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REVIEW ARTICLE

Are wearable electronic vision enhancement systems (wEVES) beneficial for people with age-related macular degeneration? A scoping review

Andrew Miller[1] | **Michael D. Crossland**[2] | **Jane Macnaughton**[1] | **Keziah Latham**[1]

[1]Vision and Hearing Sciences Research Centre, Anglia Ruskin University, Cambridge, UK

[2]University College London Institute of Ophthalmology, London, UK

Correspondence
Andrew Miller, Vision and Hearing Sciences Research Centre, Anglia Ruskin University, Cambridge, UK.
Email: adm157@pgr.aru.ac.uk

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Abstract

Introduction: Age-related macular degeneration (AMD) is the most common cause of irreversible visual impairment in the United Kingdom. It has a wide-ranging detrimental impact on daily living, including impairment of functional ability and quality of life. Assistive technology designed to overcome this impairment includes wearable electronic vision enhancement systems (wEVES). This scoping review assesses the usefulness of these systems for people with AMD.

Methods: Four databases (Cumulative Index to Nursing and Allied Health Literature, PubMed, Web of Science and Cochrane CENTRAL) were searched to identify papers that investigated image enhancement with a head-mounted electronic device on a sample population that included people with AMD.

Results: Thirty-two papers were included: 18 studied the clinical and functional benefits of wEVES, 11 investigated use and usability and 3 discussed sickness and adverse effects.

Conclusions: Wearable electronic vision enhancement systems provide hands-free magnification and image enhancement producing significant improvements in acuity, contrast sensitivity and aspects of laboratory-simulated daily activity. Adverse effects were infrequent, minor and spontaneously resolved with the removal of the device. However, when symptoms arose, they sometimes persisted with continued device usage. There are multi-factorial influences and a diversity of user opinions on promotors to successful device use. These factors are not exclusively driven by visual improvement and incorporate other issues including device weight, ease of use and inconspicuous design. There is insufficient evidence of any cost–benefit analysis for wEVES. However, it has been shown that a user's decision to make a purchase evolves over time, with their estimates of cost falling below the retail price of the devices. Additional research is needed to understand the specific and distinct benefits of wEVES for people with AMD. Further patient-centred research should assess the benefits of wEVES in user-led activities when directly compared with alternative coping strategies, allowing professionals and users to make better prescribing and purchasing decisions.

KEYWORDS
age-related macular degeneration, head-mounted display, image enhancement, low-vision aid, visually impaired persons, wearable devices, wearable electronic vision enhancement systems

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INTRODUCTION

Background

Age-related macular degeneration (AMD) is the third most common cause of blindness and the most frequent cause of untreatable blindness worldwide.[1] Prevalence was estimated as 8.4 million cases causing moderate to severe sight loss in 2015,[2] with estimates predicting an increase from 196 million cases in 2020 to 288 million in 2040.[3]

Age-related macular degeneration is a progressive disease producing central vision loss, and for many people, treatment options are either absent or do not prevent significant visual impairment (VI). AMD accounts for the majority of people registered as sight impaired or severely sight impaired in the United Kingdom.[4,5] The resulting VI is linked to increased dependence and has significant detrimental effects on a person's quality of life, psychological well-being and ability to carry out daily tasks.[6–9] Therefore, there is a need to provide reablement and rehabilitation strategies to support people with AMD to mitigate these effects.

Rationale

The primary objective of older adults attending low-vision services is to improve reading ability, with secondary objectives including activities of daily living (ADL), watching TV, writing and mobility.[10,11] There is good evidence that low-vision services prescribing assistive devices are beneficial in improving the functional ability of people with AMD.[12–14] Low-vision services in the United Kingdom predominately supply task-specific optical low-vision aids (LVAs) to resolve any identified magnification needs. In addition, clinicians offer advice about lighting and environmental control to support any contrast sensitivity (CS) impairment.

In addition to optical LVAs, electronic vision enhancement systems (EVES) and mainstream technology (e.g., smartphones) have been shown to provide useful ways of providing image enhancement and magnification to people with VI.[15–19] Low-vision services are now being called upon to recognise the benefits offered by emerging technology to people with VI.[20] Portable EVES have been validated[21,22] as a cost–effective and commonly prescribed inclusion to the Welsh Low-Vision Service, but are not supplied routinely by other National Health Service (NHS) low-vision clinics.[23] A recent systematic review of interventions designed specifically to support people with AMD found that optical LVAs were still prescribed and used more than newer visual enhancement technology. However, it was unclear if this finding was driven by performance, comfort or financial considerations.[24]

Low-vision aids can be divided into two broad categories: devices that produce image enhancement by adapting and modifying the image and those that use sensory substitution to change the visual output into another form.[25]

Key points

- Wearable electronic vision enhancement systems (wEVES) produce improvements in acuity, contrast sensitivity and the ability to complete some laboratory-simulated tasks such as recognising faces or finding items on a shelf.
- There is an absence of evidence concerning the performance or cost–effectiveness of newer wEVES compared with existing coping solutions.
- Greater functional independence and changes in quality of life predict the sustained use of wEVES, whereas discomfort, handling difficulties and high weight cause discontinuation of use.

While there is some crossover between these two solutions, a wearable electronic vision enhancement system (wEVES) that principally uses image enhancement to produce an adaptable magnified image on a head-mounted display (HMD) was first proposed 30 years ago.[26,27] These head-mounted devices consist of a camera, software to manipulate the images and a display screen close to the eye; allowing the benefits of EVES in a form that enables both hands-free and mobile use. There is no consensus on naming this category of LVA, and we suggest the term *wearable electronic vision enhancement systems (wEVES)* to collectively describe head-mounted devices that provide image enhancement.

Image presentation in wEVES largely falls into two categories[28]:

- Virtual reality (VR) presents a bright image with a wide field of view that software can manipulate readily but disconnects the user from the real world. These can be produced in a 'fully immersive' goggle or a 'semi-immersive' form which still allows an element of view around the screen.
- 'See-Through' augmented reality (AR) presents new information and enhancement in images that overlay the view of the real world. Images tend to be duller with a narrower effective visual field than the VR equivalent.

It has been suggested that the development of wEVES has taken place over two distinct generations;[29] from 1994 to 2010, the 'first-generation' devices included the original low-vision enhancement system (LVES) device and a series of other wEVES that have now left the market or exist in a new device retaining the original name. More recently, the rapid development of smartphone cameras and screen technology has enabled a 'second-generation' of wEVES to borrow and adapt these advances to reinvent the concept of a wearable device.

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Several mainstream manufacturers have also developed their own HMD, such as Google Glass (google.com/glass/start/), Microsoft HoloLens (microsoft.com/en-us/hololens) and Vuzix Blade (vuzix.uk/products/vuzix-blade-smart-glasses-upgraded). These devices are aimed at mass-market usage, but may also have some potential for supporting those with VI by acting as wEVES.[30–33] Conversely, a number of mass-market devices have also been adapted and developed to produce products designed specifically for people with VI, for example, the Samsung Gear Headset used by IrisVision (irisvision.com/) and the 'HTC VIVE' used by Vision Buddy (visionbuddy.com/).

The number of wEVES designed specifically for people with VI is increasing, but there is no compulsion to produce trial data before bringing new devices to market. In a world of fast-moving consumer electronic goods and limited budgets, it is vital to understand the breadth of available research to support clinical and consumer choices. A 2018 Cochrane review found insufficient evidence to support the use of wEVES over more traditional optical or electronic magnifiers.[34] However, it was acknowledged in the report that wearable technology was an area with a significant possibility for future advancement.

Wearable electronic vision enhancement systems are a potentially innovative enablement strategy for people with VI including those with AMD. However, these devices are unavailable on the NHS and could cost patients several thousands of Pounds Sterling to purchase. It is likely that devices that would be successfully adopted by an older cohort of users with distinct ergonomic needs and technical abilities might differ from those used by younger users with similar VI. For example, older people with AMD are more likely to have general health comorbidities such as arthritis or tremor that will affect how they can interact with the devices. Older adults are also more likely to be less comfortable with digital technology solutions. For example, over half of all adult internet non-users in the United Kingdom are over the age of 75,[35] and older adults are less likely to be users of smartphones or apps.[36] To support the development of low-vision services and better inform prospective consumers, there is a need to evaluate the evidence to determine what is known about the functional benefits and cost–effectiveness of these devices specifically for older people with AMD. Devices are developing rapidly, and available research literature was likely to be heterogeneous, varied in nature and not precise in its conclusions. Therefore, a scoping review was selected to systematically discover and describe the current knowledge and identify gaps for further research in this area.[37]

Key concepts

This scoping review's overarching concept of interest is to evaluate the benefits of wEVES for people living with AMD. The following research question was formulated:

'What is known from the literature about the usefulness of wearable electronic vision enhancement systems for people with age-related macular degeneration'?

