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Wearable eye tracking for mental health monitoring

Mélodie Vidal [a,*], Jayson Turner [a], Andreas Bulling [a,b], Hans Gellersen [a]

[a] Lancaster University, School of Computing and Communications, InfoLab 21, South Drive, Lancaster LA1 4WA, United Kingdom
[b] University of Cambridge, Computer Laboratory, 15 JJ Thomson Avenue, William Gates Building, Cambridge CB3 0FD, United Kingdom

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ABSTRACT

Pervasive healthcare is a promising field of research as small and unobtrusive on-body sensors become available. However, despite considerable advances in the field, current systems are limited in terms of the pathologies they can detect, particularly regarding mental disorders. In this work we propose wearable eye tracking as a new method for mental health monitoring. We provide two reviews: one of the state-of-the-art in wearable eye tracking equipment and a second one of the work in experimental psychology and clinical research on the link between eye movements and cognition. Both reviews show a significant potential of wearable eye tracking for mental health monitoring in daily life settings. This finding calls for further research on unobtrusive sensing equipment and novel algorithms for automated analysis of long-term eye movement data.

1. Introduction

Sensor devices worn on the body permit health monitoring and collection of contextual data in everyday life and are emerging as key enabler for pervasive healthcare systems. While considerable advances have been achieved in wearable sensing and real-time data analysis, current health monitoring systems are limited in terms of the illnesses they can detect. In particular, the onset and evolution of psychological and cognitive disorders – such as Alzheimer's, Parkinson's or multiple sclerosis – are challenging to detect using common sensor modalities. These challenges include portability, real-time data analysis and operating time.

In this paper we propose wearable eye tracking as a novel measurement technique for day-to-day mental health monitoring. Research in experimental psychology and clinical neuroscience has evidenced a strong link between eye movements and mental disorders [1,2]. In the past, eye movement diagnostics have been limited to controlled laboratory settings; the advent of truely wearable eye trackers now promises continuous eye monitoring and analysis [3].

Eventually, such devices may facilitate cognitive tests, by formal carers, or as part of informal care routine at home, thus replacing hospital visits and establishing continuous monitoring of mental disorders.

To lay the foundations for future research on mental health monitoring using wearable eye tracking, this paper presents two reviews: one of the state-of-the-art in wearable eye tracking and another of previous research on the link between eye movements dysfunctions and different mental disorders. Both reviews lead to three key findings. First, wearable eye tracking has an evident potential to contribute to pervasive health monitoring as the eye holds distinct information on mental disorders. Second, saccadic features and smooth pursuit movements are of particular relevance for mental health monitoring. Third, eye tracking in everyday life may also hold the key to advance our understanding of eye movement pathologies, as existing knowledge is limited to insights gained in controlled laboratory settings.

2. Background

2.1. Eye movement types

Eye movements can be classified according to their characteristics [4]. We hereby describe the main classes of eye movements, necessary to get the gist of the following review on the effect of mental disorder on eye movement.

2.1.1. Saccades

The eyes do not remain still when viewing a visual scene. Instead, they have to move constantly to build up a mental "map" from interesting parts of that scene. The main reason for this is that only a small central region of the retina, the fovea, is able to perceive with high acuity. The rapid movement the eyes do simultaneously to change the line of sight is called a saccade (see Fig. 1). The duration of a saccade, typically from 10 ms to 100 ms [5], depends on the angular distance the eyes travel during this

* Corresponding author. Tel.: +44 0 1524 510 368.
E-mail addresses: m.vidal@lancaster.ac.uk (M. Vidal), j.turner@lancaster.ac.uk (J. Turner), andreas.bulling@acm.org (A. Bulling), hwg@comp.lancs.ac.uk (H. Gellersen).

