered (Fitts, Jones and Milton, 1950; Dick, 1980; Marshall, 1996). Dick (1980) indicated the existence of a number of mini-scan patterns, when studying approach/landing sequences with a simulated Boeing 737. The mini-scan patterns were not only different between pilots, but also between parts of the sequence of flight. Sometimes the scanning behavior has been showing differences between experts and novices, as for car drivers (Mourant & Rockwell, 1972). Sometimes experts not only have different scan patterns than novices, but also differences in fixation times.

Apart from the foveal vision the pilot can use the peripheral vision to extract visual information. What information is used from the peripheral vision is harder to track than the information from the foveal vision, because it covers all information in the field of view, even if the information is not used.

Eye blink activity is sometimes detected together with recording of other eye movements. It can be used without or together with other eye movement data. Blink rate, blink duration, blink latency, and blink amplitude are examples of eye blink activity. Sometimes changes in pupil diameter or pupil area are recorded and analyzed. The proportion of time that the eyelid obscures more than half of the pupil is sometimes used as a measure of fatigue. This is called “perclose”, i.e. percent eyelid closure (Wierville, 1999).

To know where the pilot is looking, i.e., detecting the pilot’s eye point of gaze, it is not enough to know his/her eye movements. If the head is moving, which it sometimes is on a non motion-restricted pilot, the head movements also influences the eye point of gaze.

It is not all methods that allow as high quality on the eye movement data while measuring eye point of gaze, as when only measuring eye movements. The extra criterion, that the head movements also should be detected can sometimes motivate the collection of more than pure eye movement data. There are several methods that measure eye point of gaze but it should be remembered that the eye point of regard does not have to be the same as the eye point of gaze.

Eye movement data has been used for a long time to try to understand the mental functions among pilots and others. The relationship between eye movements and memory has been studied for a long time, as well as the relationship between eye movements and cognitive models (Stark and Ellis, 1981). The relationship between eye movements and mental workload has also been studied for a while. Eye movements have been shown useful in all of these areas of interest. More recently, the relationship between eye movements and situational awareness has also been studied.

A number of eye movement measures have been used as indicators of mental workload. Eye blink activity has been and is used as an indicator of mental workload. For example, Wilson, Purvis, Skelly, Fullenkamp, and Davis (1987) showed that pilots tend to blink less during moments in which important (visual) information needs to be processed. It has been reported that cognitive processing suppresses eye blinks (Boehm-Davis, Gray, & Schoelles, 2000; Veltman & Gaillard, 1998; Wilson, Fullenkamp, & Davis, 1994), even though some research indicates the opposite (Wood & Hassett, 1983). Used as a stand-alone measure eye blinks are useful, but together with other measures the value of the measure can be further enhanced. For example, it has been shown that the combination of eye blink activity and cardiac measures are sensitive to changes in task demands, and classifying mission segments (Wilson, Badeau & Gawron, 1993; Wilson & Fisher, 1991). Further eye movement measures that has been found related to pilot mental workload are fixation times and scanning behavior (Itoh, Hayashi, Tsukui, & Saito, 1990; May, Kennedy, Williams, Dunlap, & Brannan, 1990; Kennedy, Braun & Massey, 1995; Svensson, et al. 1997).

It has often been pointed out that it is of great importance for a pilot to achieve and maintain high levels of situation awareness (SA). Wilson (1995) expresses that "...there may be settings in which psychophysiological measures can provide information relevant to determining if an operator is or is not aware of certain types of situations and whether or not the operator is actively seeking information", and Byrne (1995) states that psychophysiological measures can "yield viable estimates of essential components of SA".

However, the relationship between eye movements and SA is not obvious and the relationship between eye movement and SA does not necessarily have to go through the concept of mental workload. An example of an attempt to measure SA with eye movement data, for example fixation rate, is a study on chess players' SA (Durso, et al. 1995). In the study five SA methodologies were compared, and one conclusion was that eye movements "seemed to be the most complicated and yielded the fewest insights". But then chess playing is an activity that is very different from flying an aircraft and expert chess players does not have to rely on vision as much as pilots. One difference could very well be that playing chess probably is less focused on Endsley's Level 1 SA (Endsley, 1995) i.e., perception of task relevant elements, than the flying of an aircraft is. Other areas of research might find more clear relationships between eye movements and SA. Smolensky (1993) stated that "Evaluation of eye movements might be used to assess certain contributing constructs to situation awareness (SA)" and "It is suggested that the relationship between eye movements and SA be explored further, with the goal of developing a valid, reliable, and non-intrusive measure of SA". As long as no good method stands clear by which SA can be assessed by use of eye movement data, SA might be best measured by other means.

Traditional cockpit interfaces has been evaluated with eye movement data for a long time. Fitts, Jones and Milton (1950) showed the benefits of recording eye movement data in a cockpit, and explained that "If we know where a pilot is looking we do not necessary know what he is thinking, but we know something of what he is thinking about”. It is hard to find a reason to why this should not be still true, even if the cockpit itself does not look the same now as when that statement was made.

Later both traditional man-machine interfaces and computerized interfaces have been studied, both inside and outside the cockpit. For instance, Goldberg (2000) reviewed eye movement-based evaluation of interface usability, and found that eye movement-based analyses were useful, if the right evaluation criteria were used.

Eye movement measures can be used both in the design of a new system and in the later evaluation of the same system. Thus, the purpose of using eye movement data to evaluate interfaces could both be a concern for a good design of the interfaces, and another concern of ensuring that the interfaces really are good.

