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ABSTRACT

We present a working paper on integrating eye tracking with mixed and augmented reality for the benefit of low vision aids. We outline the current state of the art and relevant research and point to further research and development required in order to adapt to individual user, environment, and current task. We outline key technical challenges and possible solutions including calibration, dealing with variant eye data quality, measuring and adapting image processing to low vision within current technical limitations, and outline an experimental approach to designing data-driven solutions using machine learning and artificial intelligence.

CCS CONCEPTS

• **Human-centered computing → Accessibility technologies**; **Mixed / augmented reality**.

KEYWORDS

vision loss, eye tracking, virtual reality, mixed reality, vision aids

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1 INTRODUCTION

1.1 Smart Glasses

Digital glasses are a further development of Virtual Reality (VR) and mixed reality (XR) glasses. In this position paper we start to explore gaze interactive applications for people with low vision (LV). We envisage a rapid spread in demand for such services as eye tracking enabled digital glasses reach the consumer market.

Current head-mounted display (HMD) technologies vary in their relationship to the user's eyes, available field of view, illumination, resolution, colour, stereopsis, effect on head motion, and user interface [Ehrlich et al. 2017a]. Scarfe and Glennerster [Scarfe and Glennerster 2019] categorise HMDs into three classes: Virtual Reality (VR), in which all content is virtual; Merged Reality (MR), in which all content is computer generated, but the scene is a combination content rendered based on video of the immediate environment and virtual content; and Augmented Reality (AR), where the viewer sees a combination of virtual content and a direct view of the surround.

HMDs provide accurate and realistic three dimensional vision only insofar as they accurately model the eye and visual system, taking into account perception and limited attentional resources. In the case of LV, processing the image in a helpful way according to the user's particular loss requires a detailed and individualised internal model of the user's visual field. HMDs have been designed with limited variations of the normal healthy eye in mind, whereas the LV population of users are far more variant.

1.2 Low vision

1.2.1 Prevalence and definitions. Most cases of LV are associated with ageing and the number of people affected are set to rise with ageing populations, with those over 50yrs accounting for 80% of those with moderate and severe vision impairment, and 74% of those with mild vision impairment globally. Many kinds of LV are not treatable.

1.2.2 Central and peripheral vision loss. One quarter of patients seeking low-vision services in the USA have primarily peripheral vision loss (PVL) or combined PVL and central vision loss (CVL) which is not adequately addressed by existing devices [Ehrlich et al. 2017a]. After the onset of a visual impairment, some activities of daily living (ADL) require training or change of routines, while others can only be performed with assistance from others. With major impact on ADL and a person's social life, a visual impairment may cause reduction in quality of life and mental well-being.

1.2.3 Effects on quality of life. PVL has long been understood to have a major effect on basic daily activities, including navigation [Turano et al. 2005] mobility [Ehrlich et al. 2017b], and driving [Wolfe et al. 2017] and may result in increased risk of falls [Dhital et al. 2010]. Existing devices for PVL have been reported to reduce visual acuity or cause image jump, which makes using them uncomfortable, leading users to reject these devices [Apfelbaum and Peli 2015]. Some newer HMDs allow patients to view a 'minified' or zoomed-out image in the periphery while maintaining normal central vision, but systematic testing of various information display strategies according to type of vision loss is lacking. CVL can cause problems with reading, face recognition, lip reading and following conversations, and inability to use many of the interfaces of everyday life from bank machines, phones, online interfaces, form filling, map reading, and more.

2 CURRENT AND EMERGING STATE OF THE ART

Digital glasses that provide magnification and contrast enhancement for the visually impaired have been available for more than 10 years. These assistive devices are connected to a battery pack or mobile phone. Studies have documented the benefit of the glasses. Unfortunately, they are bulky and expensive, and only a few people with visual impairment use these aids.

In everyday life, the visual field is constantly in motion, and the location of information we need to pay attention to is typically first viewed peripherally to plan a saccade, and then fixated as required, depending on the task at hand. Displays within displays, or displays in the periphery of vision, may provide a way to have a minified version of the scene and a magnified or normally represented view of closer detail available concurrently. However, this solution does not provide the cues to saccade to a particular location that peripheral vision would normally provide. The precise mapping and updating of the location of objects in relation to ourselves, which is preserved in the brain right through higher levels of visual processing, is disrupted by such a set up and makes it extremely mentally loading and difficult to adapt to.

