

Visual Search in People with Macular Degeneration: A Virtual Reality Eye-Tracking Study

Theofilos Kempapidis, Ifigeneia Mavridou¹, Ellen Seiss², Claire L. Castle³, Daisy Bradwell⁴, Filip Panchevski⁴, Sophia Cox⁴, Renata S.M. Gomes⁵

¹ TSHD, Tilburg University, Tilburg, Netherlands

² ISG University of Bournemouth, Bournemouth, United Kingdom

³ Faculty of Arts, Humanities and Cultures, University of Leeds, Leeds, United Kingdom

⁴ Emteq Ltd, Sussex Innovation Centre, Brighton, United Kingdom

⁵ Northern Hub for Veterans and Military Families Research, Northumbria University, Newcastle, United Kingdom

lncs@springer.com

Abstract. This study is the first to explore the usability of a commercial off the shelf (COTS) VR headset for people with macular degeneration (MD) in the context of visual search. Fourteen participants were recruited; 9 fully sighted and 5 with sight loss due to MD. Firstly, a visual grid search task was presented where participants were asked to identify and discriminate virtual objects and shapes. Secondly, affective audio-visual videos were presented in VR to assess participants processing of affective information. The experimental procedure involved both a physical visual acuity Snellen test and a VR Snellen test conducted within a custom virtual environment. Most participants with macular degeneration (MD) reported increased visibility in VR. They were able to discriminate positive affective content and detect objects and shapes appearing at various locations across their entire field of view. Overall performance was linked to the level of visual impairment and whether it affected one or both eyes. Importantly, all participants successfully used the off-the-shelf VR headset. These findings provide preliminary insights into the usability of VR technologies for users with MD.

Keywords: Virtual reality, macular degeneration, eye tracking, grid search, affective videos.

1 Introduction

With over 2 million people in the United Kingdom living with sight loss [1], there is a need for assistive technologies that can improve the quality of life and independence of those living with sight loss. While virtual reality (VR) has increasingly been used as a therapeutic tool for people living with disabilities (i.e., people living with cognitive and mobility impairments, pain management and anxiety disorders), its use for people living with visual impairments (V.I.) is limited and underexplored in research. Anecdotal

evidence of the positive impact that VR may have on users with V.I. has been provided by the Anonymous charity, who has for many years offered its members (all of whom have a severe sight impairment, i.e., are registered blind) opportunities to immerse themselves in a VR environment. Members reported that they could ‘see’ better through the headset and that they thoroughly enjoyed the VR experience.

In order to explore the feasibility of using commercial VR headsets for users with visual impairments, we conducted a small-scale study with individuals affected by macular degeneration (MD). These participants have severely limited central vision and are often excluded from VR research studies. Additionally, this user group may experience symptoms of mental and cognitive impairment, along with mobility challenges [2-4]. Novel VR interventions could potentially alleviate some of these issues.

This study investigates visual search capabilities using commercial VR headsets among individuals with MD. We examined potential changes in affective processing during audio-visual videos, simulating real-life scenarios (e.g., watching TV). Additionally, we measured comfort, stress, and emotional impact when using VR technology in people with MD, comparing the results to a control group to assess overall usability.

1.1 The effects of Macular Degeneration

Eye conditions which result in V.I. may impact on the peripheral low-resolution wide field, causing in tunnel vision, or the central high-resolution fovea, resulting in central-vision loss [5, 6]. Conditions such as Diabetic Retinopathy, Optic Neuropathy or Central Retinal Vein Occlusions are associated with Age Related Macular Degeneration (AMD), whilst Retinitis Pigmentosa or Glaucoma results in reduced peripheral visual field, or tunnel vision [7]. In the UK, AMD, affects around 700,000 people [8] with an estimated 196 million people globally [9]. AMD and Glaucoma are the leading causes of sight loss [10]. With increasing age comes a greater risk of V.I. as a consequence of age-related conditions [11]. AMD is a progressive eye disease associated with the deterioration of the macula (centre of the retina). A central scotoma develops where the density of photoreceptors is highly concentrated and, subsequently, individuals lose their ability to discriminate colours, shapes and fine spatial details involved in activities like reading, driving, object and facial recognition [12]. AMD has a detrimental effect on the photoreceptors in the macula, which are utilised in human visual information processing, a process which begins with the sampling of the retinal image by the photoreceptor mosaic [13]. Since age is a major risk factor for the development of AMD, cases of AMD are expected to rise in the future. According to Pezzullo and colleagues, the number of people living with V.I. in the UK will reach nearly 4 million people by 2050 [14]. Evidence shows that V.I. affects social and work-related aspects of life [15] and has been associated with higher levels of psychological difficulties, including depressive and anxiety disorders [16-18]. For elderly adults, AMD can have a significant negative impact on quality of life [19, 20]. As the elderly population in the UK and other nations grows, the need to understand and address the needs of individuals living

with V.I. becomes increasingly important. The value of utilising and adapting existing technologies in health, social, and welfare support for those living with V.I. is apparent.

1.2 Virtual Reality Studies in people with VI

The development of VR is associated with the rise of personal computers and digital simulations [21]. VR permits the simulation of environments and scenarios in controlled settings [22], whilst permitting the acquisition and visualisation of highly complex data in virtual behavioural observational studies [23]. Three major elements of VR are interaction, 3D graphics and immersion [24], delivered through various technologies including head mounted displays (HMD) with head-tracking systems, headphones (for audio), hand and eye tracking, and manipulation/navigation devices [25]. Lately, commercial VR headsets have become increasingly more accessible and popular, particularly for communication and entertainment purposes. Growing research interest in the use of VR [26] has resulted in numerous applications outside the entertainment sector, especially in healthcare and well-being. For example, VR has been used progressively as a therapeutic tool both within and outside the UK National Health Service (NHS), with clinical populations such as those living with dementia and Parkinson's Disease, and individuals who experience stroke [8, 27]. Since 2019, patients have also had the option to engage with VR-based therapies to overcome phobias and treat post-traumatic stress disorder (PTSD) [28]. However, the therapeutic role of VR in older users with V.I., especially in people with AMD, has not been extensively explored. Wu and colleagues used artificially induced central scotomas in sighted participants to gain insight into people's ability to navigate traffic safely at a virtual roundabout [29]. Authors found that crossing behaviour changed in relation to increasing size of the scotoma, results suggest that visual disruption caused by AMD persists during interaction with VR content (though potentially to varying degrees depending on disease affect). Moshtael et al conducted a study with 23 participants with AMD to test a low vision reading aid of text presented on a head-mounted display [30]. By comparing both reading speed and preference of the smart glasses when reading text printed on paper using a habitual optical reading aid, it was found that participants preferred to read from the glasses rather than from paper and demonstrated improved reading performance using dynamic text presentation. Finally, in a recent case study by Powell and colleagues, a single-user study was performed with a patient with AMD to test the improvement of vision using a commercial off-the-shelf (COTS) VR headset [8]. Results showed improved vision for object, face and colour recognition and, therefore, Powell and colleagues suggest that a simple interface setting which allows for the adjustment of lighting levels within the application, could improve the accessibility of VR for people with very low vision [8]. This case study remains the only study to date which considered a COTS VR Headset focusing on the user's visual acuity [8].