METHODS

To ensure a consistent and systematic approach, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) methodology and checklist were followed.[38] In keeping with recommendations from the Joanna Briggs Institute,[39] the scoping protocol was published on Figshare (doi.org/10.25411/aru.19410350) before the review commenced.

Eligibility criteria

This review only considered wearable head-mounted devices that offered image enhancement as their primary enablement solution. Qualitative, quantitative and mixed-methods studies were included to gain a broad understanding of the potential benefits of devices. Peer-reviewed articles, conference abstracts and other manufacturers' grey literature were included in the search, with relevant weighting given to the evidence depending on its source.

Areas of interest

Papers were sought that showed an investigation of the benefits of wEVES where some of the study population had AMD as the cause of their sight loss. Benefits included, but were not limited to, functional and cost–benefit analysis and ergonomic design criteria.

Information sources

A three-step approach to the search strategy was conducted[39] (Figure 1):

1. An initial preliminary search developed the search methodology and keywords. Search terms were designed around three concepts: low vision, image enhancement and head-mounted electronic device (Table 1).
2. A detailed second search was conducted on PubMed, Cumulative Index to Nursing and Allied Health Literature, Web of Science Core Collection and the Cochrane Central Register of Controlled Trials (CENTRAL) on 21 March 2022. Due to the nature of the topic, searches were limited by date of publication to exclude articles from before 1990. Device manufacturers' websites were searched for any relevant grey literature.
3. A third search was conducted through shortlisted articles' reference and citation lists.

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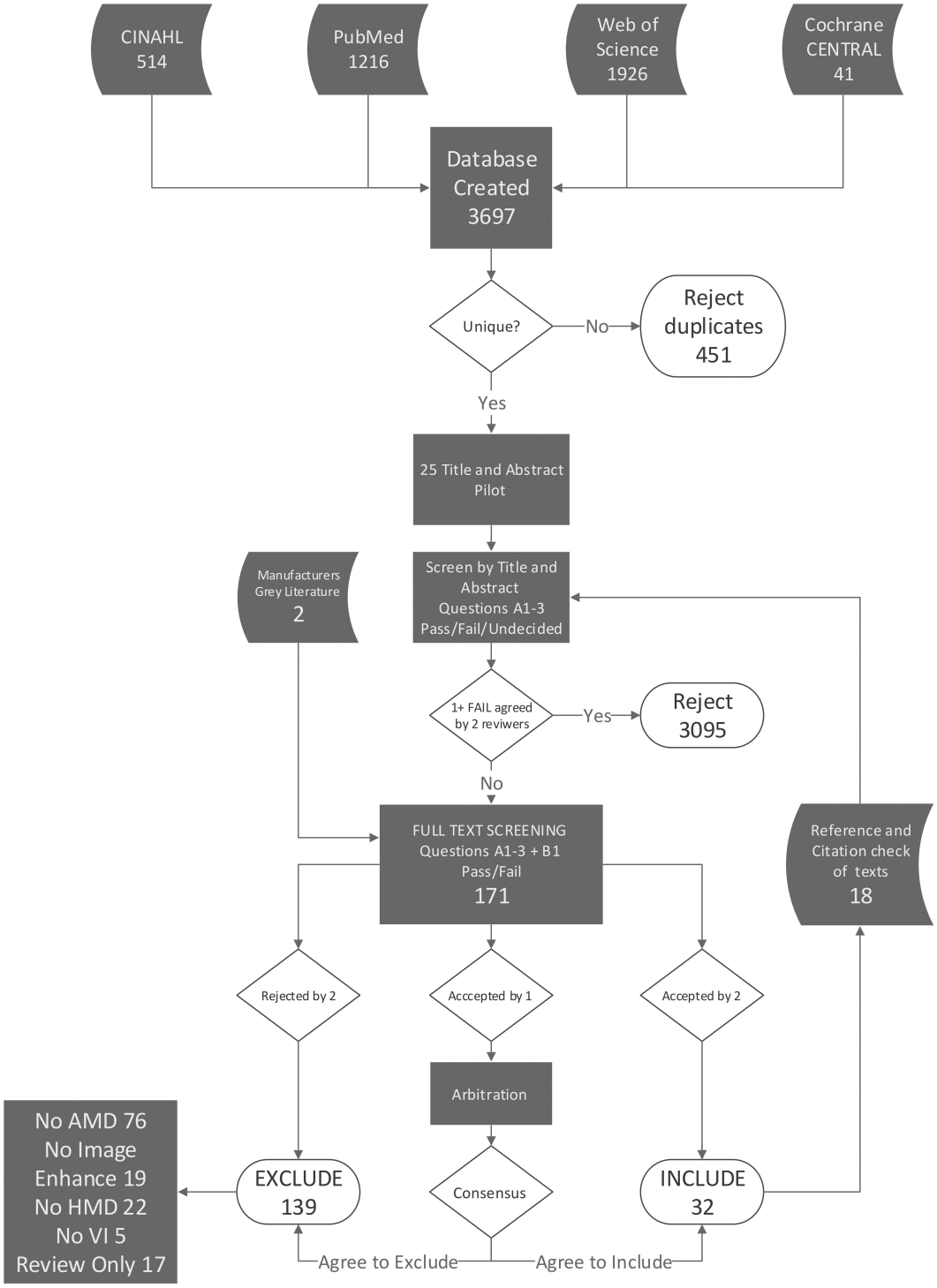

FIGURE 1 Flowchart detailing the search process. Numbers refer to the articles considered at each stage. CINAHL, Cumulative Index to Nursing and Allied Health Literature; Questions numbers refer to A1. Does the research refer to an image enhancement/electronic magnifying device? A2. Are the devices head-mounted? A3. Does the research consider people with VI? B1. Does the research consider people with AMD? AMD, age-related macular degeneration; HMD, head-mounted display; VI, visually impaired persons.

Data charting and screening criteria

Two authors (AM and KL) independently screened the unique studies identified by the searches, as shown in Figure 1. To examine the impact of devices on the target users and exclude any proof-of-concept material that had not been used by the desired audience, inclusion criteria (A1–A3) were developed to identify papers that used a head-mounted image-enhancing device with a population of visually impaired people. Provisional searches indicated that very few studies considered the needs of people with AMD in isolation from others with VI. Therefore, a further criterion (B1)

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limited the search to papers that included some people with AMD, rather than ones that exclusively examined individuals with AMD. The screening was completed in two steps using the criteria shown in Table 2: First, the abstract and title were screened using questions A1–A3, followed by full-text screening using questions A1–A3 plus B1. An initial 25-subset pilot was used to test consistency between the researchers before the screening commenced, with any disputes being resolved by discussion until consensus was reached.

RESULTS

Selection and characteristics of sources of evidence

Thirty-two papers were included in the scoping review (Figure 1); studies were grouped by the types of benefits they analysed. Where a paper showed crossover between themes, it was referenced in more than one section.

Eighteen papers reported an experimental intervention using wEVES with a study population including some people with AMD. Outcomes include differences in clinical measures, quality of life and real-world function. Study characteristics are presented in Table 3, with summary findings separated into Tables 4 and 5 by device generation to allow a clearer distinction between historic and current devices.

Eleven papers considered the use and usability of a device, including task analysis, design features and factors that promoted successful wear or device abandonment. Findings are summarised in Table 6.

Three previously included and three additional papers evaluated adverse effects and simulator sickness (SS). The additional papers are summarised in Table 7.

Four previously included papers were also considered in the final section to describe any evidence of the cost–effectiveness of these devices.

The publication date of papers shows a bimodal spread (Figure 2), supporting the concept of considering wEVES in two 'generations'. An initial peak of interest as devices emerged was followed more recently by a sharp rise in publications since 2010 as the second generation of devices has come to market.

Results of individual sources of evidence

See Tables 3–7.

DISCUSSION

Summary of evidence

Improvement in clinical visual function

There is strong evidence to show that wEVES improve distance and near acuity for people with VI, including those

TABLE 1 Concepts and search terms for PubMed search.