3 Techniques

Eye movement data can be used to detect which areas are looked at most frequently and which areas that have got the longest fixations, and thereby detect which the most interesting parts of the cockpit are. Certain instruments or certain parts of a computer display in an aircraft are more important than others. For example, the importance of the attitude director indicator has been indicated by several studies using eye movement data (Fitts, Jones, & Milton, 1950; Harris & Christhilf, 1980; Itoh, Hayashi, Tsukui, & Saito, 1990). When conflicting interests occur during a design process it is important to know the relative importance of different parts of a computer display in order to be able to make the right design decisions.

3.1 Eye movements and eye-point-of-gaze

It is important to distinguish between techniques for measuring eye movements and techniques for measuring eye-point-of-gaze (EPOG). Eye movements may be measured to determine where someone is looking. However, to be able to know where someone is looking, it is not enough to measure the eye's position in relation to the head, but also the head-position at the same time. Only if the absolute orientation of the eye in relation to the surrounding objects are known (e.g. by the combined measurement of head- and eye-movements), the EPOG can be determined. Eye movements could, however, be measured for other purposes than determining the EPOG. Often it is not only interesting to know *where* a person is looking, but also *how* the person is looking. For instance, can eye-movements tell us something about the mental state of an operator, such as the mental workload? For this purpose it is not only interesting to measure the orientation of the eye, but also measures such as, blinks and pupil diameter.

With sophisticated EPOG equipment, batteries of measures become available, for example:

a) Objects of fixation
b) Fixation dwell time
c) The frequency of fixations
d) Inter fixation interval
e) The visual scanning patterns
f) Entropy

Additional visual measures of interest for the research community are:
- Eye blink frequency
- Saccadic eye movement
- Pupil dilation, etc

The EPOG measures contribute to understanding a person's level of SA, since the person's awareness most often is directly dependent on what he or she sees. However, there are some limitations in the usefulness of these measures:

1) The measures rely on visual information, and human awareness is affected by other modalities such as auditory information (for example, cockpit radio communication). Thus, EPOG gives an incomplete picture of the human awareness. The proportions of the components of SA, as stated above, also differ according to contextual demands. This means that the influence of visual perception on SA varies. These changes can not be identified with EPOG measures.

2) A subject can be aware of an event or an object (but only large and familiar objects, such as the sun or the ground) in the field of vision even if it has never been focused or directly tracked.

3) Focusing on or tracking an object does not necessarily demonstrate a high level of awareness. Even if a person looks at an object, the interpretation of how that percept affects awareness, and thereby SA, is not measured. Additionally it is not surprising that a subject is focusing on *something*. A risk is that, a post-

hoc explanation of the visual search pattern will be misleading, and that the analyzer will look for meaning, were there is no meaning to be found.

4) Another limitation, which is a limitation of the implementation of the measures rather than of the measures themselves, is what information should be included or excluded, for example, the question of how long the shortest relevant time to analyze should be. Apart from individual differences, this can vary substantially from time to time. Sometimes only a very short glimpse is enough to make the subject aware of something and sometimes it is not. Only an absolute minimum can be given. What remains is the variable fixation duration.

5) The fifth limitation is time related. SA is dependent on information encompassing current state, past states and future states. Most of the information gained from EPOG measures is related to the current state and only a fraction can be related to past states and future states, and there are difficulties in judging which information that is related to which state. This limitation does not have to be reason enough to exclude EPOG measures as a way to indicate SA in civil aviation. In Endsley (1995), a taxonomy for classifying and describing errors in SA is presented and the result of a study of recent incidents in North American civil aviation shows that the main part of the failures is related to perceptual processes. Failures in perceiving a situation reduce the amount of correct information of the current situation more than they affect the information of future events. This could be used as an argument for the use of EPOG measures within civil aviation, since the information gained from EPOG measures is mainly within the critical field of current state information.

Krasner et al. (1998) elaborates further on conceptual problems with eye movement measurements and their links to situation awareness and cognitive overload. Duchowski (2003) also provides additional light on the conceptual foundations of eye movement measurements.

3.2 System comparison

FOI has a long experience of eye measurements and below in Table 1 five systems/techniques, all of which FOI has experience on using, are compared. The form of the table is based on the table presented in the report from NATO RTO HFM 104 on Operator Functional State Assessment report (Wilson et al, 2003).

	GazeTracker	EOG	JAZZ	Smart Eye	Video based
Measurement principle	Differential corneal reflection and electromagnetic head-tracking	Corneo-retinal electrical potential	IR-pupil tracking	Optical feature recognition	Optical video
Maturity	High	High	Low	Medium	High
Accuracy	High	NA	NA	High	Low-medium
Max range horizontal	Medium. Limited by eye movements	Medium	Medium	High. Limited by head movements	Unlimited for head
Max range vertical	Medium. Limited by eye movements	Medium	Medium	Medium. Limited by head movements	Unlimited for head
Head movements	Yes	No	Yes	Yes	Yes
EPOG	Yes	No	No	Yes	Yes
Time resolution	60 Hz	Optional	1000 Hz	30-60 Hz	Low

Fixation duration	Yes	Yes	Yes	Yes	No
Scan paths	Yes	No	No	Yes	Yes, but very time consuming
Saccade velocity	Yes	No	Yes	No, not implemented	No
Eye blink detection	Yes	Yes	Yes	Yes	Yes
Pupil diameter	Yes	No	No	No, not implemented	No
Eye blink	Yes, optional	Yes, optional	No, not implemented	Yes	Yes
Eye activity (EME)	Yes	Yes	Yes	Yes	Yes
Costs	High	Medium	Medium	High	Low, but high analysis costs
Reliability	Medium	Medium	Medium	Medium	Medium
Intrusiveness	High	Medium	Medium	Low	Low
Type of data	Eye movement and EPOG	Eye movement	Eye movement (Saccades)	Eye movement and EPOG	EPOG
Interference from surroundings	High (Electro-magnetically)	Low (Muscle activity)	Medium (Infra red illumination)	Medium (Illumination and picture background)	Low (Illumination)
Ease of use	Low	Medium	High	Medium	High
Preparation time/calibration time	High	Low	Low	Low. A couple of hour's installation if moved to new setting. Low calibration time.	Low
Analysis time/cost	Medium	Medium	Medium	Medium	High (Proportional to amount of data)