To address this gap, this study attempts to explore the usability of current COTS VR headsets with eye-tracking capabilities by people with MD. Given the value that VR may hold in the elderly care context, it considers the accessibility of VR for users with V.I. and MD, with implications on the ability to meet well-being, therapeutic, and rehabilitative needs with VR technologies. This study is an initial step towards

understanding how VR tools could be utilised for users with V.I. if adaptations to their unique sensory needs are made to enable engagement.

1.3 Study Aims

The prospective benefits that VR technology might have for the user with MD is implicated by visual improvements experienced by BVUK members, who reported “seeing better” using VR. As people with MD mainly rely on low resolution peripheral vision to assess everyday visual content, we decided to explore the under-studied use of VR environments to aid in the process. Current eye-tracking technologies allow us to see the direction of the pupil and accurately measure gaze-related overt attention. Similarly with eye-tracking embedded within VR headsets, it offers a method of establishing how people with MD might interact with VR content. Therefore, we set to further investigate the feasibility of utilising and interacting effectively with COTS VR for people with MD using head-movement and eye tracking. We summarise our findings and observations to inform future VR research on the efficiency of such measures. In this study, we compared visual acuity scores in and outside VR (Snellen tests), as well as the tests performance in a visual search VR task and the affective processing of audio-visual videos in VR. For the latter two tasks, we compared people with MD and a sighted control group.

We aimed to answer the following questions:

- 1) Can COTS VR technologies be used by users with MD?
- 2) Can eye tracking technologies be used and calibrated to users with MD?
- 3) Can people with MD recognize simple virtual objects and shapes in VR?
- 4) Do people with MD process the affective information of audio-visual videos in VR similarly to controls?

2 Materials and Methods

2.1 Participants

Participants were aged between 18-90 years old and declared they do not suffer from frequent motion sickness, nausea, or dizziness. For the MD group, participants had to have a medical diagnosis of macular degeneration or age-related macular degeneration (for AMD Group). For the sighted control group (CG), participants had to have normal or corrected-to-normal vision (i.e., did or did not require glasses to view their mobile screen when placed in front of the eyes). Individuals were not able to take part in the study if they had a cardiovascular condition or condition affecting facial movements, such as facial palsy or stroke.

Naturally, it is quite difficult to study and recruit this target group, due to the practical difficulties individuals with MD have navigating space independently. However, access to participants was enabled through Anonymous charity and its membership, allowing the recruitment of a suitable sample of users. Sixteen people in total were recruited for this study either through study advertisements (controls, non-VI) or the

associated charity (AMD group). Two participants had to be excluded due to incomplete data. Hence, the final sample consisted of 14 participants: 9 participants in the CG ($n = 5$ female & $n = 4$ male) ranging from 23 to 40 years ($M = 30$, $SD = 6.09$) and 5 AMD subjects (all male) ranging from 62 to 88 years ($M = 77.20$, $SD = 9.58$). In the MD group, two participants (MD4 and MD5) had macular degeneration in one of their eyes (single-eye MD) (aged 75 and 88 years), forming the AMD 1 subgroup. Three participants (MD1, MD2 and MD3) had macular degeneration affecting both eyes (ages 62, 74 and 87 respectively), making up the AMD2 subgroup. All 14 participants were fluent English speakers.

The study took place at the Anonymous location. The study was reviewed and approved by the Anonymous University Research Ethics Committee (ID: 39592).

2.2 Equipment

VR headset with Eye Tracker. The HTC Vive Pro Eye is a COTS VR headset, comprising built-in eye tracking using the Tobii SRanipal framework, a 110-degree field of view, a combined resolution of 2880×1600 pixels, and a frame refresh rate of 90Hz. The audio system uses built-in on-ear ‘Hi Res Audio Certified’ headphones. The data used to analyse the eye movements were collected with the Tobii Eye Tracker built in the HTC Vive headset. The output data has descriptive attributes regarding the eye movements and location, with the main features being gaze direction, gaze origin, and pupil diameter. The current study focused exclusively on the gaze direction vector, containing 3 separate values representing a vector in 3D space.

Add-on sensors. The EmteqPro MASK replaced the existing frame of the VIVE headset (see above) and was used to record data from multiple biosensors for inferring the underlying emotional states of users. The emteqPRO system comprises various sensors and allows data to be continuously recorded at fixed rates of 1000 Hz. For the purposes of this study, the facial electromyographic (fEMG) sensor data-output was utilised. Facial EMG measures the electrical activity generated by facial muscle contraction during (valenced) affective responses to stimuli [31]. The EMG sensors incorporated in the emteqPRO system are positioned on the zygomaticus, corrugator, frontalis, and orbicularis muscles. The EMG signals, which are acquired from sensors on the surface of the skin, are the result of facial muscle activity and provide insight into the facial expressivity during VR experience [31]. The SuperVision is a 64bit, user-facing Windows 10 compatible application was used to record and preprocess the data, providing synchronized affective readings. To assure synchronization between the eye tracker and the Emteq SDK, UNIX timestamps were used. The frequency rate with which the data was sampled was set at 120Hz.

2.3 Virtual Scenes/Tasks and Custom VR Environments

Three scenes were developed in total, using the Emteq VR SDK, Tobii SRanipal SDK, and Vive SDK. For all scenes, the team implemented two view modes: one for the

participant and one for the experimenter which featured a visual element controlled by the eye-gaze pointer, thus making it easy for the experimenter to monitor the eye movements on the participants in real-time.

VR Visual Acuity Snellen Test. This scene had a static visual acuity Snellen test at a distance of 6 meters from the user's eyes. The test was positioned on a virtual wall and was presented in the same way for all participants. No other objects, shadows or distracting elements were added (see Figure 3).