2.1 The need for individualised visual aids

A major constraint in existing vision aids is that they do not allow for sufficient individualisation of image processing methods applied, nor do they take account of the current direction of gaze in responding to a patient's functioning vision as the eye moves. Researchers have repeatedly called for rehabilitation approaches tailored to the unique needs of patient populations [Ehrlich et al. 2017a,b], and that solutions for extensive PVL is an enduring problem. A way to display information within the remaining vision is only possible if real-time gaze position and area of loss is precisely mapped and updated in use, and the demands on attention as a limited resource reasonably limited.

2.2 Eye movement based training in low vision

Low-vision rehabilitation (LVR) methods based on HMDs include the use of sports and performance vision training for LV [Laby 2018], reported to improve hand-eye coordination, object tracking, and visual concentration. Backus et al [Backus et al. 2018] describe the use of virtual reality to treat problems with stereoscopic vision. Fortenbacher et al [Fortenbacher et al. 2018] describe VR based exercises as highly motivating and patient engaging, citing optometric pioneers in proposing that vision therapy must reflect an understanding of the visual process beyond the mechanics of vision and take into account the principles of neuroscience, perceptual learning (PL), and neuroplasticity.

Ivanov et al [Ivanov et al. 2016] describe 'Exploratory Saccadic Training' in retinitis pigmentosa (RP) patients with severe PVL, where fewer horizontal saccades are implicated in reduced mobility. Training the patient's eye movements was found to reduce response time and increase preferred walking speed. The effects persisted over time - retest six weeks later confirmed that on average, RP patients' eye movements were similar to those of normally sighted people while walking. PVL is associated with a habitually confined range of saccades [Titchener et al. 2019], and eye movements may offer a means of measuring adaption to vision loss over time. Yoshida et al [Yoshida et al. 2014] demonstrate increased activity in the frontal eye fields (FEFs) in all patients following eye movement training, and in the parietal eye fields (PEFs) in those patients who showed the greatest improvement in reading capability following training.

Rehabilitation approaches have increasingly called for the inclusion of fixation stability as an important outcome measure [Pijnacker et al. 2011; Seiple et al. 2011; Tarita-Nistor et al. 2017]. Mandelcorn et al [Mandelcorn et al. 2013] reviews literature showing a poor correlation between anatomic changes and functional improvement in macular disease, and a strong correlation between fixation stability and visual acuity, with implications for rehabilitation and treatment. Sieple et al[Seiple et al. 2011] compared various rehabilitation approaches in AMD and found that only eye movement training improved reading speed. Tarita-Nistor et al [Tarita-Nistor et al. 2014] report an improvement in reading speed, visual acuity, and fixation stability following PL training. No currently available vision aids leverage such research findings.

Various authors have tested the efficacy of VR-based therapeutic games, some incorporating eye tracking, to support adaption to vision loss [Donmez and Cagiltay 2019; Fortenbacher et al. 2018;

Kasprowski et al. 2016], often based on principals of PL and vision therapy. They point to the need to take into account the differences between CVL and PVL, and the need to develop at-home training paradigms [Maniglia et al. 2017]. Large scale clinical research such as those from Scheiman et al [Scheiman et al. 2011, 2008] found vision therapy and PL to be the most effective treatment of a range of issues including convergence insufficiency, accommodation dysfunction and other binocular dysfunction.

Saccade training in patients with retinitis pigmentosa (RP) led to increased walking speed and a range of saccade amplitudes similar to healthy controls [Ivanov et al. 2016], increased fixational stability of a newly acquired preferred retinal location [Barraza-Bernal et al. 2017], and games to increase visual search and recognition tasks in children with LV [Kasprowski et al. 2016] were effective. Extending training to everyday, at home therapies should be a primary goal of vision aids in the future, as this could facilitate users and clinicians gaining insight into real world, every day functioning and allow systems to adapt to use.

In reviewing the evidence for plasticity in LV patients and the implications for rehabilitation, Legge and Chung [Legge and Chung 2016] report that neural visual pathways are capable of adjusting to onset of LV, or to improved vision following surgery, even in old age. Eye tracking based measures now supplement traditional clinical measures of acuity, contrast sensitivity, and field status in tracking adaption over time [Pijnacker et al. 2011; Rosengarth et al. 2013; Seiple et al. 2011; Tarita-Nistor et al. 2014].