3.3 GazeTracker

The instrument in Figure 1 is the Mooij Holding GazeTracker II. The Applied Science Laboratory Series 4000 Eye Tracker (using a head mounted infra-red source and CCD camera) and Ascension Technology Corporation Flock of Birds (magnetic head tracker) are used as subsystems. The instrument measures, pupil diameter, eye blinks, time, fixation number, duration of fixation, surface number, x-coordinate on surface, y-coordinate on surface, x-coordinate eye position, y-coordinate eye position, z-coordinate eye position. EPOG has the advantage that you actually know where the pilot is looking, since not only the eye movements, but also the head movements are used for determining where the pilot is looking. Knowing where the gaze is provides opportunities on analyzing scan patterns, and fixation frequency. Higher fixation frequency may indicate higher workload (Svensson et al. 1997; Svensson et al. (1999) found that frequencies of shorter fixations times head-up and frequencies of longer fixations times head-down increased with higher information load on a tactical situation display in a military aircraft. One of the advantages of the GazeTracker is that it has high precision in the spatial recording of the fixations.

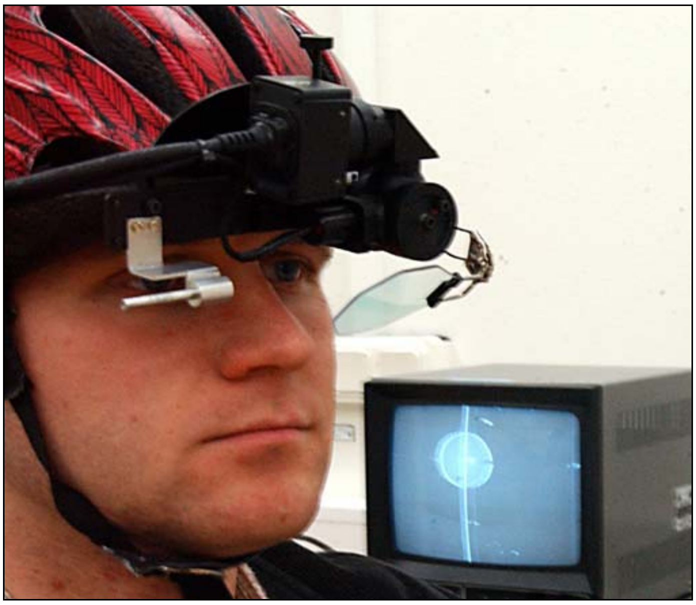

Figure 1. The Mooij Holding GazeTracker II, an Eye-Point-of-Gaze equipment.

Advantages of the GazeTracker are that it has been used a lot in simulator settings, thus several tools and methods have been developed to support the analysis of recorded data.

Disadvantages of the GazeTracker are that it is not very easy to use, it requires a long (approx 30 minutes) calibration session for each subject and that the instrument is sensitive to the electromagnetic environment.

3.3.1 Commercial aviation simulation

In a study of simulated commercial aviation the GazeTracker was used. The experiment is described in a technical report of the project (Alfredson, et al., 1998) and in Alfredson (2001). Six male commercial pilots participated. Three of the participants were recruited from the Swedish Air Force Commercial Pilot School (TFHS) and three participants were a subset of Saab's test pilots for the Saab 2000. The results showed large individual differences in gaze behavior. The participants reported headache when the helmet was too tight.

In a follow-up study GazeTracker was used in a two pilot setting (Björklund, et al., 2003). The objective with this study was to, by combining collected data from the simulator system, Eye-Point-of-Gaze, and pilot communication from thirteen pilots flying in a high-fidelity simulator, describe how and when the cabin crew in a modern glass cockpit simulator discovers mode transitions on the Flight Mode Annunciator (FMA). The results show that the crews in this study follow a great number of strategies to supervise mode transitions. The strategies used differ from the official procedures given by the airline companies, and there are differences between the captain and the first officer as well as between the pilot flying and the pilot not flying. Results also show that there were no differences in visual verification between manually induced and automation induced mode transitions, in contradiction to previous research.

3.4 EOG – Electro-oculogram

Electro-oculogram is a very simple way of measuring eye movement activity by placing electrodes around the eye. These electrodes do not measure the eye directly, but they pick up the electric activity of the muscles controlling the eyeball, see Figure 2. The signal is most easily recorded as AC (Alternating Current), preferably with a slow frequency. There are several ways to analyze the signal. Magnusson (2002) has calculated the area under the EOG-curve (the integral) for a certain time window moving through the data. This value then represents the amount of eye movements occurring in that time window. A high value means that the participant has moved his/her eyes a lot, and a low value that he/she has moved the eyes only very little. Eye-movement-energy (EME) is measured as the integral under the EOG-curve. Thus, if the eyes move a lot the EME increases, and if the eyes are staring it decreases. The EME is a very simple and quick way of analyzing the EOG signal, and even though it includes artifacts it can still be useful for a course measure of overall eye movements.

Figure 2. EOG electrodes used during real flight.