Virtual Environment displaying affective videos. This scene contained a simple video presentation environment featuring a 2D-screen, fixed to the viewpoint of the user, atop a dark grey background. Ten videos in total were presented on this screen; five neutral, three positive, and two negative videos, all with audio. Short breaks, each lasting 15 seconds were added between the videos to allow the participants time to verbally self-rate their affective state in terms of their valence levels (ranging from 1- negative, to 9- positive) and arousal levels (ranging from 1- low, to 9- high) after each video. Each video had a 30-second duration, and the video sequence presented was as follows: neutral, positive, neutral, negative, neutral, positive, neutral, negative, neutral, positive.

Visual Search Task. This scene featured a custom-made grid search task. A customisable grid was designed which was automatically generated upon a set number of rows and columns could be selected. The grid featured numbers and letters indicate the columns (x-axis) and rows (y-axis) respectively. The grid was designed to spread throughout the whole field of view, with its four corners being partially beyond the observable range (see green outline in Figure 1). For this experiment a seven-by-seven grid was chosen, consisting of 49 squares in which an object randomly spawned (see Figure 1). The grid was purposefully fixed to the view of view the VR-headset wearer and not affected by their head rotations, effectively spreading the grid to the full field of view of the user with all grid spaces visible. For each grid location, an object spawning algorithm was developed, in which the duration of apparition of the object and the break duration between those was also customisable. Two 3D objects were selected for the study, a cube, and a ball. The colour of the objects was randomly allocated from a selection of four colours: yellow, red, blue, and green. Virtual objects (time, shape, and colour), keyboard strokes and eye tracking (position, meeting the object) were annotated in the data using UNIX timestamps (for an example see Figure 1). Eye tracking, event annotations and the emteqPRO sensor data were recorded simultaneously throughout the experiment.

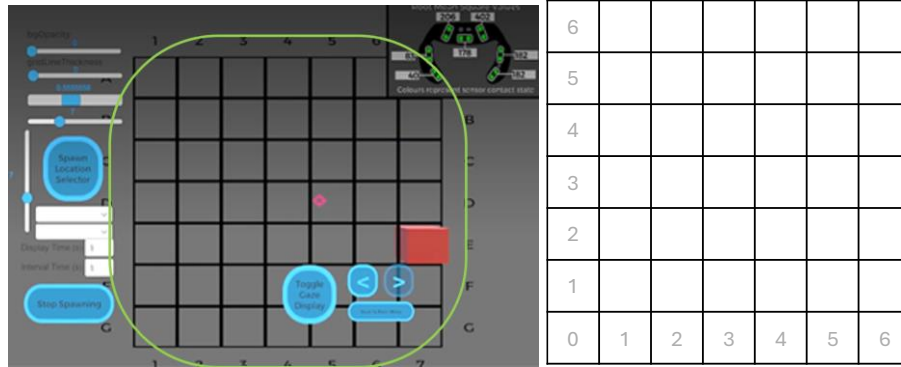


Figure 1: VR Environment on the left with green outline for the field of view in VR, and search grid on the right. Each square shown in the grids is a possible object location; 49 locations in total.

Participants saw the seven-by-seven grid and were instructed to detect and discriminate the shape of the presented object by pressing the “A” keyboard key for a cube and the “L” key for the sphere shape. If the participant could not see the object or could not discriminate the shape, no key would be pressed. The objects appeared randomly at the locations displayed on the grid shown in Figure 1. This task continued until an iteration of either shape had appeared in each grid location a minimum of 3 times. Participants were asked to minimize speaking during the 15-minute duration of the task and were reminded that their performance was not being judged.

Five metrics were defined, extracted, and averaged for each visual grid position (eye-tracking data) and the participants responses (user-based key responses), (a) Object detection reaction time (time between the object’s stimulus onset until the object detection by the user in seconds); (b) Object detection accuracy (percentage of correctly detected objects relative to all displayed objects; any key press – correct response; no key – incorrect response); (c) Shape discrimination accuracy (percentage of correctly discriminated shapes (spheres vs cubes; relative to all displayed objects); (d) Object-to-gaze detection distance (distance between the target object and the eye-gaze pointer at the time of the object detection), (e) Normalised object-to-gaze point (normalised to centre cumulative gaze direction data measured from object onset to offset). The five metrics were extracted for each grid location and each participant, separately, before averaging them across groups.

The object-to-gaze detection distance, is the distance between the eye gaze pointer and the object’s centre. To measure the difference, the min and max gaze x and y coordinate gaze values were used to map to the grid’s coordinates per individual, for the horizontal and vertical spacing, respectively. Once the grid cells coordinates were extracted per participant (adjusted for each participant separately), the gaze distance feature was calculated as the distance between the two points: (1) one is the cell’s centre where the object was displayed, while (2) the coordinates for the other point are calculated as a mean of the gaze vectors values (a combination between the right and left eye) once the object was detected by the participant (at key press as the detection event).

Figure 2 shows the simulated grid with blue circle as the target's location and green as the location of the user's gaze during the detection keypress event.

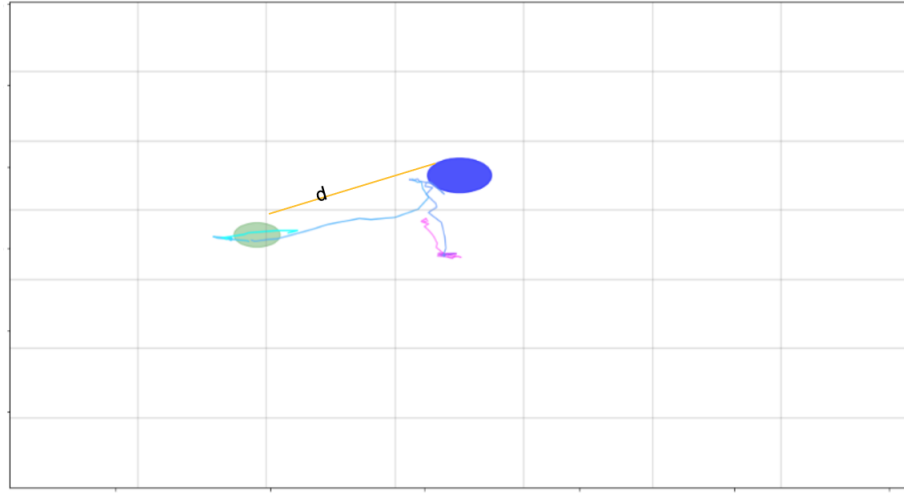


Figure 2: Example of the simulated grid with superimposed gaze data and coordinate of the target object (blue circle) and the coordinates of the user's gaze at the point of keypress (green circle). The distance was calculated between the centres of the circle (see yellow line).