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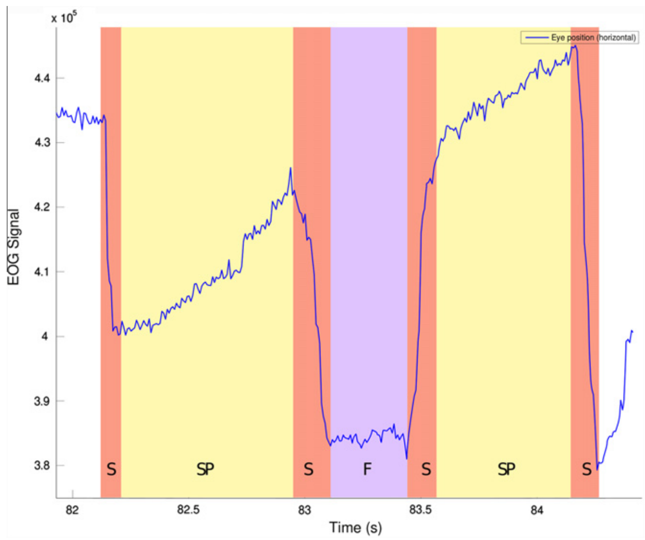

Fig. 1. Example of EOG signal showing saccades (S), smooth pursuit movements (SP), and fixations (F). The graph represents horizontal position of the eyes versus time, with a decrease in the signal representing an eye movement towards the left and an increase representing a movement towards the right.

movement: the so-called saccade amplitude. Their velocity (about 600°/s) is another way of characterising saccades.

2.1.2. Fixations

Fixations (see Fig. 1) are the stationary states of the eyes during which gaze is held upon a specific location in the visual scene. Fixations are usually defined as the time between two saccades.

2.1.3. Smooth pursuit movements

Smooth pursuit eye movements (SPEM) are the voluntarily tracking performed when stabilising gaze on a moving visual target, like a bird or a car. They differ from saccade with their slower velocity and longer duration (see Fig. 1).

2.1.4. Vestibulo-ocular reflex

The vestibulo-ocular reflex (VOR) is a fast eye movement triggered to stabilise gaze on a stationary object during head movements. The VOR compensates for such head movements by moving the eye in the opposite direction. The VOR is difficult to differentiate from smooth pursuits only using eye tracking data, i.e. without any information on head movements.

3. Wearable eye trackers

These different eye movements can be acquired through eye tracking systems. For use in daily life, eye trackers need to be portable and capable of real-time processing. Despite considerable technological advances in recent years, the development of Mobile Eye trackers is still an active topic of research. We present here a review of the most recent wearable eye tracking devices, sorted according to the technology they use.

3.1. Video-based eye tracking

Several commercial eye trackers are currently available, the most popular of which are video-based. Video-based eye trackers make use of infrared components: an infrared LED illuminates the eye and a video camera records images of the eye. The images are then processed to extract the centre of the pupil and the infrared reflection on the cornea, from which gaze position can be calculated. While being highly accurate, this technique obstructs part of the visual field with the LED and the camera. For this reason, recent mobile video eye trackers tend to use a special material that is transparent but reflects infrared light, to give the look-and-feel of glasses and minimise the user's disruption.

Examples of video-based eye trackers include the *Mobile Eye* by Applied Science Laboratories,[1] the *iView X HED* by SensoMotoric Instruments[2] and the *Dikablis* by Ergoneers GmbH[3] (see Fig. 2). These systems are portable but they require additional headgear and laptop for video processing. Recently, Tobii Technology released their *Tobii Glasses*[4] that consist of a set of glasses and a small pocket-sized processing and data storage unit. The system is portable for use in mobile settings but limited to eye movement recording at low frequency and only for up to 1 h. SensoMotoric Instruments are about to release their *SMI GazeWear*[5] that has similar limitations with respect to operating time but will allow to acquire eye movement data from both eyes (so-called binocular tracking).

In parallel to these efforts, several open source projects aim to develop inexpensive hardware and software solutions for video-based eye tracking. In particular the work of Jason Babcock[6] and Positive Science[7] shows how an accurate eye tracking system can be built for a fraction of the cost of a commercial unit. The designs have also been used in recent work investigating the eye movements of infants [6]. The comparison with the first video-based eye trackers developed by researchers [7,8] shows a rapid evolution in design and portability.

Other projects in the community include: *openEyes*,[8] *Opengazer*,[9] and the *ITU Gaze Tracker*.[10] Open source projects like these provide researchers with ability to alter equipment to specific scenarios and quickly prototype ideas without major restrictions.

Video-based eye trackers require considerable computational power. This prevents them from being used over long periods of time on batteries alone. The average operating time is between 2 h and 4 h according to manufacturers and our experience. Mobile Eye trackers need to have low-power consumption to be used in day-long studies.

3.2. Eye tracking using electrooculography

Efforts to extend the operating time of wearable eye tracking systems led researchers to consider more lightweight measurement techniques, such as electrooculography (EOG).