Other ways of interpreting the signal includes guesses of eye-point-of-gaze. This can be done by automatically filtering the EOG signal looking for specific characteristic changes, for instance a movement of the eye from looking down to looking up. Obviously one can only make guesses, since the signal contains artifacts and that the same eye movements not always produce the same changes in EOG. Attempts to extract EPOG information from EOG data with the help of artificial neural networks are have been made and are described in Coughlin (2002). Further, to accurately find eye-point-of-gaze, one needs to measure head movements. Blinks, however, can be extracted quite accurately, at least non-transitional blinks. By using a magnetic coil technique for the head tracking and eye position measured using the electro-oculogram Viveash, Belyavin, Waters, and Stott (1996) showed that eye point of gaze can be detected in operational conditions, with fair accuracy. In that study an accuracy of +-7 degrees was reported for the direction of gaze, over three flight trials.

Figure 3. EOG measured during real flight at TFHS, Ljungbyhed 2003.

The main advantage of using EOG is its simplicity and relative non-intrusiveness. The eye-movement-energy (discussed above), is very easy to calculate. EOG has been measured in simulated as well as in real flight (Magnusson, 2002). EOG is fairly easy to measure; the electrodes can be fitted comfortably in the face and can even be used under a helmet. EME is the easiest measure even though it does have some drawbacks.

The disadvantages include that the EOG signal itself might contain artifacts, such as other facial muscle movements, and as mentioned earlier, the same eye movement does not always produce the same change in the EOG curve.

3.4.1 Sim vs Real flight

In Magnusson (2002) the results of a study conducted at the Swedish Air Force Wing 17 in Blekinge are presented. Here EOG data was collected during simulated and real air to ground missions and exhibit very similar patterns in the simulated and the real missions.

3.4.2 Armored Combat School

EOG data has been collected at the Armored Combat School in Skövde in the tank platoon simulator, Besättningsträningsanläggning stridsvagn 122 (Castor, Nählinder, & Lindström, 2003) (see Figure 4) and during a real company level exercise at Revingehed armor training field.

Figure 4. Measuring EOG at the Armored Combat School in Skövde, 2003.

3.5 Jazz

The JAZZ equipment from Ober Consulting, Poland can be seen in Figure 5. JAZZ is a novel system for measuring eye movements and is currently being evaluated by FOI. It is a small, wearable, non-intrusive device specialized in accurately measuring saccadic eye-movements. A shorter range of saccadic extent may indicate increased mental workload (May et al. 1990). The instrument measures horizontal and vertical eye movements, horizontal and vertical head movements, haemoglobin and oxyhaemoglobin plethysmography, time, ambient light, and also records sound. One of the advantages of the Jazz system is its high sampling rate (1 kHz) for the eye movement recordings.

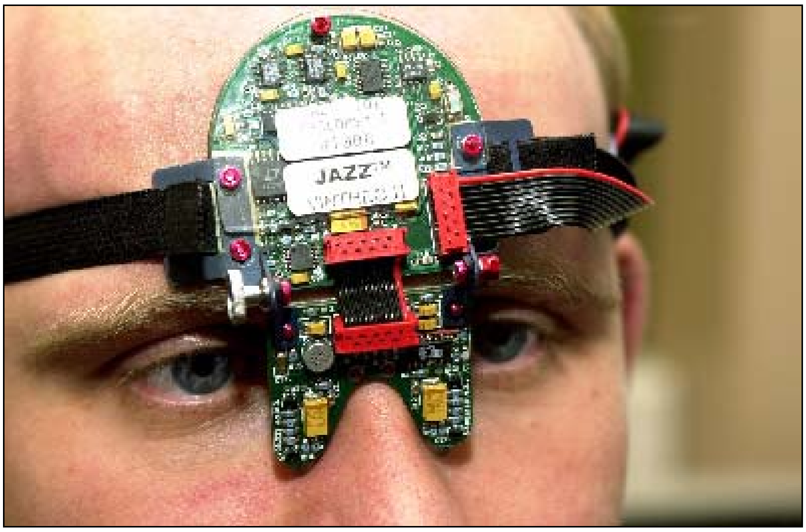

Figure 5. The Jazz system from "Ober Consulting", measures saccadic eye movements.

Advantages of the Jazz system are that it is very easy to use for the experimenter, being self-calibrating, and that it is not very intrusive to the participant. It weighs very little and is easy to wear. Glasses can be worn on top of the equipment.

The largest disadvantage of the Jazz system is that it has not been thoroughly tested, and it is yet suffering from lack of supporting tools for analyzing (some of) its data, and that is does not measure eye-point-of-gaze. In order to record the data, it must always be connected to a computer – it has no storage space in itself.

3.5.1 Fighter controller simulator evaluation

Six participants, five male and one female participated in a study of a simulated version of the software supporting military fighter allocators and fighter controllers in Sweden. Three fighter allocators and three fighter controllers participated. As a reference to the simulations, one of the fighter controllers also conducted two real sessions in an actual control and report centre conducting real missions.

Three of the participants reported that they did not mind using the equipment, since it did not cause any inconvenience to them. One of the participants reported slight tendencies of vertigo and nausea. One reported that the equipment disturbed the field of view, and another reported that the head movements were not fully natural, due to the unnatural measuring situation. One of the participants wore glasses on top of the measuring equipment, without reporting any inconvenience. The study is unpublished.

3.5.2 Combat boat

The Jazz system has been used to quantify differences in saccadic eye movement between maneuvering a real combat boat and maneuvering a combat boat simulator. The data collection was performed at the Amf 4 regiment in Göteborg. The results are currently being analyzed. The participants all agreed that the equipment was neither obstructive nor uncomfortable.