The normalised object-to-gaze point (fixation) data from object onset until object offset was extracted per object, grid cell and averaged across all. Due to our interest in the general gaze patterns across participants with MD and the CG, the eye-gaze motions for each object were centrally normalized for each individual cell to the centre of the grid.

2.4 Pre-VR and Post-VR Questionnaires

Two separate questionnaires were utilized: a demographic short survey before the VR trial (pre-VR); and an experience questionnaire at the end of the VR trial (post-VR).

In the pre-VR questionnaire participants were asked to report their age, their gender, English fluency, previous experience with similar experiments ('yes' if they had any), and previous experience with VR (rated on a scale from 1-9).

In the post-VR survey participants were asked to self-rate their levels of valence (from 1- negative, to 9- positive) and arousal (from 1- calm/sleepy, to 9- aroused, excited) after the experience, and their stress levels during the experience (from 1- low, to 9- high). In addition, they rated their previous experience with VR technologies (from 1- low to 9- high), the task difficulty (from 1- low to 9- high), comfort of the VR headset (from 1- low to 9- high), and whether they would use VR in the future for reading, browsing, game playing, or watching a movie (yes/no with open text).

2.5 Physical Visual Acuity Snellen Test

The Visual Acuity Snellen Test was conducted by placing the visual acuity Snellen test on the wall at a distance of 6 meters from the user's eyes. Participants were asked to identify the letters row by row, top to bottom, following the experimenter's direction. A replication of that test was later performed within VR. Note, a score of 20/20 is considered 'normal/average' for a fully sighted person, and 20/16 is considered 'better than average'.

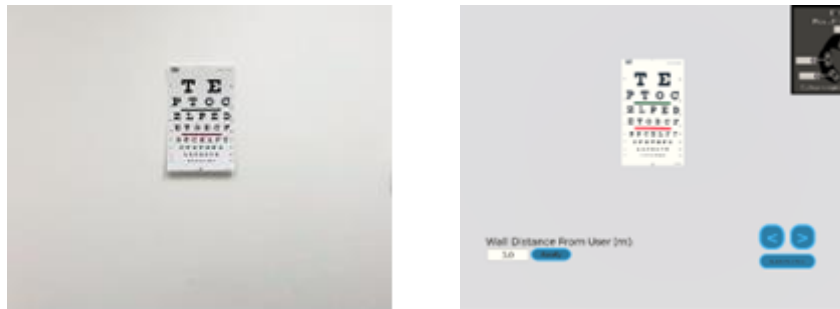


Figure 3: Snellen test in real life on the left and Snellen test in the VR environment on the right.

2.6 Experiment Procedure

Interested volunteers received the participant information sheet from anonymous institution prior to the study. Upon arrival, participants received a briefing about the experiment and had the opportunity to go through the participant information sheet and ask questions about the study. Then, a more detailed explanation of the technologies and the tasks, and a reminder of the withdrawal rights, was given, before participants signed the consent form (Participant Agreement Form). At this point, a participant number was allocated to each participant and used to link the written responses from the questionnaires with the data recorded in the study. Participants were offered assistance throughout the study. Participants were asked to complete the pre-VR questionnaire and the physical visual acuity test (Snellen). Once that step was completed, participants were instructed to sit in front of the testing computer and were assisted with correct application of the VR headset and emteqPRO sensors. An eye-tracking calibration and emteqPRO calibration steps were performed with the assistance of verbal guidance from the experimenter (two of the participants with MD in both eyes could not independently complete the calibration). This was achieved by guiding participants to look towards the location indicated by the calibration procedure. The calibration for the emteqPRO mask consisted of a 2-minute baseline recording followed by maximum activation calibration (including the activation of the zygomaticus, frontalis and corrugator muscles). At this point, participants were asked if they were comfortable enough to continue with the VR task. Upon confirmation, the virtual visual acuity Snellen test was conducted within the virtual environment, and then the series of 10 short affective videos was

displayed, Participants were asked to rate arousal and valence levels after each video. The final VR task was the grid search task involving object identification and discrimination. After the visual search task was completed, the VR headset was removed, and the experimenter provided the post-VR questionnaire. The overall duration of the study was approximately 60 minutes per user.

3 Results

3.1 Visual Acuity test (Snellen)

The results in Table 1 show the accuracy for the physical Snellen test and the virtual Snellen per participant in the ‘Physical’ and ‘Virtual’ conditions. Overall, 12 participants (85%) could read at least the top line of the Snellen tests. Two of the participants with MD in both eyes (AMD2) could not see the first row; MD1 and MD3. Of the remaining participants, 50% improved acuity scores when repeating the Snellen test in VR, whereas 50% had similar scores. This indicates improvements for the VR Snellen test across all participants who were able to read.

Table 1. Physical and Virtual Snellen Scores for CG and AMD groups.

Participant Number	Age	Physical	Virtual
<i>Control Group</i>			
CG1	25	20/25	20/16
CG2	27	20/20	20/20
CG3	37	20/20	20/16
CG4	26	20/20	20/16
CG5	40	20/40	20/25
CG6	31	20/16	20/16
CG7	37	20/20	20/20
CG8	23	20/20	20/20
CG9	24	20/20	20/20
<i>AMD1 Group</i>			
MD4	88	20/30	20/30
MD5	75	20/40	20/30
<i>AMD2 Group</i>			
MD1	62	-	-
MD2	74	20/60	20/50
MD3	87	-	-

Participants with scores 20/20 have a normal, average vision, while participants with scores 20/16 can see at twenty feet what an average person can only see at sixteen feet, while the opposite is true for participants with 20/25, 20/30, 20/40, 20/50 and 20/60 as they have progressively poorer vision.

3.2 Affective Audio-Visual Videos in VR

Valence and Arousal Self-Ratings. When comparing the AMD Group to the CG, it can be seen in Figure 4 that participants in both groups self-rated levels of valence and arousal in a similar way for each corresponding video category. Valence ratings were lower (more negative) for negative videos compare to positive videos, with intermediate ratings for neutral videos. Arousal ratings were lower for the neutral video category compared to the other two affective (positive and negative) categories. There was higher variability for the neutral videos (arousal and valence ratings) in people with MD.