The eye can be modelled as a dipole with its positive pole at the cornea and its negative pole at the retina. Assuming a stable corneo-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. Using two pairs of skin electrodes placed at opposite sides of the eye and an additional reference electrode on the forehead, two signal components, corresponding to two movement components – a horizontal and a vertical – can be identified. If the eye moves from the centre position towards the periphery, the retina approaches one electrode while the cornea approaches the opposing one. This change in dipole orientation causes a change in the electric potential field and thus the measured EOG signal amplitude. By analysing these changes, eye movements can be tracked. EOG typically shows

[1] http://www.asleyetracking.com
[2] http://www.smivision.com
[3] http://www.ergoneers.com
[4] http://www.tobiiglasses.com
[5] http://www.eyetracking-glasses.com
[6] http://www.jasonbabcock.com/eyetracking_hardware.html
[7] http://www.positivescience.com
[8] http://www.thirty-sixthspan.com/openEyes/
[9] http://www.inference.phy.cam.ac.uk/opengazer/
[10] http://www.gazegroup.org/downloads/23-gazetracker

Fig. 2. Mobile Eye (courtesy Applied Science Laboratories), iView X HED (courtesy SensoMotoric Instruments), Tobii Glasses (courtesy Tobii Technology) and SMI GazeWear (courtesy SensoMotoric Instruments).

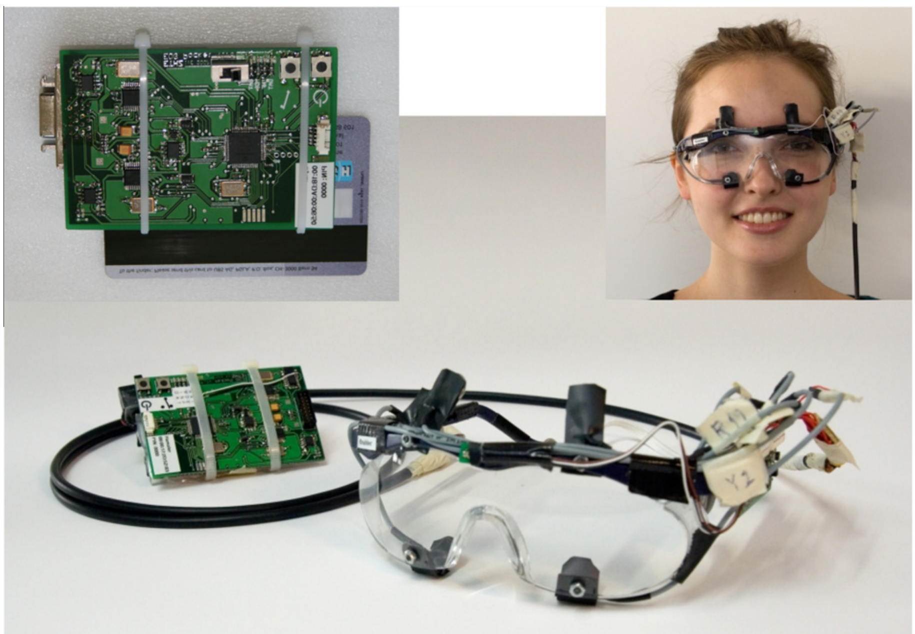

Fig. 3. Wearable EOG goggles [9].

signal amplitudes ranging from 5 μV/degree to 20 μV/degree and an essential frequency content between 0 Hz and 30 Hz [10].

In earlier work Bulling et al. have demonstrated the *Wearable EOG goggles*, a low-power EOG device capable of over 7 h of eye data recording and online eye movement analysis [9]. Data can be sampled at a resolution up to 250 Hz with a 20 bits resolution. Dry electrodes are integrated into a pair of goggles and attached to a pocket-worn device that performs real-time EOG signal processing. It can also store the data on a memory card or transmit it via Bluetooth (see Fig. 3). EOG has also been integrated into headphones using an electrode array [11]. The device could be miniaturised to fit in-ear headphones, however this raises issues with low signal-to-noise ratio and poor separation of the horizontal and vertical eye movement components.