3.6 Smart Eye

The Smart Eye Pro system represent one of the latest developments in eye movement measurement equipment and is a remote eye tracking system (i.e. no equipment on the head of the subject is needed). The system tracks the head and presents the eye point of gaze by the use of pattern recognition algorithms applied on images provided by 2-4 cameras. The cameras are used to track a number of features of the face (e.g., eye corners and nostrils). See figure 6. See Figure 7 for a view from the profile development section where the features of the face and eyes are identified.

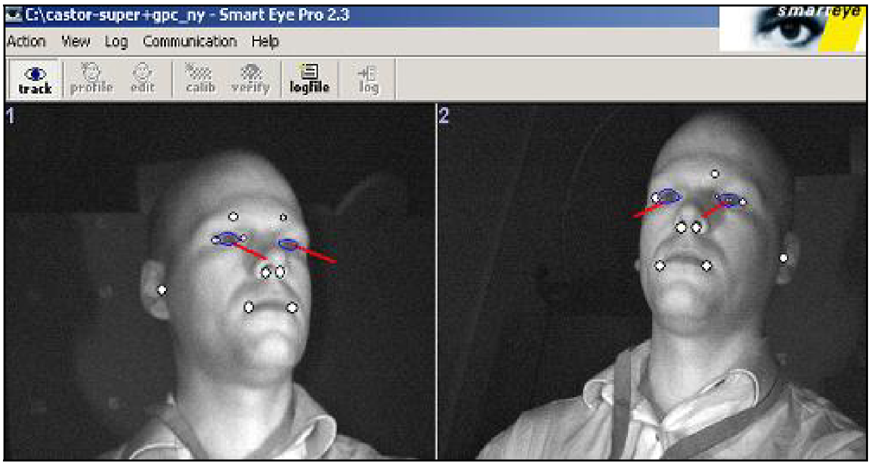

Figure 6. Video feed from two cameras with gaze vectors, the tracked facial features and eyelid opening shown.

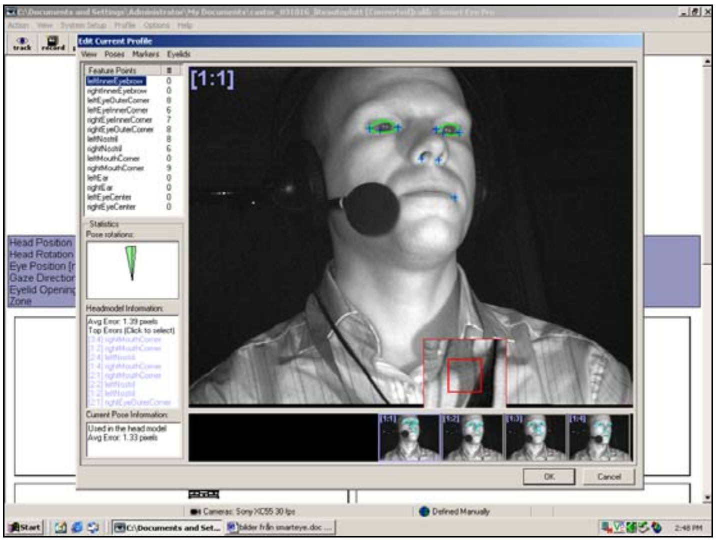

Figure 7. Profile development in the Smart Eye system.

The Smart Eye system was recently purchased by FOI and evaluation is still in progress. Thus, the following information on performance and features of version 3.0 of the Smart Eye Pro system is provided by Smart Eye (Smart Eye, 2004):

- Measurements performed at a high frame rate (currently 30 Hz up to 60 Hz).
- Allows for large head motions (translation and rotation) using two or more cameras.
- Easily adaptable to various measurement situations with flexible camera mount positions.
- Handles occluded cameras using 3D head models.
- Handles high illumination variations (works in complete darkness) using active IR illumination.
- Fast intrinsic and extrinsic camera calibration through a simple checkerboard procedure.
- Pixel density approximately 15 pixels per degree.
- Accuracy of head pose: Rotation 0.5 degrees Translation < 1 mm.
- Accuracy of gaze-vector measurement: 1 degree.

- Eyelid closure is measured in up to 60 discrete steps.
- Consensus and quality values for all measurement values.
- Graphical tools for definition of gaze zones and visualization of gaze tracks.
- Scene camera extension for overlay of users view.
- Statistical tools on demand for post-processing of measurement data.
- Easy to use Active-X interface to other windows applications.

The Smart Eye method uses calibrated stereo, which means that 3D positions can be triangulated directly using knowledge of camera properties (focal distance, lens distortion) and the relative camera positions. In each video-frame the head pose is estimated using a simple and robust method based on tracking of individual facial features and a 3D head model. The initial head model is generic and adapted to the user. The head modeling is initialized using a simple to use step-by-step application, where the user marks landmark features in the face images. Once the system runs in tracking mode, the 3D feature locations are determined from their previous locations and a motion model. If tracking should suddenly be lost, a fast face detection procedure finds the face again, and the tracking is resumed. While the face is being tracked, gaze direction and eyelid positions are determined by combining image edge information with 3D models of the eye and eyelids.

The objects and areas of the setting in which the subject is sitting that are of interest to the researcher is defined in a world file. In the log files from the system these defined areas and objects then appear and statistics can be calculated. The user of the Smart Eye system can also use a World Coordinate System file with which the system is calibrated, in order to provide enhanced performance.

A SceneCam module can also be added to the Smart Eye system. This camera films the environment the subject is observing and present the subjects estimated gaze point on the view from the SceneCam.