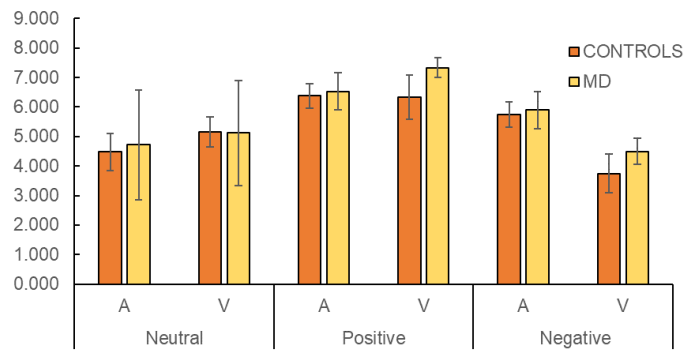


Figure 4: Arousal (A) and valence (V) average self-rating scores per affective category (ranging from 1- low, to 9- high) for affective videos. Orange bars represent the CG and yellow bars represent the participants with MD.

Facial EMG activation. For each EMG channel, the normalised, root mean square (RMS) activation was extracted for each video. The data were normalised against the initial calibration session. Group differences were found in average facial expressivity, as shown by the EMG plots in figure 5. Neutral videos elicited low overall facial intensity across all channels, although a small increase in frontalis and corrugator activation for the AMD group was observed. Activation on the corrugator is linked to negative affective states and could be a result of confusion or squinting the eyes [32]. Positive videos induced strongly increased EMG activation for the zygomaticus and orbicularis muscles surrounding the eye and cheek area, denoting positive reactions. Those facial reactions appeared to be stronger for the CG compared to the AMD group, especially for the zygomaticus muscles. Negative videos did not appear to induce strong responses overall. Finally, corrugator and frontalis EMG activity appeared to be elevated to the same level for all three video categories for the AMD group only. In summary, AMD

participants had higher corrugator and frontalis activity for all affective video categories, and weaker zygomatic responses in the positive video category compared to CG.

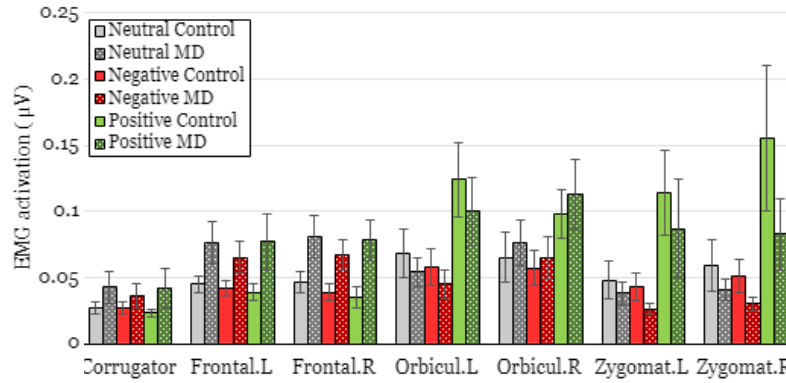


Figure 5: Average EMG activation per channel for each affective video category. Light grey bars represent neutral videos for the CG; dark grey bars represent neutral videos for participants with MD; light red bars represent Negative videos for the CG; dark red bars represent negative videos for participants with MD; light green bars represent positive videos for the CG; dark green bars represent positive videos for participants with MD.

Affective Video Recognition. After the experiment, the participants of the AMD group were asked whether they could recognise the content of the videos. Some of the participants with MD in both eyes responded that they were unable to recognise the details in the video. However, participants were able to get sufficient information from the audio/sound of each video, especially for the positive videos. Positive videos included a child laughing to paper being shredded, a racoon eating from a bowl and two adults laughing together; neutral videos showed an excavator digging a hole in the ground, clouds moving in a blue sky, walking down a street in a big city and a scene from a nature reserve; negative videos included a spider nest being cut open and revealing the baby spiders as well as a dog having ticks removed from its body. On the other hand, the participants with MD in one eye only, were able to process the videos using their residual eyesight.

3.3 Visual Search Task

Mean object detection reaction time. The time between the object's stimulus onset until the object detection by the user was measured in seconds. Figure 6 shows the mean object detection reaction times for the CG, AMD1 and AMD2 groups. Mean detection reaction times seem to be increased for the AMD1 and AMD2 groups compared to the CG; especially in the periphery for the AMD1 group, and in the centre and periphery for the AMD2 group.

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Figure 6: Detection time in seconds (CG - left, AMD1- centre, AMD2 - right), the brighter colour indicates slower object detection reaction times. The indexes (0-6) correspond to the grid locations shown in Figure 1.

Object detection accuracy rate. Figure 7 displays the object detection accuracy rate (in percentage) for each group and grid location. It shows that object detection accuracy was reduced in the AMD2 group compared to the other two groups.

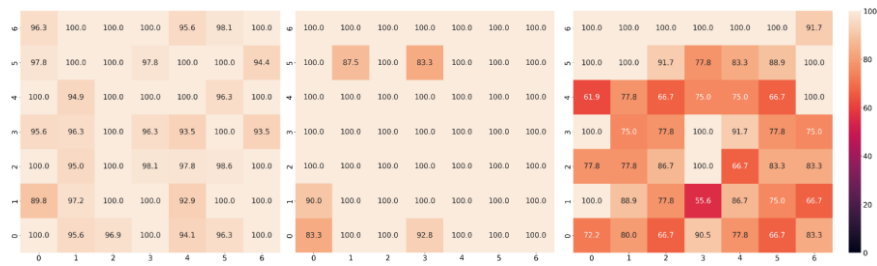


Figure 7: Detection rate of objects. Percentage of how many of the spawned objects are detected. Bright colour suggests higher detection rate (CG - left, AMD1 - centre, AMD2 - right).

Shape Discrimination Accuracy Rate. This was measured as a percentage of correctly discriminated object shapes (sphere versus cube). Since MD affects overall shape discrimination, we expected this effect to be visible when distinguishing the two 3D shapes (see Figure 8). Results confirmed this assumption. The AMD2 group seemed to have reduced discrimination ability compared to AMD 1 group in the visual centre, whereas the AMD 1 group seemed to be more affected in the upper peripheral visual field.