Bulling et al. have shown that their *Wearable EOG goggles* are able to recognise eye gesture with and average accuracy of 87% [9]. In parallel line of work they demonstrated a reading context recognition rate of up to 80.2% [12] and a blink detection performance of up to 99%. They also reported a F1 score, an accuracy measure that considers both the precision and recall of a test, of 0.94 on saccade and fixation detection using EOG [13]. All of these results show that EOG-based wearable eye tracking provides high accuracy for the detection of the main eye movement characteristics.

In an ongoing effort we are developing a new eye monitoring system based on EOG. It continues the work of Bulling et al. in terms of signal processing algorithms, accuracy and performance but is built from off-the-shelf components. Our system consists of a *Mobi8* device from Twente Medical Systems International[11] (TMSI) for EOG signal acquisition and a custom iPhone application for data collection, annotation, processing and storage (see Fig. 4). The *Mobi8* is capable of sampling with a resolution of 24 bits at rates up to 2048 Hz. It records the EOG signal which is transmitted via Bluetooth to the iPhone running a custom Bluetooth driver BTstack.[12] The system uses the Context Recognition Network Toolbox (CRNT) [14] as it contains a reverse engineered version of TMSI's proprietary driver. This allows the system to decode the incoming data stream and store the EOG values in a tabular format. A first pilot study showed that the device allows for 12 h of continuous eye movement monitoring on a single battery charge. This system does not obstruct the field of view, is lightweight, based on off-the-shelf components and customisable through the iPhone interface. The iPhone is a suitable interface for real-time analysis and feedback and to provide the user with a pervasive experience as well as for longitudinal data collection, that is to say for studies recording throughout the whole day. The iPhone also allows real-time transmission of data over TCP/IP.

[11] http://www.tmsi.com/
[12] http://www.code.google.com/p/btstack

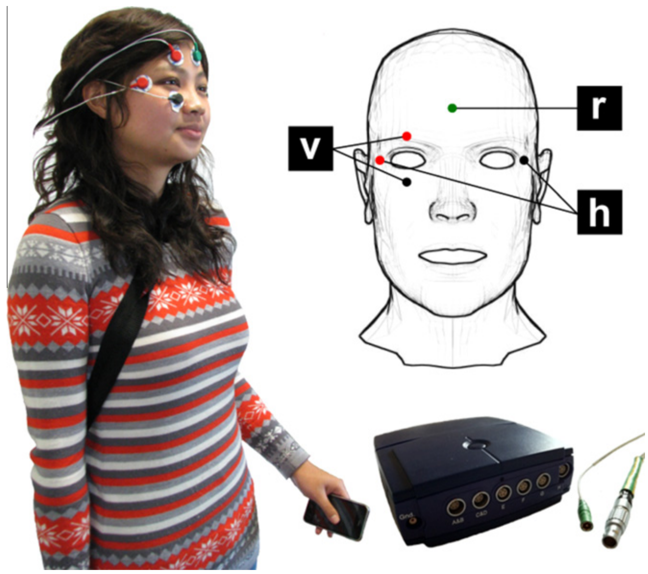

Fig. 4. The system we are developing. The image demonstrates the placement of the EOG electrodes on the head and shows the iPhone and the Mobi8 device carried by the user.

3.3. Discussion

Our review of the state-of-the-art in wearable eye tracking technology shows that commercial systems typically rely on video-based eye tracking. These devices are just now becoming small enough for mobile recordings. They are still not yet suited for daily mental health monitoring. Wearability is a key factor: these settings call for more lightweight systems that provide long recording time, real-time eye movement analysis and customisability to the needs of a particular patient. EOG is a promising alternative to video-based eye tracking as it only requires little processing, can be implemented using on-body sensors and shows high accuracy and performance on standard eye movement recognition tasks.

Our prototype EOG device is an example of the kind of device that would meet the requirements for pervasive daily health monitoring. In addition, common devices such as a mobile phone can be used to enhance the user experience and provide real-time analysis and feedback.

4. Eye movements and mental disorders

Eye motricity is a fragile function that is linked to the central nervous system. For this reason disorders and diseases that affect the cerebral cortex, the brainstem, or the cerebellum have a strong influence on eye movements. The analysis of the resulting eye movements dysfunction can give insights as to which part of the brain is damaged [15] and is a reliable marker for dementia and a number of other brain related diseases [1,16]. There has been extensive work on the effect of mental disorders on eye movements and this section intends to give an overview of the large panel of diseases detectable by analysing eye movements of patients.