Concept 1	Concept 2	Concept 3
For people with low vision	Image enhancement	Head-mounted electronic device
Keywords: 'Low Vision'[tw] OR AMD[tw] OR Visual impair*[tw] OR Visually impair* OR Impaired Vision OR Blind[tw] OR Sight Impair*[tw] OR 'Vision, Low'[Mesh] OR 'Visually Impaired Persons'[Mesh] OR 'Macular Degeneration'[Mesh]	Keywords: Magni*[tw] OR LVA[tw] OR Assistive[tw] OR Display[tw] OR Video[tw] OR Image[tw] OR Enhancement[tw] OR Accessible[tw] OR Tech*[tw] OR Screen[tw] OR 'Low vision aid'[tw] OR Electronic[tw] OR EVES[tw] OR 'Sensory Aids'[Mesh] OR 'Image Enhancement'[Mesh]	Keywords: Worn[tw] OR Head[tw] OR HMD[tw] OR Wear*[tw] OR 'Wearable Electronic Devices'[Mesh] OR 'Eyeglasses'[Mesh]

Note: [tw] refers to the PubMed [Text Words] field tag search. [Mesh] refers to the National Library of Medicine Medical Subject Headings controlled vocabulary of biomedical terms.

Abbreviation: AMD, age-related macular degeneration.

TABLE 2 Inclusion questions A1–3 and B1 and exclusion criteria used to screen the search (see Figure 1).

Inclusion questions	Exclusion criteria
A1. Does the research refer to an image enhancement/electronic magnifying device?	Not in English (only if a translation was unavailable).
A2. Are the devices head-mounted?	Primarily sensory substitution devices (e.g., devices producing audio or haptic output).
A3. Does the research consider people with visual impairment?	Not a head-worn device.
B1. Does the research consider people with AMD?	None of the study population with AMD.

Abbreviation: AMD, age-related macular degeneration.

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TABLE 3 Characteristics of 18 research papers for first- and second-generation wearable electronic vision enhancement systems (wEVES) intervention studies.

First author	Country	*n* (AMD)	Age (yrs)	Sex	Device	Study	Outcome measures	Location/Duration
First generation: 1994–2010								
Thierfelder (1998)[40]	Germany	25 (10)	56.4 (16.2)	14 F, 11 M	LVES	wEVES vs. Habitual Vision	CVF and 'existence of reading and writing'	Lab only
Ortiz (1999)[41]	USA	10 (2)	17–79		LVES	wEVES vs. CCTV	CVF	Lab only
Ballinger (2000)[42]	USA	78 (54)	36–85, Mean 68	3 F, 75 M	LVES	wEVES vs. habitual vision vs. monocular	CVF	Home trial (no time scale)
Sonsino (2000)[43] CA	USA	20 (5)	22–92		POWERVISION	wEVES vs. CCTV vs. optical magnifier	CVF, timed activity to read a bill and questions on ease of reading	Lab only
Weckerle (2000)[44]	Germany	17 (4)	17–85, mean 49 ± 21	1 F, 16 M	LVES	wEVES vs. habitual vision	CVF, 3 timed activities; reading, writing and mobility	Lab only
Peterson (2003)[45]	UK	70 (40)	F 71.8 (20.6), M 68.3 (22.8)	35 F, 35 M	TVi Zoom and I/O glasses (HMD)	wEVES vs. mouse vs. CCTV vs. optical magnifier	CVF, ease of use structured questionnaire, 3 timed activities: reading a map, medicine label and column change	Lab only
Culham (2004)[46]	UK	20 (10)	54–82, Mean 73.5		Jordy J, Flipperport F, Maxport M NuVision N	wEVES vs. habitual vs. LVA	CVF, 3 timed activities reading, writing a cheque and identifying grocery items on a shelf	2 weeks home
Goodrich (2004)[47]	USA	23 (9)	Mean 71.4		NOMAD	wEVES vs. mouse vs. CCTV vs. optical magnifier	CVF	Lab only
Second generation: post-2010								
Moshtael (2016)[48]	UK	10 (10)	52–91	5 F, 5 M	Epson Moverio (ST) vs. Homido headset and LG G3 (FI-VR)	wEVES vs. wEVES vs. habitual vision	CVF and 4-item structured qualitative interview about ease of use, user preference and aesthetics	Lab only
Troyer (2018)[49] CA	USA	25			Jordy (SI-VR) vs. eSight (SI-VR) vs. IrisVision (FI-VR)	wEVES vs. wEVES	CVF and structured questionnaire assessing performance, willingness to purchase and aesthetics	Lab only
Wittich (2018)[50]	Canada	51 (7)	13–75	30 M, 21 F	eSight (SI-VR)	wEVES vs. habitual vision	CVF, VA LVLFQ-48, modified MLVAI and facial recognition test	3 months
Crossland (2019)[51]	UK	60 (6)	18–93, Mean 51.4	23 F, 37 M	GiveVision Sight Plus (FI-VR)	wEVES vs. habitual vision	CVF and semi-structured qualitative interview exploring willingness to use, and participants' views of a device	Lab only
Deemer (2019)[52]	USA	30	19–93, Med. 54	13 F, 17 M	IrisVision (FI-VR)	wEVES vs. habitual vision	AI, SSQ and semi-structured qualitative interview exploring willingness to use and ease of use.	7–10 days in home

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TABLE 3 (Continued)

First author	Country	*n* (AMD)	Age (yrs)	Sex	Device	Study	Outcome measures	Location/Duration
Lam (2020)[53] CA	USA	5 (5)	54–76, Mean 68	—	Oculenz (ST)	wEVES vs. habitual vision	CVF	Lab only
Werblin (2020)[54] CA	USA		Mean 72 (max 103)	—	IrisVision (FI-VR)	wEVES usage	Questionnaire exploring usage and 'areas of life change' with IrisVision device.	Existing users
Yeo (2020)[55]	Korea	39 (23)	54.6 ± 22.7	23 F, 16M	Samsung S7, Gear VR and Relumino software (FI-VR)	wEVES vs. habitual vision	CVF, self-reported 6-item functional ability questionnaire and semi-structured qualitative interview exploring willingness to purchase, usage and improvements.	2 weeks home
Kammer (2021)[56]	USA	20 (20)	74–92, Mean 85	—	Eye-01 (ST)	wEVES vs. habitual vision	CVF, VA LVLFQ-48 and 3 timed activities: searching a bill, viewing a shelf at 1 m and reading a sign.	Lab only
Lorenzini (2021)[57]	Canada	57	21–82, Mean 54.5	—	eSight (SI-VR)	wEVES vs. habitual vision	VA LV VFQ-48, PIADS, QUEST and SSQ	6 months

Abbreviations: AI, activity inventory; AR, augmented reality; CA, conference abstract; CCTV, closed-circuit television magnifier; CVF, measures of clinical visual function; F, female; FI-VR, fully immersive VR-type headset; LVA, low vision aid; LVES, low-vision enhancement system; M, male; MLVAI, Melbourne Low-Vision Activities of Daily Living Index; *n*, number of participants; NEI-VFQ 25, National Eye Institute Visual Function Questionnaire 25; PIADS, Psychosocial Impact of Assistive Devices Scale; QUEST, Quebec User Evaluation of Satisfaction with assistive Technology; SI-VR, semi-immersive VR headset with view possible around the device; SSQ, Simulator Sickness Questionnaire; ST, see-through AR headset; VA LV VFQ-48, Veterans Affairs Low-Vision Visual Functioning Questionnaire.

with AMD (Tables 4 and 5). This improvement is noted in a wide variety of different devices, in lab studies, home trials and across first-generation[40–42,44] and second-generation devices.[49–51,53,55,56]

First-generation devices did not consistently show improvement in CS,[46] perhaps due to limitations in display quality. However, more recent studies with second-generation devices show reliable improvement in CS for people with different causes of VI, including AMD.[50,51,55]

Reading speed with second-generation wEVES tends to show either no significant change compared with habitual vision[50,53,55] or a decrease.[43,48,51] Reductions in reading speed are postulated to be due to image movement and field restrictions of the devices being assessed. Studies reporting no change in reading speed did show that wEVES improve reading accuracy,[55] or allow reading of smaller print with the same fluency as larger print without the device.[50]

Studies with first-generation devices tended to be lab-based whereas more of the studies using second-generation devices have included observation in a real-world home trial. First-generation devices have been compared with traditional desk-based CCTV, with reading speed found to be slower with the wEVES[45,47] or similar to CCTV.[41] Where optical devices were compared with first-generation devices, wEVES were not consistently better than optical aids for reading (in terms of speed, accuracy or acuity)[43,45,47] or practical tasks[45,46] but did provide longer reading duration.[47] These findings may have been influenced by the slow refocusing times and limited screen resolution of the wEVES tested. It would be of considerable interest to revisit these comparisons with newer second-generation devices, which have tended to be compared only with users' habitual vision.