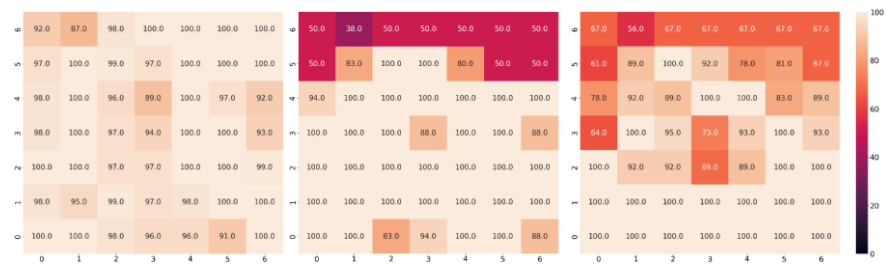


Figure 8: Discrimination rates for shapes. Percentage of how many shapes were correctly

discriminated. Brighter colours reflect a higher discrimination rate (CG - left, AMD1 - centre, AMD2 – right).

Object-to-gaze detection distance. Figure 9 shows the results on the average distances per group. Overall, similar distances between the CG and the AMD2 group were observed, while AMD1 appeared to possess lower distance values across the grid cells compared to the CG. The comparison between the CG and the AMD groups may not be directly of interest because the distance was calculated at the point of the key-press event detection, for which users of the CG appeared to be considerably quicker than the other two groups, within 400-600 ms. Instead, when comparing the two AMD groups with similar detection times, larger distances can be observed in the AMD2 group compared to the AMD1 group, especially in areas surrounding the central grid.

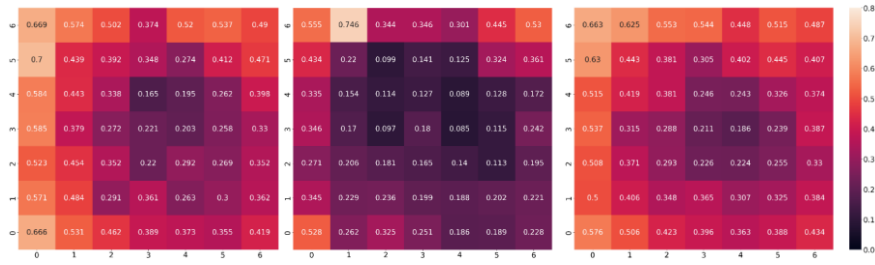


Figure 9: Distance between the average gaze direction point and the centre of each objects cell. Darker shades suggest near overlap with objects (CG - left, AMD1 - centre, AMD2 - right).

Table 2: Overall scores as averages across all grid locations per group. Control Group – CG; AMD 1 group – one eye affected; AMD 2 group – both eyes affected AMD all group – combination of AMD 1 and AMD 2 groups.

	Detection duration	Detection distance	Object detection	Shape discrimination
CG	0.55s	0.40	97.7%	98%
AMD 1	0.92s	0.25	88%	99%
AMD 2	0.90s	0.40	87%	84%
AMD all	0.91s	0.34	88%	90%

Normalised object-to-gaze point. The result for the normalised object-to-gaze point is presented as a heatmap for each group in Figure 10, showing group means, and in Figure 11, for individual plots for participants with MD.

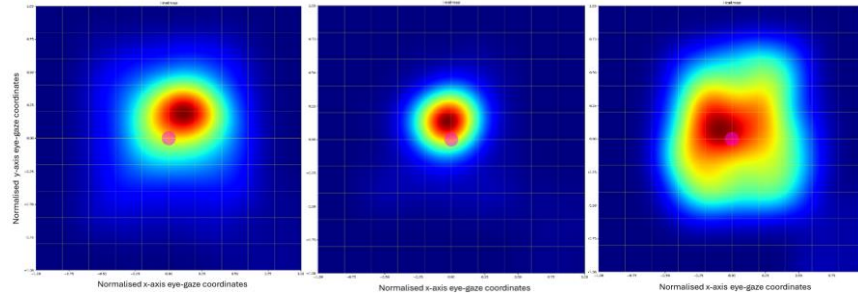


Figure 10: Normalized gaze data, displaying the general viewing area for all objects CG - left, AMD1 - centre, AMD2 - right).

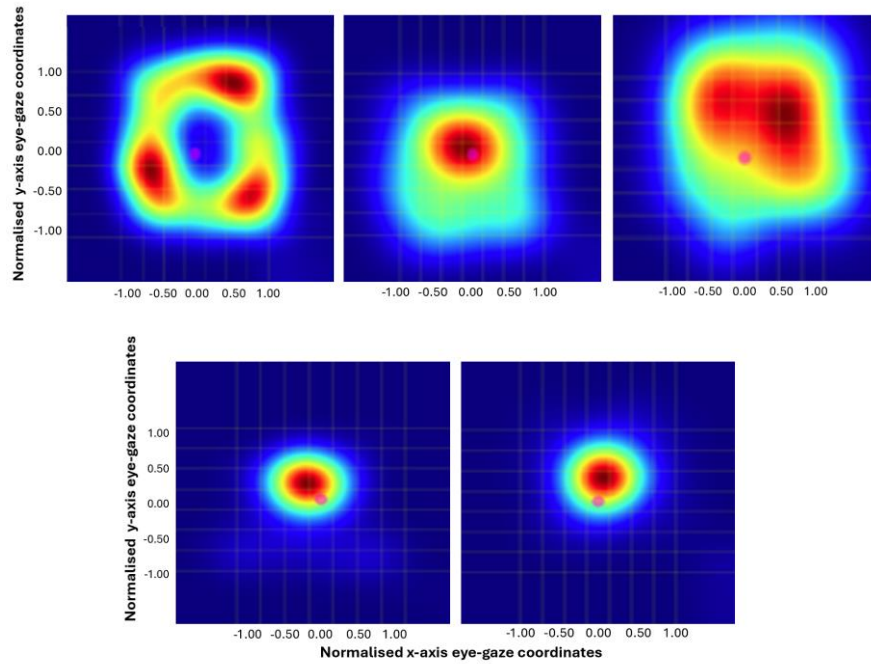


Figure 11: Gaze data heatmap, displaying the general normalised viewing area for all objects across locations normalised to position (0,0) as indicated by the pink circle in the centre of the grid. From top to bottom and left to right the figure represent gaze data from participants: MD1, MD2, MD3, MD4 and MD5.

3.4 Self-Reports

Overall VR experience. Of the 14 participants, 9 had participated in a similar experiment before (all from the CG). When asked to rate their VR experience, CG had a

positive experience (CG: $M = 7.11$, $SD = 1.52$), while the AMD1 and AMD2 groups had a more negative experience (AMD1: $M = 1.5$, $SD = 0.50$; AMD2: $M = 2$, $SD = 1.41$). Using VR in the future. 56% of the CG said yes, they would use VR again within a different context (e.g., playing games or watching videos), compared to 50% of the AMD1 group and 33% of the AMD2 group.