3.7 Video based

In the study by Fitts, Jones and Milton (1950) a camera was installed behind and to the side of the pilot, and photographs were made of his eyes by the reflection of a mirror. By doing so, the pilot's normal fixation and movement patterns were not disturbed. A similar approach has been used in Svensson, et al. (1997) by video taping the pilot's eye movements, to be able to record the duration and frequencies of eye fixations head up and dead down. Since the recording techniques has followed the technical evolution over many years between the studies above, for example, the use of a video camera, the prospects of collecting good eye movement data, in an easy and effective way has improved. On the other hand other factors may make it more difficult. A modern cockpit has less traditional instrumentation and more computer screens. The information on a computer screen is often dense and cluttered compared to traditional instrumentation, and the displays are often changing rapidly, especially displays in military aircraft. Not only is the cockpit interfaces changing, but with it also the scanning behavior among the pilots that use the cockpit. Itoh, Hayashi, Tsukui, and Saito (1990) indicated that a modern cockpit with integrated displays could lead to new scanning behavior among civil pilots.

By using a video camera it is possible to record where the subject is looking, if both the head movements and eye movements are recorded. This was done by Schieber, Harms, Berkhont, and Spangler (1997) and Svensson, et al. (1997). By using a video recording, not only is the eye point of gaze possible to extract, but the videotape can also be used to analyze other behavior, like oral communication. If the videotape is analyzed by hand it could very well be very time consuming.

Eye point of gaze has also been recorded in operational aircraft using helmet mounted camera that records both the scene in front of the pilot and his eye movements within the scene. An early example of this is presented in Thomas (1963).

3.7.1 Information complexity in combat aircraft

In a study of information complexity in combat aircraft a video based recording was made (Svensson et al., 1997). Eighteen active fighter pilots participated. The pilots' eye movements were video taped. The pilots were given two main tasks during low level – high speed flight; to fly and to handle tactical information. The durations and frequencies of eye fixations head-up and head-down were recorded manually from the video tape. The pilots showed frequencies of shorter fixation times head-up and the frequencies of longer fixation times head-down increased as a function of the average information load on tactical situation display.

3.7.2 Saab's advanced simulator

In a study using video based recordings Saab's advanced simulator for multi-role military aircraft were used Alfredson (2002). Six male military pilots participated. The scenario consisted of two tasks, with one focusing head-up and one with focus head-down. A video recording was made of the pilot's face recorded by a video camera placed in front of the participant. In this study the researcher played the videotape and conducted a qualitative study on the participant's eye blink behavior. The researcher noted when the participant was looking head-down or head-up. He noted when the participants blinked and looked for personal characteristics among the participants blinking behavior. The pilots showed typical blinking behavior in that they typically blinked during eye movements, during fixation changes between head-down and head-up, or vice versa, and that they blinked more after the runs. This experiment also shows that it is mainly during the changes between head-up/head-down or head-down/head-up that that the blinks occur, rather than between fixations within each of the areas. It is also notable that there seems to be personal characteristics or personal regularities in blinking behavior.

4 Lessons Learned

4.1 General

Even if the mental state of the pilot can be agreed upon as important for an evaluation of cockpit displays, it is not obvious that eye movement data is the best source of information on the mental functions of the pilot. However, information about eye movements should be considered as one important source of information, because eye activity cannot be regarded as being separate from the pilot's mental activities.

Objective measures play an important part when interfaces are evaluated, but the combination of subjective and objective measures can often result in synergies. By comparing pilot comments to dwell times on displays Harris and Christhilf (1980) came to the conclusion that pilots tend to say that they look at a display with their peripheral vision, while what they really meant was that they look at it with a quick glance. An important conclusion is thus that when eye movement data is used together with other data it becomes more valuable than if it is used stand-alone.

4.2 Specific

4.2.1 Gaze Tracker

A quick and easy way to check the accuracy before and after the simulation session is to let the subject look at, say, three pre-defined spots in the recorded surfaces, both before and after the simulation session.

It is important to keep the time for calibration of the EPOG system as short as possible. Otherwise the subject's motivation drops drastically. Each subject is going through the calibration routine every time the EPOG equipment is used. If the calibration time is long, it will be obtrusive to the subject (this has been stated by subjects in the study). Ways to make the calibration time shorter are:

- By giving brief information to the subject, about the purpose of the experiment, at the first approach, and just before the calibration by giving detailed information of the procedure or letting the subject watch an instruction video of what is going to happen during the simulation or to do rehearsal calibrations with the subject beforehand.
- Adhesive tape can be used to mark out the lower left corner of each surface to be recorded, with the corresponding surface number. This will be useful when communicating with the subject, during the calibration, resulting in shorter calibration times.

Do not let the helmet be too loose on the head, since it will then change its position relative to the head during the calibration and/or the simulation. The helmet should not be too tight, as the risk of headache then increases.

Subjects using any kind of glasses may have to be excluded. Since even contact lenses may cause problems, it is our recommendation to only use subjects without glasses or contact lenses.

If possible, use an open simulator. A closed cockpit has got less space than in an open simulator. Metal objects cause a lot of disturbances for a magnetic tracker system, as well as the electro magnetic environment caused by surrounding electronic equipment.

Sometimes the subjects' eyelid and/or eyelash are partly covering the pupil. This is a problem, as it significantly affects the accuracy of the recorded eye data. Ways to reduce this problem are:

- By adjusting the angle of the visor the eye camera may picture the eye slightly from above or slightly from below, which may help in some cases.
- It has been experienced that sometimes the subject has a tendency to spontaneously open up his eye more when the actual simulation starts, than it was during the calibration routine. Even if it is too early too speculate if this is a general behavior and the reasons for that behavior, it can be

valuable to know the existence of such behavior for anyone that is going to use a similar procedure.