Subjective and objective improvement in functional vision

Several studies have assessed the ability of first- and second-generation devices to support users' ability to perform practical tasks by adopting both subjective and objective outcome measures. Most studies had mixed populations, with only one investigation undertaken in a sample solely with AMD.[56] Changes in functional ability were assessed using standardised Patient-Reported Outcome Measures (PROMs),[50,52,56,57] a non-validated 'self-evaluation function score'[55] or by observed ability to complete tests of timed instrumental ADL (TIADL).[45,46,50,56]

Compared with users' habitual vision, second-generation wEVES show improvements in perceived ability in 'reading'[50,52,55] and 'visual information' tasks.[50,52] However, perceived ability in 'mobility',[50,52,55] 'writing'[55] and 'visual-motor' (manipulation) tasks[52] do not improve. With the fully immersive VR HMD, it is suggested that the

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TABLE 4 Findings from second-generation wearable electronic vision enhancement systems (wEVES) intervention studies.

Author	Purpose	Main finding	Other findings	Distance acuity	Near acuity	CS	Reading speed	Factors affecting device use or discontinuance
Moshtael (2016)[48]	Evaluate 2 types of wEVES visibility and desirability for users with AMD. Measure the extent to which the display can be seen and read and subjective feedback	Compared with reading with habitual vision ('paper'), 50% found Epson 'Smartglasses' easier or much easier, and 65% found 'Smartphone headset' easier or much easier	Reading speed is slower with devices than 'paper'. Paper 123 (7) wpm, smartglasses 97 ± 8 smartphone headset 98 ± 17. Smart glasses rated more highly than the smartphone headset for comfort and design				↓	
Troyer (2018)[49]	Provide comparative data on participant's objective and subjective responses with 3 wEVES: eSight (E), IrisVision (I) and Jordy (J)	All devices provided significant improvement in distance VA. IrisVision received the highest rank on preference/performance and perceived cost		J ↑ I ↑ E ↑ J = I > E				
Wittich (2018)[50]	3-month prospective trial to investigate the short- and medium-term effects of eSight device	eSight shows immediate and sustained improvements in objectively measured visual ability, including CS, distance and near acuity	MLVAI ↑ VA LV VFQ-48 Overall ↑ Mobility Alone → Face recognition ↑ Observed subjective and objective improvement in ability to complete functional tasks	↑	↑	↑	→	17/74 left 3-month study: 2 discomfort, 7 insufficient benefit, 1 difficulty operating
Crossland (2019)[51]	Evaluate the efficacy of GiveVision SightPlus and determine which people would use a wEVES like this	SightPlus improves objective measurement of visual function in people with low vision	47% would use a wEVES like SightPlus, 45% would not. Reasons for not wanting to use the device were weight 43%, appearance 23% and image lag 20%	↑	↑	↑	↓	Younger, longer duration of sight loss, better baseline CS and higher use of electronic devices explained 41% of the increased willingness to use
Deemer (2019)[52]	Observational study, testing effectiveness and use of two approaches to magnification within a wEVES	Functional vision improvements in reading and visual information processing. No improvement in patient-reported visual-motor function or mobility. Mean usage 71.8 min daily for TV, faces and reading. 37% reported the device as 'easy to use'	Activity Inventory: Overall goal ability ↑, visual-motor function (manipulation) →, mobility →, reading ↑ and visual information ↑. Outside home function ↑, inside-the-home function ↑					SSQ 17% headache 13% nausea 7% moderate eyestrain. Symptoms showed little change over time
Lam (2020)[53]	Pre-pilot study to examine capabilities and efficacy of novel hardware and image remapping software device 'Oculenz', for participants with AMD	Mean critical print size for reading improved from 6/55 to 6/24 (reported as 20/182 to 20/80) with Oculenz without magnification	Improvement in facial recognition (no data reported)		↑		→ (@N30)	

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TABLE 4 (Continued)

Author	Purpose	Main finding	Other findings	Distance acuity	Near acuity	CS	Reading speed	Factors affecting device use or discontinuance
Werblin (2020)[54]	Measure the effectiveness of IrisVision in improving QoL and assess the ability of the device to produce functional and behavioural improvements	75% of users were men. 80% used the device ≥3 h/day. 50% of users find new applications for the device after 7 weeks of use	79% used for recognising near detail, 95% used the device for viewing TV and streaming video					75% of users were found to be men
Yeo (2020)[55]	Evaluate the clinical usefulness of a Samsung VR wEVES for users with VI	Significant improvements in DVA, IVA, NVA, CS and reading accuracy with the device after 2 weeks of home use. Reading speed did not change	Non-validated 'self-evaluation function score' shows ↑ face recognition, ↑ TV or movie watching, ↑ short-distance reading, ↑ long-distance reading, → walking alone, → writing	↑	↑	↑	→	Level of vision or use of existing low-vision devices did not affect improvement in self-assessment function score. VA did not affect levels of satisfaction
Kammer (2021)[56]	Examine the performance of the Eye-01 device with reading and sample tasks of daily life for people with AMD	Improvement in CPS with the device compared with habitual vision	VA LVLFQ-48 no data reported on the effect of wEVES Improved ability to complete TIADL with device compared with spectacles (numbers able to complete a task). Search bill = 5 specs 12 devices; Identification of cans = 3 specs 16 devices; Grocery store signs = 2 Specs, 11 devices	↑	↑			No baseline measures are predictors of users who improve in task function. Presence of ring scotoma linked to adverse reading performance
Lorenzini (2021)[57]	Randomised study exploring the effect of telerehabilitation on QoL and functional vision in individuals with VI using eSight	Improvement in functional vision and users' quality of life with the device. The effect is independent of telerehabilitation or manufacturer self-training program	VA LV VFQ-48 Overall ↑ PIADS ↑ QUEST ↑ Baseline to 3/12 → Baseline to 6/12					SSQ scores were stable over a 6-month study. Symptoms were predominately mild and oculomotor-related symptoms

Abbreviations: ↑, statistically significant increase; →, no statistically significant change; ↓, statistically significant decrease (compared with habitual vision); AMD, age-related macular degeneration; CPS, critical print size; CS, contrast sensitivity; DVA, distance visual acuity; IVA, intermediate visual acuity; MLVAI, Melbourne Low-Vision Activities of Daily Living Index; NVA, near visual acuity; PIADS, Psychosocial Impact of Assistive Devices Scale; QUEST, Quebec User Evaluation of Satisfaction with assistive Technology; specs, spectacles; SSQ, Simulator Sickness Questionnaire; TIADL, Timed Instrumental Activities of Daily Living; VA LV VLFQ-48, Veterans Affairs Low-Vision Visual Functioning Questionnaire; VI, visual impairment; VR, virtual reality.

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TABLE 5 Findings from first-generation wearable electronic vision enhancement systems (wEVES) intervention studies.

Author	Purpose	Main finding	Other findings	Distance acuity	Near acuity	CS	Reading speed	Promotors to success with wEVES
Thierfelder (1998)[40]	Assess the LVES as a solution for people with VI who had unsatisfactory outcomes from traditional rehabilitation means	25 people tested: 5 (3 AMD) achieved 'satisfactory reading and writing', 1 (1 AMD) 'satisfactory reading'	A potential solution for those with macular disease who cannot be rehabilitated in a comparable way with more straightforward aids					Central vision loss, including AMD. People with few other existing coping strategies
Ortiz (1999)[41]	Assess the effectiveness of LVES, as a reading solution for people with VI compared with a CCTV and large print with specs	Reading performance (speed and comprehension) is equivalent with LVES and CCTV	Critical print size improves with LVES compared with habitual vision. Reading speed is equivalent with the device compared with large print		↑ Spectacles		→ CCTV → spectacles	Due to display resolution, LVES is only beneficial to users with acuity of 6/30 to 6/120
Ballinger (2000)[42]	Multicentre study to determine the effectiveness of LVES as a visual rehabilitation device	Users showed improvement in distance VA and CS compared with HV. Improvement was the same in AMD and non-AMD groups	After an extensive training programme (median 8 h), median use of the device at home was 2 h/day	↑ HV →Bins		↑ HV		Due to display resolution, LVES is only beneficial to users with an acuity 6/24 to 6/240
Sonsino (2000)[43]	Compare speed and accuracy of text reading using 'Powervision', CCTV and optical magnifiers	Powervision reading slower and less accurate than CCTV and optical magnifiers	Powervision has lower mean rating of 'ease of use' than CCTV and optical magnifiers		↓ CCTV ↓ LVA		↓ CCTV ↓ LVA	
Weckerle (2000)[44]	Evaluate task performance with the LVES regarding daily living activities such as reading, writing, CS, and mobility	Objective measures of CS improved	Subjective assessment of reading and walking improved			↑ HV		Tasks needing <8× mag. Younger users who were better at handling the device and those with fewer existing coping strategies
Peterson (2003)[45]	Examine whether the objective performance of near tasks is improved with various EVES compared with the subject's own optical magnifier	All manipulation and reading tasks were slower with HMD than with CCTV or optical magnifier. Manipulation with HMD may be improved by see-through simultaneous vision design	Self-reported 'ease of use' of wEVES was similar to optical magnifiers but less than CCTV. HMD showed faster reading speed, but slower column change than optical magnifiers				↓ CCTV ↓ Mouse / screen ↑ Optical mag	Previous EVES experience shows no difference in reading speed, size, or functional activities compared with novice users