VR headset comfort and ease-of-use. All 14 participants found the VR headset easy to put on and the task instructions clear to follow. When asked to rate how comfortable the headset was on a scale of one to five, CG reported low comfort (CG: $M = 3.66$, $SD = 0.71$) whereas the AMD users rated more favourably (All AMD group participants: $M = 4.6$, $SD = 2.61$; AMD1: $M = 6$, $SD = 4.24$; AMD2: $M = 3.6$, $SD = 1.15$).

VR task and experience enjoyment. Participants were asked to briefly describe how the VR experience was for them: 29% of all participants reported a positive overall experience with comments such as ‘interesting’ and ‘enjoyable’; 29% of participants gave a neutral review, ‘it was ok’. 42% of participants found the experience negative overall, finding it ‘headachy’ and ‘dizzy’. 33% of the CG participants gave positive answers, 22% gave neutral answers, and 44% were negative ‘uncomfortable’, ‘headachy’. The two AMD1 participants (single-eyed AMD) reported positive and neutral responses (‘It was fantastic’ and ‘I wouldn’t pay to do it’). Finally, the three AMD2 participants (both eyes affected) gave mixed reviews with statements such as ‘terrible’, ‘very positive’ and ‘interesting but nothing exciting due to lack of vision’. Overall, 58% of participants either enjoyed the experience, considered it interesting, or felt neutral towards it.

4 Discussion

User-machine interaction (UMI) is pivotal in modern technology, allowing users to effectively operate devices and instruments. As healthcare costs rise and demand for user-friendly medical XR technologies grows, Human-Machine Interface (HMI) systems play a crucial role in product development. However, individuals with macular degeneration (MD) face unique challenges due to their visual impairments. With this study, our team explored existing user-machine interaction techniques and their applicability on a selection of individuals with MD, a group that is often excluded from relevant user research. Aspects of their experience were assessed, both in subjective reports but also from smaller interactive tasks aimed at assessing improvement in visual acuity in VR using COTS, their capacity to detect and discriminate shapes and objects, and the processing of information in affective videos. The tasks were also performed by a non-visually impaired group to assess general trends.

The comparison between the visual acuity in the real space and in the virtual space demonstrated an improvement in 50% of participants in VR compared to the physical test (see Table 1). All participants did the physical test condition first, and then after the calibration and introduction to the VR headset they conducted the same test in the virtual environment. Therefore, there was enough time between the two test to eliminate

any impact from the participants getting used to and memorising the test. In the AMD group, two out of three participants who were able to see the physical test reported improved visual acuity scores in VR, indicating clearer visibility of letters in a virtual setting. These preliminary findings may indicate potential benefits of VR generally for users with MD, albeit the limited sample size. When asked about their experience, whilst some people found that reading the virtual letters in the visual acuity test was made easier due to brightness, sharpness and higher contrasts, others found letters too bright and, in some cases, even blurry. This supports findings from Powell and colleagues, who found marked improvements in the ability of people with MD to identify, observe and describe objects using pass-through AR and VR applications due to increased luminance (brightness and contrast) [8]. Bullimore and Bailey (1995) proposed that these luminance levels allow for fixation closer to the fovea, which offers higher visual resolution [33]. Indeed, VR devices typically provide brightness levels above those experienced in normal domestic environments, which should contribute to greater visual accessibility for users with MD [8]. Literature suggests that improving the viewing experience and enhancing clarity in VR may require the adjustment of certain parameters for each individual, especially for users with MD [7, 34]. Thus, customizable viewing experiences may be required, which are tailored to the individual's eye conditions, environment and task [35]. Whilst lighting conditions were sufficient for vision within this experiment, levels were not measured quantitatively. These parameters and their specific benefits on people with MD could be systematically investigated in future studies.

Results on the audio-visual affective video task indicated that although visual clarity and discrimination of visual cues is more difficult for some users with MD, they were able to discriminate between positive and negative video content as shown in the self-reported valence and arousal scores. Participants stated that when image was unclear, the context was clarified by auditory cues. Thus, this finding evidences the important role that auditory information in processing, navigation, and enjoyment of VR experiences for individuals with VI.

Additionally, the participants' facial responses to the affective videos were assessed with f-EMG. Positive facial reactions on muscle zygomaticus and orbicularis were detected during positive videos in accordance with the video's nature for both groups. The activation of the corrugator and frontalis muscle (muscles over and between the brows, often related to negative emotional facial expressions) consistently occurred for the MD groups regardless of the affective video category. Surprisingly, these muscles were not sensitive to the emotional content, as we anticipated stronger responses during negative videos which were not observed. Instead, clearer activations were evident in the cheeks and eye region during positive videos. Generally, frontalis muscle activity is related to emotions of fear, surprise, and/or to squinting the eyes. Their challenges in visual perception may have contributed to these consistent muscle responses [36]. Further investigation into the relationship between facial muscle activity and emotions during VR experiences—such as real-time self-reporting or measuring biophysiological markers of emotion—could significantly benefit future research on facial expressivity among participants with MD during VR interactions.

VR applications often involve interacting with virtual objects, manipulating them, and navigating through immersive environments. For this, we attempted to assess usability and inform future design process when using COTS VR on object and shape detection. The ability of users with MD to detect objects and to discriminate their shapes within VR was measured with an interactive visual grid-search task with eye-tracking. Based on the literature, we expected that the size of the scotoma in the eyes in individuals with AMD is the dominant impediment in visual focus, reducing abilities in object detection and scene identification [12, 37]. This was the case but results also supported the feasibility of using VR tasks for users with MD, as evidenced by the ability of the participants with MD to identify 3D objects and shapes during this task. Although, CG participants maintained higher average object detection and shape discrimination rates than (all) AMD groups (see Table 2). Still, accuracy rates above 80% for both object detection and shape discrimination for AMD participants. Results also showed that vision is disturbed in certain areas of the virtual visual planes for different AMD individuals (especially around the corners of the screens); this might reflect the varying extent with which MD impacts on the individual. In the current study the obstruction in recognizing objects and shapes was increased in the AMD2 group compared to the AMD1 users. This result suggests that the extent to which MD affects individuals' ability to identify objects or shapes or interact with VR technology might depend on whether one or both eyes are affected. Thibaut and colleagues showed there are disparities between AMD subjects (~63%) and controls (~95%) in object identification during VR interactions [12, 38]. Future investigations of this nature could explore these potential disparities in conjunction with optometric assessment, in order to identify the visual capacities in VR for individuals with varying symptoms and diagnosis of MD. Furthermore, quick grid-search tasks could be used in the future to identify areas of reduced visibility for users with MD, enabling the tailoring of customised viewing settings and filters to improve their immersive VR experience.