- Since the simulator cockpit normally is quite dark, the subject's pupil will be enlarged in that environment. The tendency is that the eyelid then covers a larger area of the pupil. To be able to receive reliable data from the eye tracking part of the EPOG equipment an extra light source was installed in the cockpit.
- By asking the subject to force the opening of the eye, an acceptable situation may arise, if no other possibilities have been found to be sufficient. If this is done the risk is also that: 1) the helmet's position relative to the head might be changed, since the forehead tends to move the helmet when the subject is trying to open his eye. 2) Repeated or for a long time, attempt to open the eye may cause fatigue or even headache. 3) Since the activity of trying to open the eye is not a part of the normal pilot task, it may cause distortion of the normal pilot behavior.

The communication between the experimenter and the subject is an important part of the calibration routine. It is therefore of great value if the EPOG equipment is placed within speaking distance of the subject.

There is always a potential risk of losing data as the subject moves the position of the visor. It is good to be aware of this when it happens for several reasons. For example, it is easier to make a correct judgment of what to do about it. The simulation could continue until the end or could be stopped. If it is stopped, a small adjustment of the visor, in combination with a quick check, is a possible way to handle the situation. Another way to handle the situation is to do a new, full calibration. After that calibration the question is whether the simulation should be continued or restarted or if it is best to move on to the next simulation.

A video camera recording the subject's head and face has several advantages:

- The video camera can be used to facilitate synchronization of data. For example, the observer may be asked to read out loud some events, for example the time for the start of EPOG registration.
- The video film may be analyzed afterwards to detect if and at what time the EPOG data were disturbed, for example, by a hand on the visor. In this way it is easy to find the corresponding shift in the recorded EPOG data even if the disturbance did not cause lack of data.
- The recorded video film can be used as a complement to the EPOG equipment, by recording when the subject is looking at the instructor, who normally is not a pre-defined surface.
- The video film may be analyzed in order to receive quantitative data.

As there are several factors to consider when choosing subjects to take part in a study, it is not easy to ensure that the subjects chosen are acceptable, before they have tried the EPOG equipment. For example, they have to have quite open eyes, and a head shape that fits into the helmet without causing headache. It is therefore our recommendation to test each subject in advance, under similar circumstances to the simulation situation, to reduce the risk of ending up with a non-suitable person as a subject.

By placing a larger, virtual, surface behind each surface, a frame is created that may help in deciding whether fixations recorded close to the surface, should be interpreted as belonging to the surface in the top layer.

Some adjustment of data could be made offline by manually linearly adjust the data if there are known reference points used in the collection of data. Such reference points could be areas that you know for sure that the subject has attended.

4.2.2 JAZZ

The Jazz system is fairly easy to apply and to set up. However, it requires a connection to a computer to store data. It is very light-weight, but can still be a bit obtrusive especially if one wants to wear glasses on top of the system. It can be done without problems if one doesn't move around too much but the glasses must be placed a bit further away from the eyes than normal.

Since the system is using sensors in the infrared part of the spectrum to detect eye-movements, the data gets disturbed by aggressive infrared environments, which may limit the use of the system in some contexts. The microphone, that is a part of the system, could be used to synchronize the data from Jazz with other equipment, by making a sound.

4.2.3 EOG

EOG has proven fairly simple to use. It is quite easy to apply the electrodes and get a good signal. The electrodes – even though placed in the face – are usually not obtrusive and participants report that they quite quickly forget about the electrodes. It is important to make sure that helmets and other headwear does not interfere with the electrodes or cables.

If electrodes are placed both over, under and beside the eye both vertical and horizontal eye-movements can be detected.

The cables should be placed carefully as well as the recorder itself. The recorder has successfully been placed in a leg pocket or strapped around the waist. Before deciding where the recorder should be placed it is important to consider several factors: length of cables, movement of the participant, and if there is a need to be able to manipulate anything on the recorder itself, for instance to turn it on.

However, the EOG signal only indirectly measures eye movements. Instead, it measures the activity of the muscles that control the eyeball. Artifacts, such as activation of other muscles, are almost impossible to get rid of. The usefulness of collecting EOG can therefore be debated. However, the simplicity of use and data collection still makes the method attractive.

The analysis requires special software that is not available commercially. A convenient way of analyzing EOG data is to calculate the integral of the signal, as a measure of eye-activity.

4.2.4 Smart Eye

The performance of the Smart Eye system is very much up to the quality of the profile of the current subject. FOI have used the system in a military aviation context with pilots doing many and quick transitions between the head-down displays in the cockpit and a head-up position. The pilots also move closer to and away from the head-down displays which results in a rather large head movement box. Perhaps because of this, the number of poses (which relates to the number of pictures used in the profile development) that is recommended by Smart Eye (i.e., 3-4 poses) does not appear to be applicable in a flight setting. More poses appears to be needed to achieve satisfactory tracking performance from the system.

FOI also needs to do more research on what profile development procedure that should be used. Currently the resolution in the x axis usually is satisfactory, but it is only sometimes correct in the Y axis. There have also been problems when the head of the pilot is "looking up" but when the eyes are looking down. The system has then registered this as a head-up gaze direction.

When the equipment is moved to a new site an installation process that takes a couple of hours is needed. The new environment needs to be measured, the cameras need to be placed in good positions and the World Coordinate System (WCS) file needs to be defined. An important feature of the system is that the cameras can be placed in more or less arbitrary positions, which is crucial in many settings.