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TABLE 5 (Continued)

Author	Purpose	Main finding	Other findings	Distance acuity	Near acuity	CS	Reading speed	Promotors to success with wEVES
Culham (2004)[46]	Compare four wEVES and determine performance differences for laboratory-based clinical measurements and practical visual tasks for users with macular disease	Optical aids remained the best devices for optimum functioning for the majority of tasks	Some wEVES performed better than optical devices for individual users and specific tasks. No single wEVES was consistently superior overall or suited the majority of users	wEVES vs. optical LVA ↓ N ↑ J ↑ F	wEVES vs. optical LVA ↓ N ↓ J → M → F	→ wEVES vs. Spectacles	↓ wEVES vs. optical LVA	No consistent predictors of wEVES benefits. Trends suggest better success with younger people & those familiar with technology and CCTV, especially for high acuity tasks
Goodrich (2004)[47]	Compare reading performance using a prototype HMD laser display (NOMAD), CCTV, and optical magnifier	Reading speed with wEVES is similar to an optical magnifier but slower than a CCTV	wEVES gave a longer reading duration than an optical magnifier and similar to a CCTV				↓ CCTV → Optical Mag	

Abbreviations: AMD, Age-related macular degeneration; Arrows indicate the comparison of wEVES with another solution: ↑, statistically significant increase; →, no statistically significant change; ↓, statistically significant decrease; bins, optical distance binocular magnifier; CCTV, closed-circuit television magnifier; CS, contrast sensitivity; EVES, electronic vision enhancement system; F, Flipperport; HMD, head mounted display; HV, habitual vision; J, Jordy; LVA, low-vision aid (optical); LVES, low-vision enhancement system; M, Maxport; N, NuVision.

limited field of view, poor depth perception and lack of binocular disparity offered by the device account for the lack of improvement.[52] Others conclude that fully immersive wEVES predominantly benefit sedentary rather than dynamic tasks.[55] While the open-sided eSight design is not specifically designed for movement, it was suggested that the lack of degradation in mobility demonstrated the need for more research into the potential for the semi-immersive device to support dynamic tasks safely.[50]

Objectively assessed ability to complete daily living tasks also improved with wEVES compared with habitual function, as evaluated by the Melbourne Low-Vision Activities of Daily Living Index (MLVAI) or TIADL tests. Melbourne Low-Vision Activities of Daily Living Index (MLVAI)[50] or TIADL tests.[50,56] TIADL tests showed that wEVES increased the number of users able to search a bill, find a can on a shelf or read overhead signs[56] and show significant improvement in facial expression recognition.[50,55]

Only first-generation devices have compared users' abilities with wEVES to their other coping strategies. These studies showed that wEVES offered no improvement over other optical or electronic magnifying solutions for tasks including writing a cheque, identifying grocery items[46] or reading maps and medicine bottles.[45,47] Further research is indicated to understand the relative benefits of the newer generation of devices compared with existing coping solutions.

It is well accepted that the psychometric properties of subjective Likert scale questionnaires can be optimised by the use of Item Response or Rasch theory to convert ordinal data to interval measurements.[72] The Veterans Affairs Low-Vision Visual Functioning Questionnaire (VA LV VFQ 48),[73,74] the MLVAI[75] and the Activity Inventory[76] have been developed using Rasch analysis for adults with low vision and have demonstrated good psychometric properties[77] The 'self-evaluation function score'[55] cannot be regarded as a high-quality outcome measure as ordinal Likert rating values were summed and the instrument was not validated. Assessing the ability to complete an activity of daily living allows examination of specific tasks in greater detail, and when these are timed will result in interval data. However, objective and subjective outcome measures of the same activity will not provide the same findings,[78,79] with subjective measures influenced by psychosocial factors such as depression.[80] Future research should ensure that the functional improvements provided by wEVES are both tested and analysed using broad high-quality instruments that demonstrate interval measurement properties.

Subjective changes in quality of life

It is unsurprising that the included studies have not used a measure of Health-Related Quality of Life to assess the impact of wEVES, as these have been shown to have

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TABLE 6 Summary of findings from papers related to the usability and design of first- and second-generation wearable electronic vision enhancement systems (wEVES).

Author	Purpose	*n* (*n* AMD)	Outcome measures	Main outcomes	Other findings	Comfort/aesthetics	Promotors to success	Functional utility
Culham (2009)[58]	Elicit users' responses to using four wEVES and correlate opinions with performance	20 (10)	Modified VF14 and bespoke structured questionnaires rating aesthetics and performance (1 pre and 1 post)	Opinions on devices not predicted by age, gender, diagnosis, or previous CCTV experience	Newly diagnosed patients responded most positively to wEVES	Comfort was influenced more by weight than size. Comfort, although important, was not predictive of rating once magnification had been considered	Image quality and magnification are the most critical factors in the overall subjective rating of the devices	0.30 logMAR and 60 wpm are the levels at which users perceive the device is starting to fulfil their requirements
Profita (2016)[59]	How does a user's disability affect judgments of social acceptability of wEVES	1200	Structured questionnaire using a 5-point Likert scale to gauge response to videos showing wEVES use with and without disability	Fully sighted observers considered HMD use more socially acceptable if being used to support a person with a disability	When informed of user's disability, interactions were rated to be less awkward and viewers considered the user to be less rude		'The social weight of a device can drastically impact adoption and use of that device'	
Zolyomi (2017)[60]	Understand social and emotional impacts associated with early adopters of eSight	13 (2)	Semi-structured interviews (critical incident technique)	People with VI should be thought of as having 'skilled vision'. Designers should design compatible technologies based on the users' abilities	Users describe tensions between their wish to enhance their vision, their skills using technology, and expectations of what technology can offer	In some social situations, opacity and bulkiness of the headgear interfered with the ability to interact in a naturalistic manner	Participants show diversity in opinion. Participants describe changes in their emotional readiness to adopt AT	
Hoogsteen (2020)[61]	Examine how wEVES are perceived and the factors that influence adoption	29 (5)	Telephone semi-structured interviews exploring attitudes towards wEVES as assistive tools	Designs need to balance functionality, aesthetics, and device interaction	No consensus on the method of interaction with wEVES. 48% (14) preferred buttons as this allows the device to be used inconspicuously	Inconspicuous device design is key to use for 66% (19) of users. However, almost half would use publicly if they offer functionality	Most participants preferred a compact device with appearance of spectacles. Most willing to carry small support devices	

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TABLE 6 (Continued)

Author	Purpose	*n* (*n* AMD)	Outcome measures	Main outcomes	Other findings	Comfort/aesthetics	Promotors to success	Functional utility
Kumagai (2020)[62] Jeganathan (2019)[63]	Explore the factors impacting preference for wEVES among individuals with VI	20 (5)	IVI and semi-structured interviews rating aesthetics, performance, and device preference	Ocular pathology and self-reported well-being produce differences in user-selected device and relative importance of design factors	Users ranked ease of use (especially of controls and screen) equally as important as visual improvement		Visual improvement, usability and contrast enhancement were main promotors for users with AMD	No participants could imagine using devices for walking
Starke (2020)[64]	Quantify visual task demands to understand user requirements and device design	32 (7)	One-week self-recording study using a spectacle-mounted camera to identify when a perfect visual aid is needed	Users had no aid or coping strategy for 57% of recorded activities. 'Perfect LVA' needs to be flexible to meet diverse needs of users	49% of tasks were reading. Tasks identified: 78% indoors, 58% at home, 68% object of interest within reach		Quick start-up, multi-plane of focus, ideally facilitates walking, large dynamic range, high magnification	Three most common tasks: finding something on a shelf, reading package labels and using appliance dials, buttons, and remotes
Golubova (2021)[65]	Define the visual task needs of those living with sight loss	32 (7)	Bespoke structured questionnaire following 1 week use of a spec-mounted recording device	Lack of consistency and diversity in responses suggestive of different user clusters with divergent design needs	Most tasks <5 min. Disagreement between users. Priority 63% quick, 28% longer tasks Although wearable, a lot of users would carry and use ad-hoc	Half of participants had concerns about aesthetics, and the device is 'conspicuous or labelling'. However, opinion is split as 25% had no concerns	Themes for a 'perfect' LVA: portability, magnification, and reliable performance	Reading is the most important and frequent task. Large variety of other tasks with no correlation between frequency and importance to user
Lorenzini (2021)[66]	Determine predictors of the continued use of a head-mounted LV device	109 (18)	Online survey: Adapted PIADS and QUEST. Bespoke structured questionnaire to explore use and discontinuance	Device-related QoL measures were robust predictors of device continuance	LV rehabilitation experience, demographics, ocular, or general health did not predict sustained use	Main reasons for device discontinuation: 29% weight, 21% discomfort, 13% image quality, 13% embarrassment	Higher PIADS and QUEST scores and lack of headaches with the device best predictors of success. Successful users more likely to be older and better educated	