3 LEVERAGING EYE MOVEMENTS IN VISUAL AIDS

In taking advantage of mixed and augmented reality HMDs, visual aid applications could augment every environment to make it more accessible, for example, highlight the edges of steps and handrails in badly lit stairwells. They could take advantage of algorithms for real-time facial- and object recognition which are now becoming standard on mobile phones, unobtrusively identifying people or objects the user encounters and reporting it to the user in their preferred mode. In 2017, Microsoft launched an application, "Seeing AI", for the visually impaired, which uses the built-in camera of a smart phone to recognise friends, interpret scenes, scan bar codes and read text aloud. All of these systems can be adapted for use on glasses and controlled by gaze. The critical decider of what methods successfully enhance visual function will be their ability to comfortably scaffold visual perception, working with variance in individual retinas and with the cognitive and perceptual processes of individual brains.

We propose a research approach that combines basic research into eye movements in low vision, particularly as they relate to functional vision in everyday tasks, with mixed reality and a machine learning-based approach to individualisation and prediction of optimal processing for the remaining field of view. We outline a user-driven approach to interface design that considers both the social aspects of enabling technology, and mental load of current visual aids in low vision users. Though vision aids that use head-mounted displays with some basic form of integrated eye tracking are currently under patent review, we are yet to see such systems come to market.

3.1 Activity recognition

Eye movements and other sensor and image information in AR HMDs can provide data for recognition of the users activity, such as when the user is reading, walking, or moving the hands in the field of view. The glasses can then automatically switch to the visual aid setting that the user prefers for this particular activity. Pupil dilation and fixation duration may show if the user is spending an unusual amount of cognitive resources on an activity. Eye movements also contain information on the person's alertness, and size of successive saccades contains information about whether the person is taking in a scene, locating obstacles while manoeuvring through it such as when walking, or exploring detail for higher order processing, or whether there is an intention to act, such as when reaching to grasp an object. Eye movements are closely related to reaching and grasping movements of the hand and arm, and specific patterns of eye movements towards an object can predict intention to interact with it.

Studies of eye movements in real-world tasks were first performed when mobile 'real world' eye-tracking became reliable in the 1990s and have been replicated, refined, and reinterpreted many times as models of vision and perception have evolved [Land et al. 1999; Pelz and Canosa 2001; Sullivan et al. 2021]. The temporal patterns of gaze behaviour and action and the location of gaze to prioritised information related to upcoming subtasks provide an empirical basis from which to consider what to prioritise for image processing in order to provide scaffold visual and augment visual resources in vision loss.

3.2 Technical Challenges

A number of areas of technical innovation are implied, including calibrating users with low vision, dealing with eye data quality limitations, event detection in the presence of fixation instability, and human perception and sensitivity to lag, processing requirements, and portability. Attempting to adjust certain areas of the image based on inaccuracy in the estimated direction of gaze or in the estimated retinal disparity, as would be the case with either low data quality or lag, is known to cause a visual-vestibular conflict which can cause motion sickness and dizziness. Accurate eye tracking and careful image processing methods are essential to supporting low vision safely and comfortably.

In cases where eye movements are at the root of the vision loss such as in nystagmus or any binocular dysfunction; the beat and extent of eye movement is often task or position dependent, or dependent on the direction of preceding eye movement. It cannot be modelled as a constant repeating pattern of image displacement, but it can be predicted, and measured in close to real time with an eye tracker. Tracking eye movements and adjusting the image in real time is the only possible solution for stabilising the image on the retina in cases where training fails to adequately improve eye movement control, and such approaches could conceivably restore more normal vision in those cases, given low enough system delay.

3.3 Outlook for future vision aids

Progress in the development of HMD based vision aids has been relatively slow. Methods such as image-remapping strategies were first explored in the laboratory in the 1980s [Loshin and Juday

1989; Peli and Peli 1984] but have not yet made it into commercial systems. Although the past rate of progress has been limited by the cost of HMDs and processing power required, the technology is now sufficiently mature to deliver.

The bulkiness of many current systems makes them uncomfortable to wear for long periods and difficult to walk safely with - they obscure most of the face, and capture attention from others in social contexts which makes the user stand out when they may not want to. Hardware development for mainstream VR, AR and XR is, on the other hand, developing rapidly. There are now a small number of commercially available HMDs for the VR/AR market with eye tracking (e.i. FOVE, VARJO, Microsoft Hololens 2, and 7Invensun) and there are some examples of eye tracking equipment which may be attached or integrated into VR/AR HMDs.

Integrating HMDs with eye tracking as a means to extend the number of people who can benefit from visual aids is now technically feasible, as can be seen in patents filed. The use of HMDs among patients with vision impairment, if devices deliver on the possibilities, is likely to increase dramatically and the results are likely to extend beyond low vision users to improve vision in a variety of usage scenarios.

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