4.1. AIDS Dementia Complex

The Acquired Immunodeficiency Syndrome Dementia Complex (AIDS Dementia Complex, or ADC) is a neurological disorder that appears in persons contaminated by AIDS. Nowadays, ADC is detected using brain scans or a lumbar puncture. While brain scans involve the patient to lie in an MRI scanner, lumbar puncture requires an operation with partial anaesthesia and stationary rehabilitation in a hospital for several hours. Sweeney et al. recorded the eye movements of HIV-1 seropositive patients performing smooth pursuit to determine whether dysfunctions of this movement appeared before the patients showed other signs of ADC [17]. They showed that smooth pursuit impairments are a good early indicator for the apparition of ADC in HIV-1 infected patients and may increase with the progression of ADC. Detecting eye movement abnormalities may not only be a less invasive way to detect the early apparition of ADC [18] but would also allow for a day-to-day monitoring of its progression.

4.2. Alzheimer's disease

Progressive neurological diseases, such as Alzheimer's, Parkinson's, Huntington's and Wilson's diseases, are known to impair eye movements [19,20]. As the specificity of eye movement impairments can help clinicians to localise lesions, it has been a useful tool for them to assess a diagnosis or the severity of these diseases [19]. Smooth pursuit dysfunctions have been observed [19] and can quantify motor dysfunction in Alzheimer's disease [21]. In addition, Crawford et al. have shown that Alzheimer's disease impairs inhibitory saccades [1], which are due to neurodegeneration in the frontal and prefrontal lobes [22], that are region of the brain that are suggested to be responsible for inhibition [23]. The anti-saccade task, which requires patients to voluntarily look away from a target, could serve as an early marker for Alzheimer's disease and monitor its progression [22]. If Alzheimer's patients were to be monitored on a daily basis, we could for instance imagine a home device allowing them to test their anti-saccade performance regularly.

4.3. Autism

Autism is a neuro-developmental disorder and trying to detect its signs from early childhood is an active field of research. The earlier the detection is done, the earlier adapted social interaction and games can be applied to the child [24]. Recent studies are focused on detecting autism from the infants' gaze, as children that present autistic syndromes tend to look less at eyes and more at mouths [25], thus show a pattern of eye movements when looking at faces that does not match the one observed in normal children. In a previous study, Rosenhall, Johansson and Gillberg also showed that 55% of the autistic children they tested made hypometric saccades, which means these saccades are too short to reach the target [26]. They also note that saccade velocity is reduced compared to control subjects and that smooth pursuit measurement is unreliable in child population. Since evidence of eye movement dysfunctions in autism has been shown, researchers start to use special lightweight infra-red based trackers and head-mounted trackers to visualise where children look at [2]. Developing mobile, lightweight eye tracking solutions is crucial for this research field that requires further long-term studies in real environment settings [25].

4.4. Dyslexia

Children with dyslexia, which is a learning disability, are found with difficulties to read. Abnormal eye movements have been found in dyslexic children and for some time researchers wondered whether it were impaired eye movements that were causing dyslexia. Nowadays the theory tends to be that it is dyslexia itself that is causing abnormal eye movement patterns in dyslexic children, although this is not widely accepted amongst researchers [27]. It has been shown that children with dyslexia show longer fixations and increased regressions in reading [28] and Biscaldi, Gezeck and Stuhr found a correlation between abnormal saccadic control and reading disabilities when studying 185 persons [27]. Monitoring eye movements on a daily basis or over long periods of time could potentially give researchers new insights on dyslexia.

4.5. Drugs consumption

Drugs consumption, including alcohol, cocaine, heroin but also diverse medicine, influence the central nervous system (CNS) and can thus have an effect on eye movements [29]. The effects of drug consumption on eye movements and attention is a useful study to monitor the effects of medicine on the CNS, but also for car drivers monitoring as the driving process requires high attention and quick reaction times [29]. Studies on alcohol consumption have reported reduction of saccade velocity and accuracy, an increased saccadic latency and smooth pursuit impairments, all of which are dose-related [29,30]. However, Costa and Bauer pointed out that other studies failed reproducing these results or failed to prove a clear relationship between alcohol and cocaine dependent patients and smooth pursuit impairment [31]. In the same study, they showed the effect of Antisocial Personality Disorder (ASPD), more than drug consumption or abuse, on smooth pursuit dysfunctions.