(Continues)

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TABLE 6 (Continued)

Author	Purpose	*n* (*n* AMD)	Outcome measures	Main outcomes	Other findings	Comfort/aesthetics	Promotors to success	Functional utility
Ruffieux, (2021)[67]	Understand difficulties, needs and expectations of 'smartglasses' for people with VI	50 (11)	NEI-VFQ 25 and two novel questionnaires: Difficulties in Recognising Faces and Emotions (DRFE) and Expectations on Smart Glasses as Assistive Device (ESGAD)	Differing pathologies shared similar expectations regarding functionalities to improve social interactions	Differing daily needs identified across pathologies, and therefore devices need to offer individualised solutions	Importance of device design and comfort highlighted. Design should avoid stigmatisation	Desirable Features: Hands-free; Audio for more extended info only; Contrast change; Specs able to be worn underneath	Differing ocular pathologies caused changes in expected functionality for wEVES. Facial recognition & reading are the primary needs for people with AMD
Weir (2021)[68]	To understand user opinion on the design of document reader VR for people with VI	11 (2)	Semi-structured interviews exploring usability and user preferences for a wEVES	Proposed a 10-point framework for people designing HMD applications for people with VI	Preferred method of interaction: 55% (6) controllers, 36% (4) voice 9% (1) both	Frequent complaints of problems with device weight, especially with older users. Need for simple, intuitive, natural controls		

Abbreviations: AMD, Age-related macular degeneration; AT, Assistive Technology; CCTV, closed-circuit television; HMD, head mounted display; IVI, Impact of Visual Impairment questionnaire; LVA, low vision aid; NEI-VFQ 25, National Eye Institute Visual Function Questionnaire 25; PIADS, Psychosocial Impact of Assistive Devices Scale; QoL, quality of life; QUEST, Quebec User Evaluation of Satisfaction with assistive Technology; VF-14, Visual Function Index; VI, visual impairment; VR, virtual reality.

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TABLE 7 Summary of papers related to adverse effects and simulator sickness.

Author	*n* (*n* AMD)	Age	Purpose	Main finding	Other findings
Chauvire (2013)[69] CA	23 (12)	62–81, Mean 70	Assessing the impact of image size and movement in an HMD on the balance of people with AMD compared with age-matched controls	Visual motion generated by the HMD did not induce stronger balance disruption in users with AMD than in control subjects	Immersive VR causes more balance disruption than non-immersive AR for all participants
Chun (2021)[70] CA	21	Mean 65.3	2–4 week home trial investigating the impact of pupil decentration and heterophoria on SS symptoms in users of the IrisVision device	No correlation between phoria measures and SS symptoms	Predicted phoria measures using the HMD correlate well with Maddox Rod findings
Luu (2021)[71]	52 (17)	Mean 66.49 (7.32)	To understand how vision changes caused by different eye diseases affect the processing of visual information critical for self-motion perception	Users with AMD reported reduced severity and frequency of cybersickness on the Fast Motion Sickness scale compared with healthy controls	Users with AMD experienced greater self-motion perception and immersion in the virtual world compared with healthy controls

Abbreviations: AMD, Age-related macular degeneration; AR, augmented reality; CA, conference abstract; HMD, head-mounted display; SS, simulator sickness; VR, virtual reality.

lower sensitivity to rehabilitation interventions compared with Vision-Related measures of Quality of Life (VRQoL).[14] However, only two studies were found that used any measure to assess the changes of VRQoL due to wEVES.[57,66] The Psychosocial Impact of Assistive Devices Scale (PIADS) was used in a study of 57 eSight users to understand the impact of a telerehabilitation training package on the functional independence, well-being and quality of life of the user compared with the manufacturer's conventional coaching.[57] Device usage led to improvements in assistive technology-related quality of life in both groups between 2 weeks and 3 months of use but not between baseline and 2 weeks. The improvement lag was suggestive of a necessary but brief period of adaption to the device and how it fits into the regime of users' existing coping strategies. Change in PIADS scores was not dependent on the training method (conventional coaching or telerehabilitation), but device purchasers had higher scores than renters. It was suggested that an element of cognitive dissonance due to the amount spent on the device may have influenced scoring. In a separate online survey of 109 (18 AMD) existing eSight users in North America, higher PIADS scores were also associated with sustained device use.[66]

Psychosocial Impact of Assistive Devices Scale is a 26-item PROM assessing the impact of assistive technologies on a person's competence, adaptability and self-esteem.[81] The outcome measure is a summed ordinal score and has not yet been psychometrically evaluated with Rasch analysis, which would enhance confidence in the quality of the instrument.[72] However, it has been shown in a systematic review to be reliable with good content, validity and test–retest reliability.[82] The paucity of studies assessing the effect of wEVES on the QoL indicates the need for further work to explore if the observed changes in mixed populations are reproduced in studies specifically for people with AMD.

Use and usability of wEVES

Task analysis

Analysis of occasions when a wEVES would be used has been examined using a survey of 50 people with VI ($n = 11$ AMD)[67] and by observation of 32 visually impaired users ($n = 7$ AMD) wearing a spectacle-mounted camera to film when a 'perfect' wEVES was required.[64] There was consensus between studies that reading was the main priority for device usage, with near activities accounting for 49% of all tasks captured in the observational study. The survey segmented results by pathology and noted that participants with AMD expressed less need for mobility and locating items compared with people with glaucoma or retinitis pigmentosa, suggesting the need for tailored solutions to meet the differing needs and expectations of potential users of wEVES.

The two studies fundamentally differed in their findings regarding the need of devices for facial recognition. Facial recognition was a main priority in the survey but ranked 42 out of the 56 tasks identified in the observational study. Significant variation between the studies may be due to the recording methods used to gather data. The need to wear a device to document difficulty within a social setting may cause a disparity in findings compared with idealising a situation within a survey group. It should be considered whether desirability to use a device for a specific task may be tempered by the social constraints of doing so.

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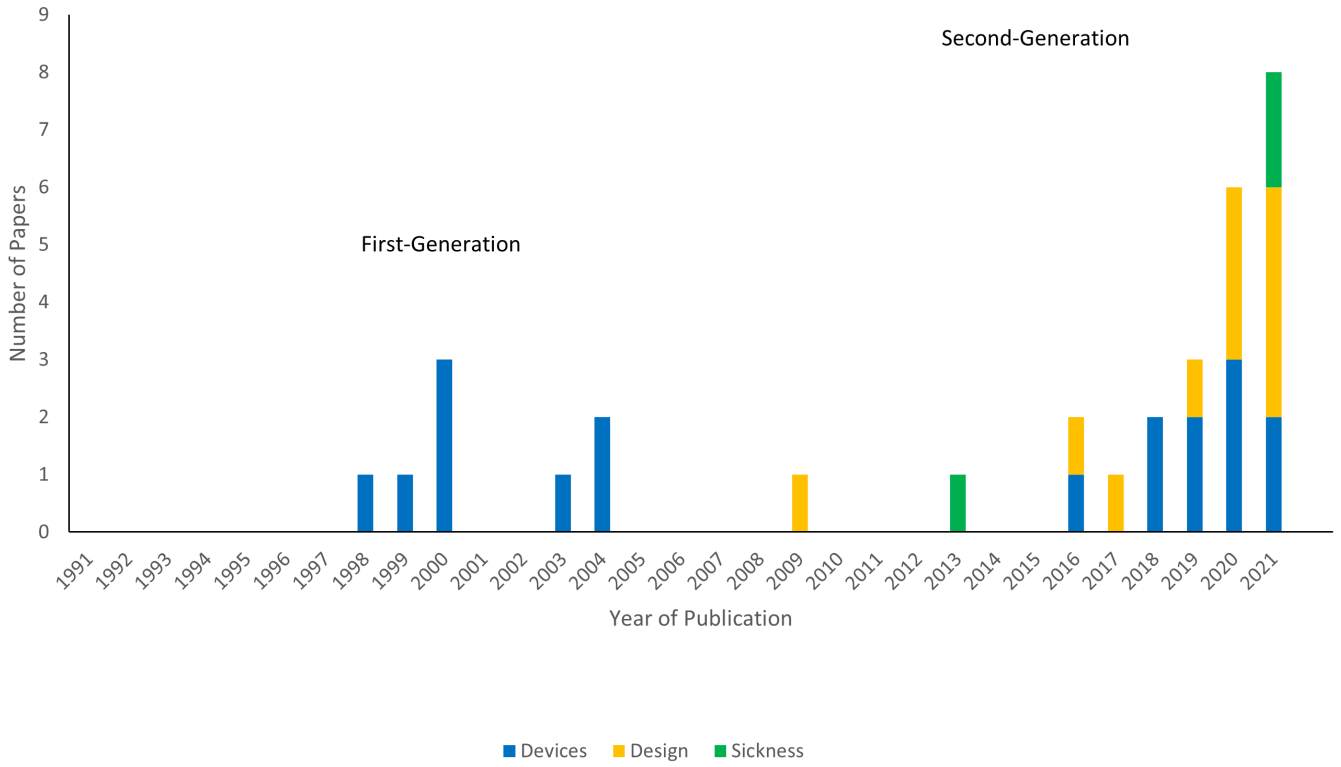