In the current study, shape discrimination was employed to explore the ability of users with MD to categorise and identify objects. In previous studies, participants with MD took longer to identify isolated objects and objects from a scene in comparison to their age matched controls [12]. Additionally, in past studies focusing on visual search for people with MD [43] it was obvious that people with MD had longer intersaccadic intervals, indicating slower processing between fixations and manual calibration of the eye tracking equipment was necessary for some of the participants with MD [44]. Object categorization and identification require different cognitive processes; for instance, object categorization uses coarse visual information, whilst identification relies on finer details which are disturbed by visual scotoma [12]. Grill-Spector and Kanwisher suggested that there is additional information processing involved in tasks of object categorization which may increase reaction time [39]. Eye tracking evidence could also explain increased detection duration, as people with MD have been found to make more saccades and have shorter fixation durations [12]. This is supposed to reflect gaze instability associated with a reliance on peripheral vision [40]. The visual exploration aspect of this study was not the main focus of the current research, but exploration requirements in VR may have greater implications for everyday task requirements (i.e., finding faces or objects) than in the identification of objects in isolation.

One finding which warrants further exploration is the mean detection distance between the object and the gaze of the participants. This distance was expected to increase in relation to the central eye scotoma, and the subsequent use of peripheral vision in users with MD. However, the control group obtained similar distance scores for the object detection as the AMD2 group. When comparing the AMD groups, the AMD1 group had a lower mean distance score compared to the AMD2 group. A potential explanation for this is that distance was measured when the participants responded to the target. At this time, participants might have not fixated the target object yet, or they may have already shifted their gaze away from the target object. Secondly, the control group users reported their detection outputs more swiftly (~550ms) (within expected range of 600ms, as supported by Döring et al. [41]) compared to the AMD groups, which was ~900ms. Participants also had very low levels of error in detection and shape discrimination, this might have influenced the distance score. To note, however, that the reaction times for the AMD groups were similar and the mean distance scores were higher for the AMD2 group compared to the AMD1 group.

Regarding the overall VR experience, participants with MD reported similar scores to the participants of the control group, indicating overall comfort and enjoyment, and good levels of acceptance for subsequent studies and in trying new VR applications. However, some participants reported headaches and dizziness, and over half reported that the headset and/or mask was uncomfortable. Those who reported feeling stressed during the experiment mentioned that it was mostly caused by forehead pressure. Reports from previous research suggests that headache/motion sickness appears to be a common experience for some users of VR headset [42]. Nonetheless, such issues could be reduced, for example, if the duration of the experience was shortened or more frequent breaks offered. Additionally, the unfamiliarity of wearing such equipment might be a contributing factor in some people's response to feeling uncomfortable. Further research could investigate the types of off-the-shelf applications which could be utilised by people with MD or other types of V.I. for well-being, and training purposes, in order to ensure comfort and enjoyment.

4.1 Limitations and future direction

The results from this small-scale study provide preliminary insight into the suitability of VR technologies for users with MD, the feasibility of VR in presenting simple objects and shapes which can be seen and recognised by users with MD, the feasibility in employing eye- and face-tracking technologies with users with MD, and the ability to utilise off-the shelf commercial headsets and VR audio-visual with these users. Despite, this, the current study has some limitations and future research is needed in this area. Firstly, it is difficult to make true comparisons between participants with MD and the CG due to the small sample sizes. The limited numbers of users with MD recruited for this study was due to a reluctance of most individuals to attend the study laboratory. Thus, future investigations might want to consider providing a mobile study paradigm tailored for people with MD in order to increase sample size and validate the observed effects. In addition, there was a high disparity in age and gender within and between

the groups which could have affected our findings. In future studies, potential ageing effects should be controlled, for example, by having an age matched control or by having ageing as a co-variate in the analysis.

Two people from the AMD group also mentioned that they struggled to see the grid fully during the search task. Future studies could seek to customize features such as magnification and luminance to meet the needs of individual users with V.I. This research provides only a start to the conversation surrounding VR for individuals with MD and other forms of V.I. Results suggest that there may be potential for this technology to help address the potential impacts of V.I. on both the physical and mental well-being of those affected. Future research is required to explore the feasibility and efficacy of using VR in different clinical and non-clinical contexts for people with V.I., and to ensure accessibility of this technology for these users.

5 Conclusions

As the population with V.I. grows worldwide, particularly as a result of age-related conditions such as AMD, there are significant implications for adapting the ways in which care is delivered to individuals with V.I. to better meet their health and social support needs [10]. At present, VR is being used as a therapeutic tool for sighted users, to treat a number of physical and psychological conditions which also affects the community with V.I. [45]. There is a need to explore the extent to which VR modalities are accessible to users with V.I., and how such equipment might be adapted for optimal use in home entertainment, rehabilitation, and therapeutic/care settings. Research exploring VR accessibility for individuals with visual impairment is essential; the experiences of users with V.I. with VR is poorly documented and its value as a therapeutic modality in their lives is unknown. Research is needed to address the following key questions regarding accessibility and usability of VR for those with V.I..

The first key finding of this study was that the comparison between the visual acuity in the real space and in the virtual space demonstrated a general improvement (by 50% of participants) in VR. Secondly, the results on the affective videos revealed that participants with MD were able to discriminate between positive and negative video content, despite that visual clarity and discriminating visual cues is more difficult for them. Consistent with expectations, the control group outperformed participants with MD across all four grid search tasks. However, most shapes, objects and grid locations were still detectable by individuals with MD. Notably, those with impairment in both eyes faced the greatest challenges but still exhibited heightened sensitivity to changes when objects appeared more frequently than anticipated. These findings align with the results from the visual acuity test, emphasizing the increased visibility in VR. Importantly, all participants were able to use the COTS VR headset. These results shed some preliminary lights into the usability of VR technologies for users with MD.

The existing literature highlights VR as a versatile and effective therapeutic tool across various clinical contexts, with its growing adoption within NHS treatment pathways. However, its accessibility for users with visual impairments remains underexplored. Considering the potential impact on well-being, quality of life, and therapeutic

outcomes, further research is necessary to understand how VR can be effectively utilized within the V.I. community. Ultimately, this exploration aims to enhance universal accessibility to VR technologies. However, further research is needed to explore how current VR technologies can be adapted and designed to address the needs of the MD and VI community, ultimately increasing their access to VR experiences.

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