4.6. Schizophrenia

Schizophrenia is a mental disorder characterised, among others, by ASPD. Previous studies have proven that schizophrenia impairs smooth pursuit [32,33] and increases the frequency of saccades, especially catch-up saccades during smooth pursuit [34]. Although eye movement impairments in schizophrenic patients have been studied for more than 35 years, it is still an active research field and researchers aim to create portable, inexpensive devices for further studies [35]. Holzman and Levy chose to use EOG for its portability, despite the fact that they recognise it may be less precise than video-based trackers at the time of writing [36]. They found smooth pursuit impairment not only in schizophrenia but also in psychotic patients. According to them, there are 2 different types of impairment in smooth pursuits, type 1 being pursuits replaced by rapid eye movements or saccades and type 2 being small amplitude rapid movements intruding pursuit, leaving the shape intact but having a cogwheel appearance. They also state that smooth pursuit impairment may qualify as a genetic indicator of the predisposition for schizophrenia. Interestingly, non-smooth pursuit records are also found in the close family of schizophrenic patients and a good number of psychotic patients without schizophrenia are found to have bad SPEM too [36].

4.7. Multiple sclerosis

Multiple sclerosis is an auto-immune disease, meaning that the body's immune system attacks the body itself. It is particularly dominant in western countries and affects the brainstem and the spinal cord, resulting in cognitive and physical impairments. One of its characteristics is that the immune system wrongly recognises the myelin, which is the substance protecting the neurons, as a foreign body and thus damages it. Then, electric signals cannot be appropriately conducted between nerves and neurons. The longest neuron in the brain is the medial longitudinal fasciculus, responsible for the conjugation of movements between both eyes. Because of its length, it has statistically the highest chances for being the first one affected by this disease. When damaged, it results in impairments in eye conjugation, named internuclear ophtalmoplegia [37]. By measuring a difference of velocity in saccades between both eyes, clinical researchers can then potentially make an early pre-diagnosis of multiple sclerosis [38] or classify the patients in a more accurate disease state [19]. Indeed, eye tracking recordings of saccade peak velocities seems to show detection of abnormalities in eye movements in patients earlier than with a simple clinical examination [37–39]. Mastaglia, Black and Collins carried out an electrooculographic study over 108 patients with definite or suspected multiple sclerosis and found that 71% of them presented abnormal smooth pursuit movements and 44% presented abnormal saccade velocities [39].

The daily monitoring of a patient with multiple sclerosis could, among other benefits, be a reliable indicator of the progression of the disease.

4.8. Summary of findings

The above review of work in experimental psychology and clinical research on the link between eye movement and cognitive disorders and illnesses leads us to a number of overall findings. First of all, across a range of mental disorders, we find evidence that eye movement holds distinct information that can contribute to health monitoring and assessment. Characteristic eye movements and markers have been identified for a range of conditions.

Secondly, there is some detail in the eye movement that is of particular relevance for diagnostics, rather than the macro-level scan path of the environment. Smooth pursuit eye movement in particular is one of the first to be impaired when a mental disorder appears. However, while there has been extensive research on saccade and fixation detection algorithms and their evaluation [40–43,13], there is no recognised algorithm for smooth pursuit detection.

A third key observation is that, in spite of the breadth of existing work, understanding of eye movement pathologies and what they indicate is still limited. As existing research is almost exclusively based on experiments in controlled settings, there is hardly any data on eye movements in natural settings. We believe that significant new knowledge can be gained when eye movement is analysed in the context of everyday activities.

5. Conclusion

In this paper we have proposed wearable eye tracking and eye movement analysis for mental health monitoring in everyday environments. We have presented two reviews: one of the state-of-the-art in wearable eye tracking equipment and another of previous research in experimental psychology and clinical neuroscience on the link between eye movement and mental disorders. Both reviews demonstrate the viability of wearable eye tracking for long-term recordings in mobile settings and the distinct potential of eye movement analysis for mental health monitoring. The reviews show that for this application both high accuracy and longitudinal observation are particularly important and that EOG has advantages over video-based approaches in that respect. The reviews also documents that numerous mental illnesses affect different types of eye movements in very specific ways. This calls for the development of new algorithms to robustly discriminate all types of eye movements. Amongst these, smooth pursuit is of particular relevance but has not yet been addressed in existing work on automated eye movement analysis.

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