FIGURE 2 Date and type of publication of included articles. 'Devices' indicates publications reporting an experimental intervention with a wEVES; 'Design' indicates a paper showing the use or usefulness of a device and 'Sickness' are papers discussing adverse effects and simulator sickness with wEVES. wEVES, wearable electronic vision enhancement systems.

Imagined[51] and actual[52,54] use of a wEVES were also assessed by semi-structured interviews following a trial or purchase of a device. It was found that watching TV, recognising faces and elements of detailed work such as reading were the times when devices were reported or perceived to be useful by participants. In addition, self-reported time using the device was described in two of these studies. Data indicated a large disparity, with the face-to-face interview showing a mean of 71.8 min/day[52] and the participants of the telephone interviews reporting that 80% of users were using the device for 3 h and 25% 'nearly full-time'.[54] It is unclear if this disparity is due to inconsistency with self-reporting of this type of data or because the telephone interviewees were purchasers of the device rather than new users. Further studies using objective recording of usage are needed to explore and validate these findings.

Design of device

Several studies exploring users' opinions of wEVES suggested that the aesthetics of the device are of considerable interest, with the weight of the device being the principal design concern for users.[47,51,58,66,68] Semi-structured interviews with 29 people with VI (n = 5 AMD) from Belgium, the Netherlands and the United Kingdom also found that participants had greater concerns about the appearance of the device than its functionality.[61] 66% of respondents stated the wish for an inconspicuous device that appears like a pair of conventional spectacles, with tactile buttons rather than audio controls to aid discreet use. However, studies do reflect a level of polarisation of user views, with some users being significantly more motivated by the device's functionality despite any aesthetic issues.[60,65] Some of this split may have been based on pathology[62,63] or demographic lines, with one paper reporting, 'participants explained that they care more about functionality over aesthetics due to their age'.[61] While there is a degree of consensus on some areas of design, the broad diversity of opinion indicates the requirement for customisation within devices to meet users' needs.

A survey of 1200 people without VI in the United States found a negative reaction to images of a person using a wEVES-type device in public, citing concerns the device could be used for covert recording and surveillance.[59] However, acceptability did increase as respondents understood the device was being used to support a user's disability. The creation of wEVES that 'almost' look like spectacles, while desirable to those wearing the device, may create a less empathetic dynamic for the public in understanding their use. Social pressures can considerably impact the potential adoption and use of a device; therefore, it is to be considered if wEVES use within the VI community will only become socially accepted as HMDs are more ubiquitous in the mass market. Ultimately, the success of wEVES may be driven by innovation for people without visual disabilities.

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Factors relating to the successful use or abandonment of devices

Several studies have considered factors that correlate with or promote successful wear within their secondary outcomes. These include improvement in vision produced by the device,[58,62,63] more use of mainstream technology[46,51] and the absence of ring scotoma.[56] A survey of purchasers of the IrisVision device in the United States found that 75% of ongoing users were male, despite demographics suggesting a higher proportion of VI in females.[54] It is unclear if this variation was a peculiarity of the population responding or indicative of a broader appeal of devices to men rather than women.

Despite the significant improvements in visual function and functional ability that these devices provide, studies show considerable levels of dropout and disinterest in purchasing. The issues identified include discomfort, insufficient benefit and handling difficulties,[50] weight, appearance and image lag.[51] In addition, subjective reporting of 'ease of use' of first-generation wEVES was lower than a comparable desktop EVES.[43,45] Second-generation devices' subjective 'ease of use' has been investigated using a single 5-point Likert scale but without comparison with other coping solutions or objective assessment.[52,55] One investigation reported strong agreement that the device was easy to use,[55] with another reporting 11 out of 30 participants agreeing that the device was 'very easy to use'; however, considerable numbers of these participants still found focusing (27%) and controls (20%) 'hard to use'.[52] The only study that investigated factors related to the successful use of wEVES as its primary outcome surveyed 109 eSight users living in North America to identify factors correlated with 'device discontinuance'.[66] The best predictors of sustained use were greater functional independence, quality of life of the user with the device (PIADS), absence of headaches with the device and higher satisfaction with technology and the service received at fitting and follow-up (QUEST). For clinicians looking to dispense wEVES, this is suggestive that psychological factors contribute to the success or abandonment of devices. However, it should be noted that the online nature of the study precluded any objective assessment of visual function as a potential factor. Furthermore, this study evaluated factors related to the continued use of a purchased device, and so findings cannot be extrapolated to predict the views of those who do not purchase due to dissatisfaction at the demonstration stage or those unable to buy due to cost.

Studies with second-generation devices reported no correlation between successful usage with the length of time with disease, co-morbidity, education levels[66] or use of existing devices.[55,66] These findings are at odds with the conclusions of a study of first-generation devices, which reported a trend suggestive of more success with younger, more technically capable participants.[46] The differences could indicate the greater complexity of the early wEVES compared with more modern designs or the increasing confidence and familiarity of people of all ages with touch screens and other technology in the intervening years.

Abandonment of assistive devices is common across all areas of rehabilitation, with estimates of discontinuation varying between 20% and 83%.[83,84] Device abandonment of the eSight was reported to be at the lower level of the range, i.e., between 17.4%[66] and 23%[50] discontinuation following a comprehensive demonstration phase. Further research work to understand the take-up rate of devices from initial demonstrations would be helpful to prescribing clinicians.

As with other design characteristics, there appears to be division and diversity in thought about promotors to success, but there is an indication that both practical and psychological factors tend to influence continued usage. There are multiple factors at play that may not be split on simple demographic or pathological grounds and indicate a need for an individualised approach to prescribing.

Adverse effects and sickness

Simulator sickness is caused by conflict between visual and vestibular systems due to a lag between display updates and head rotation. It is a common side effect in healthy individuals using an HMD and is typically less severe and of lower incidence than motion sickness.[71] Preliminary data from 50 IrisVision users with low vision suggest that SS symptoms are unrelated to the measured phoria of the user.[70]

Two investigations (Table 3) used the Simulator Sickness Questionnaire (SSQ)[85] as a tool to evaluate SS with the fully immersive IrisVision[52] and the semi-immersive eSight devices.[57] Symptoms tended to be 'slight' or 'moderate', with both studies finding the most significant symptoms related to oculomotor function, including headache and eyestrain. This finding echoed other work showing the absence of headache as a predictor of continued use of the eSight device.[66] SSQ was found to be stable during the 7- to 10-day home trial[52] and throughout a longer 6-month follow-up.[57] While symptoms did not increase over time there is also an indication that those presenting with early manifestations of SS may find them to be persistent.

Crossland et al.[51] reported the frequency of adverse effects with a fully immersive VR headset, noting symptoms to be relatively uncommon and resolving spontaneously upon removal of the device. The most common symptom reported was dizziness (7%), and as people with VI are already at increased risk of falls,[86,87] careful consideration of potential adverse effects needs to be made when dispensing wEVES.