In the same way as for the Gazetracker the researcher can add virtual objects that are somewhat larger the real zones and objects when the file described the world are defined. Thus, the researcher can capture gaze point estimations that are along the edge of a display.

Currently the profile development is a manual task that requires some skill on behalf of the researcher but Smart Eye is working on an automatic profile development procedure.

4.2.5 Videobased

To go through a video recording to find out were a subject has been looking is both time consuming and call for some skill. A good tip is not to use too many surfaces in the analyses. For instance, it is fairly easy to se if a pilot is attending the head-up or the head-down instrumentation, it is possible to distinguish between gaze directed to a couple of head-down displays, but it is very difficult to judge which part of a display the pilot is attending. Also, blinks can normally be detected on a video recording.

Video based recording and analyses are a well suited technique to use in “quick and dirty” settings, such as for hypothesis generating in a pilot study. It is easy to use for small data sets, but soon gets very time consuming if long video recordings are to be analyzed.

The transformation from video recording into data files may be facilitated by means of a small computer programming effort. To use a key-board with specific keys representing areas of interest (e.g. head-up and head-down) may then be used simultaneously as the video is watched, resulting in a time stamped list of attended surfaces.

A video recording can be used for both quantitative and qualitative analyses. Also, a video recording can be used as a complement to other techniques, for example, to determine where a person is looking when he or she is looking outside the measuring envelope of another technique.

5 Discussion

By combining eye movement data with other measures the eye movement data can be put into context. The context of a cockpit display is the cockpit and the tasks carried out by the pilot in the cockpit. Since a lot of the information flow from the displays is passing the pilot's eyes, it is of interest where the pilot is looking. By knowing where the pilot is looking it is possible to draw some conclusions about the computer interfaces that the pilot is using, and how to change interfaces, so that they better serve their purposes.

The need to understand mental functions is clear when it comes to understanding what a pilot is interpreting from a display. To be able to adapt the displays to all the needs of a pilot it is necessary not only to understand where the pilot is looking, but also why he/she is looking there. If eye movement data can help building an understanding of the interaction between the pilot and the display, it is interesting to see how far this understanding reaches.

In recent years there has been a rapid development of different types of eye movement equipment and technologies. In the report we have described the equipment currently in use by FOI, but a number of other developers also have products on the market, many of which have appeared the last three years. The area of eye movement measurement thus seems to be charging ahead and many new applications can be expected.

The combination of theoretical knowledge with this rapid technical evolution may create very powerful adaptive systems in the future. Adaptive function allocation has been tested based on operator performance and mission relevant variables (Scallen & Hancock, 2001). Improved route navigation was shown with an adaptive interface compared to a traditional interface (Bennett et al, 2001). Performance enhancements for adaptive aiding during high mental workload have been showed (Wilson, Lambert, and Russell, 2000). The long time goal is to adapt the information presented to the pilot in real-time as an integrated part of a decision support system. Future research hopefully manages to sort out which information is needed for future adaptive aircraft and also what quality of that information that is demanded. In the meantime we have to work with several techniques in parallel, trying to make the best use of the advantages of each of the techniques. Perhaps, in the future, we will see a technique with all the advantages of the techniques reflected in this paper, and with none of the disadvantages. Perhaps that technique, then, will be the one used in a future adaptive aircraft system.

The current limits are set both by the current theoretical understanding of, for example, eye movements and mental concepts, and the practical limitations, as the equipment available at this time. Both these limits are moving forward, so that new knowledge can be reached, but are there also other limits beyond those?

Some limits are more obvious than others are. The fact that not all presentation in a cockpit is visual makes it obvious that eye movement data is not enough to evaluate the human-computer interaction in the cockpit? Or what about the fact that a lot of the mental activities of the pilot can never be detected through the recording of eye movement data. With this kind of large limitations it is easy to understand why eye movement data often is used together with other data.

By combining eye movement data with other data, and making a more complete evaluation of an interface, eye movement data may have greater value to the understanding of the human-computer interaction than the stand-alone use of eye movement data. However, it is not obvious which kind of eye movement data that should be used in combination with other data.

It will be interesting to see which role eye movement data will play, as new display technologies begin to replace and complement the traditional computer display. How does the use of head mounted displays change the situation? Some techniques of recording eye movements will not be easy to combine with head mounted displays. On the other hand perhaps detectors of eye movements incorporated in such a system can create new opportunities to evaluate various kinds of displays in a cockpit. New questions can be raised, like: Will it be fruitful to adjust the displays in real time, using the eye movement data?

If so, whole new perspectives arise. Not only is the enhanced training abilities, that were described earlier possible, but also an evaluation of the displays in the cockpit could be possible, in real time. The presentation on the displays could therefore also be adjusted to where the pilot currently is looking. For example, a display that appears in the peripheral part of the field of view could stop showing detailed information that the pilot can not extract anyway, and instead show salient information on computer screens in the peripheral parts of the field of view, if needed.

With real time monitoring of the eye movements yet other functions will become possible. Since eye movement data has been used to detect mental functions and states of pilots, it would be possible to do this also in real time. A simple feature would be to detect when the eyes are closed a certain time. This information could, for example, be used to decide when to activate automated functions by the system, when the pilot is assumed to be less capable than necessary.

Maybe the eye tracking system could indicate even the mental workload of the pilot. Information about the pilots mental workload could then, if found suitable, be used, to adapt the computer displays to the current situation.

Eye movements and fixations are controlled by external as well as internal processes. External stimuli or cues call our visual attention, and internal mental processes (as our intentions) control our visual search behavior. Accordingly, measures of eye activity reflect and reveal dynamic changes of cognitive processes, which are hard to disclose by means of other techniques.

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