Two laboratory-based studies directly evaluated the experience of HMD use for individuals with AMD (Table 7). A conference abstract by Chauvire et al.[69] showed that using an HMD in immersive form produced balance instability for all individuals, but the findings were similar in users with AMD to age-matched, fully sighted controls. A more recent

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peer-reviewed paper investigating 'vector motion' and cybersickness in HMD found that self-motion was perceived differently by people with peripheral vision loss, central vision loss and those with full sight. It was found that people with AMD experienced deeper immersion in the VR world with an HMD but lower levels and milder intensity of cybersickness compared with their fully sighted controls. It was proposed that this was due to VI lessening the sensory conflict created by the device.[71]

An understanding of the risks of SS is beneficial to prescribers. The evidence shows that symptoms tend to be relatively mild, stable and resolve quickly upon removal of the device. Thus, it is suggested that those experiencing symptoms at an initial assessment for devices should be evaluated more critically for their long-term suitability for a wEVES.

Cost–benefit analysis

No papers that conducted a cost–benefit analysis with wEVES were found. Three articles were found that used a willingness-to-pay model to show a sense of the value of the devices to populations with central vision loss, including AMD. A 2009 UK-based comparison study of four different wEVES asked 20 people with early- and late-onset macular disease about their willingness to pay for the devices at the initial fitting and following a 2-week home trial. Willingness to pay directly correlated with their overall rating for each device tested; however, it did not correlate with clinical visual performance. At the initial clinical assessment, willingness to pay ranged from £0 to £2000 (pounds sterling), with a mean of £366 (SD £71).[58] In a 2019 observational study of second-generation devices in the United States, 30 users were asked about their willingness to pay following a 7- to 10-day home trial.[52] A bidding format was used, with participants being asked if they would pay decreasing amounts starting at US $20,000 until they indicated a willingness to purchase. Participants' final bids ranged from $15,000 to $2, with a median bid of $1250.

Both studies looked at the impact of willingness to pay over time. The first-generation devices showed a decrease in the numbers willing to purchase and in the mean amount participants were willing to pay following a home trial.[58] In a follow-up conference abstract of the second-generation device, six of the 33 participants were willing to purchase the device following a home trial; one within the first quartile of use, two each in the second and third quartiles and one within the fourth quartile.[88]

In both studies,[52,58] willingness to pay was significantly below the market cost of the devices. This mismatch of value and price may be affected by polarisation between those seeing utility, and hence value, in the device compared with others for whom the wEVES was less successful. Alternatively, as users were willing to pay the cost of a 'high-end video camcorder'[58] it is suggested that value might be led by the price of mass-market consumer electronic goods as opposed to devices specifically designed and engineered for niche consumer demand.

Opinion and purchasing intent tend to develop and emerge over time, and the value expressed may not reflect the devices' total cost. This mismatch establishes a need for practitioners to identify and support suitable candidates over time rather than relying on a single demonstration followed by a decision to purchase.

LIMITATIONS

All the reviewed papers examined study populations including people with AMD; however, most included participants with a range of ocular pathologies. Frequently, studies do not segregate findings by pathology and tend to homogenise the needs of people with AMD among the population of people with VI with differing demographic and visual needs. This process often makes it impossible to disentangle and add weight to findings within mixed demographic studies and apply them to the population of interest in this review. Therefore, the overarching findings of a study may not apply or may be at odds with the individualised needs of people with AMD. Where studies have separated AMD from other pathologies, they have shown differences in the potential usage of devices and preferred design characteristics.[62,63,67]

Many studies evaluating second-generation devices are sponsored or authored by people with commercial interests in the devices. This potential conflict of interest in the scope of the study or the selection of findings is candidly acknowledged in one paper recognising that corporate sponsorship of research leads to questions about bias. But they counter that in a time of austerity, working in an area that does not require research data prior to the release of wEVES, 'close cooperation with industry is one of very few options in our drive to present clinically relevant data that advance rehabilitation best practices'.[50]

RECOMMENDATIONS FOR FUTURE RESEARCH

With the emergence of wEVES, it was recognised that there was 'a pressing need for a prospective controlled trial of these devices versus conventional LVAs'.[89] While this need was addressed to some degree with papers looking at first-generation wEVES, more recent papers evaluating second-generation wEVES have generally considered improvements compared with habitual vision, in isolation from other coping strategies (see Table 3). Evidence of improvement compared with a baseline situation is of considerable interest to prove the concept of utility in a new device. However, it does not provide prospective users with relevant information on what type of device may be best suited to their needs. Furthermore, wEVES are generally

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considerably more expensive than other rehabilitative devices, and in the United Kingdom are more likely to be purchased by a user rather than loaned to them by the NHS. The prospective user therefore requires information not only regarding the relative functional improvements provided by wEVES but also their cost–effectiveness. A device that provides slightly greater improvement in functional ability but is considerably more expensive than an alternative may be less attractive. To answer questions about what type of device is most suitable for a user requires comparative studies of currently available wEVES with other coping solutions.

In evaluating the benefits of wEVES compared with other devices, care needs to be taken in the selection of appropriate and robust outcome measures. It is important to consider not only improvement in VI through assessment of clinical visual function but also the impact of devices on activity limitation and the quality of life. Activity limitation can be assessed objectively through observed ability to complete specific ADL, whereas activity limitations and quality of life can both be assessed subjectively using PROMs. Within the papers selected, there was no evidence of participant co-design to ensure the applicability of the outcome measures to those potentially using the device. In future research, it is recommended that the design of the study includes measures chosen to ensure both validity and relevance to the population of interest. In addition, attention should be paid in the selection and analysis of outcomes to using high-quality instruments that demonstrate interval measurement properties and are targeted to participants' function.[72]

Finally, a range of different factors need to be considered in the evaluation of wEVES. Improvement in functional ability, quality of life and cost have been mentioned above, but cosmesis, ease of use, practicality, versatility, safety and availability are also issues of practical relevance to prospective users. 'Competitive enablement' has been proposed as a conceptual approach to evaluate the suitability of EVES for non-generic characteristics.[90] This model proposes that different competing devices are evaluated by consumers while they perform a series of self-identified problematic tasks that are selected by the users as relevant to their daily life. Within this structure, the full range of benefits of wEVES could be appraised against different coping solutions for people with AMD.

CONCLUSION

Wearable electronic vision enhancement systems produce hands-free image enhancement and can potentially support the needs of people with VI, including those with AMD, in a new and revolutionary way. There is clear research evidence showing improvements in acuity, contrast and aspects of laboratory-controlled daily activity compared with baseline measurements without devices. There are also data showing ongoing use after purchase and, by extension, implied effectiveness of devices. However, the limiting field of view and detachment from the real world means that the benefit from these devices tends to restrict their current usefulness to predominately sedentary tasks.

It is not only visual output that predicts the successful use of wEVES: design and form considerations of the current devices and self-reported well-being can influence the successful use of the device. Adverse effects with the devices tend to be minor and resolve quickly with device removal; however, those reporting early symptoms may find them to be persistent.

Many studies have explored wEVES with mixed groups of people with different pathologies and demographics. The diversity of user opinion and multi-factorial influences on success shows that it is impossible to homogenise the needs of people with VI. To understand the idiosyncratic benefits of wEVES for people with AMD better, further patient-centred research should be directed towards this group's individualised needs and expectations.

Finally, there is scant research looking at the benefits of second-generation devices directly compared with other assistive solutions. To allow professionals and users to make better prescribing and purchasing decisions, the benefits of wEVES should be assessed by users with AMD performing tasks relevant to their lifestyle and most importantly, compared directly with other coping strategies. With this information, we will better understand the usefulness of wEVES for people with AMD.

AUTHOR CONTRIBUTIONS

Andrew Miller: Conceptualization (equal); data curation (lead); formal analysis (equal); investigation (lead); methodology (lead); project administration (lead); validation (equal); writing – original draft (lead); writing – review and editing (equal). **Michael D. Crossland:** Conceptualization (equal); funding acquisition (equal); methodology (supporting); supervision (equal); writing – review and editing (equal). **Jane Macnaughton:** Conceptualization (equal); methodology (supporting); supervision (equal); writing – review and editing (equal). **Keziah Latham:** Conceptualization (equal); data curation (supporting); formal analysis (equal); funding acquisition (equal); methodology (supporting); project administration (supporting); supervision (equal); validation (equal); writing – original draft (supporting); writing – review and editing (equal).

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CONFLICT OF INTEREST

The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

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ORCID

Andrew Miller https://orcid.org/0000-0001-7811-0152
Michael D. Crossland https://orcid.org/0000-0001-6833-6043
Jane Macnaughton https://orcid.org/0000-0001-5593-5274
Keziah Latham https://orcid.org/0000-0002-4060-0006

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