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Abstract: Low-vision conditions resulting in partial loss of the central visual field strongly affect patients' daily tasks and routines, and none more prominently than the ability to access text. Though vision aids such as magnifiers, digital screens, and text-to-speech devices can improve overall accessibility to text, news media, which is non-linear and has complex and volatile formatting, is still inaccessible, barring low-vision patients from easy access to essential news content.
This position paper proposes virtual reality as a promising solution towards accessible and enjoyable news reading for low vision. We first provide an extensive review into existing research on low-vision reading technologies and visual accessibility solutions for modern news media. From previous research and studies, we then conduct an analysis into the advantages of virtual reality for low-vision reading and propose comprehensive guidelines for visual accessibility design in virtual reality, with a focus on reading. This is coupled with a hands-on survey of eight reading applications in virtual reality to evaluate how accessibility design is currently implemented in existing products. Finally, we present a proof-of-concept using browser-based graphics to demonstrate the feasibility of our proposal with modern virtual reality technology.

Key-words: human-computer interactions, accessible reading, low vision, virtual reality

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Vers une conception accessible de la lecture d'actualités en réalité virtuelle pour la basse vision

Résumé : Les conditions de basse vision entraînant une perte partielle du champ visuel affectent fortement les tâches et les routines quotidiennes des patients, et aucune de celles-ci n'est plus notable que la possibilité d'accéder à du texte. Bien que les aides visuelles telles que les loupes, les écrans numériques et les dispositifs de synthèse vocale puissent améliorer l'accessibilité globale au texte, les médias d'information, qui sont non linéaires et présentent un formatage complexe et volatile, sont toujours inaccessibles, empêchant ainsi les patients malvoyants d'avoir accès aux contenus des nouvelles.

Ce papier positionne la réalité virtuelle comme la prochaine étape vers une lecture de nouvelles pour la basse vision, qui soit accessible et agréable. Nous menons d'abord une étude approfondie des recherches existantes sur les technologies de lecture en basse vision et l'accessibilité des médias d'information modernes. À partir de recherches et d'études antérieures, nous analysons ensuite les avantages de la réalité virtuelle pour la lecture en basse vision et proposons des directives globales pour la conception de l'accessibilité visuelle en réalité virtuelle, en mettant l'accent sur la lecture. Ceci est associé à une étude pratique de huit applications de lecture en réalité virtuelle pour évaluer comment cette conception de l'accessibilité est actuellement mise en œuvre dans les produits existants. Enfin, nous présentons un cadre qui intègre les principes de conception résultant de nos analyses et études et nous implémentons une preuve de concept en utilisant des graphiques basés sur un navigateur afin de démontrer la faisabilité de notre proposition avec la technologie moderne de réalité virtuelle.

Mots-clés : interactions homme-machines, lecture accessible, basse vision, réalité virtuelle

1 Introduction

Low-vision conditions generally refer to visual impairment that cannot be corrected nor cured, and can result in partial loss of the visual field. From the numerous daily activities affected by low vision, reading is most strongly impacted due to the standard formatting of documents. In particular, newspapers pose a unique challenge due to their unpredictable layout, timely nature, dynamic content, and condensed formatting [1], making it hardly accessible to low-vision readers, and a burden for news publishers to create accessible versions. Yet news reading has become an essential activity in modern society as a form of social connection, entertainment, and learning [2]. With an estimated 180 million people suffering from low vision and rapidly rising [3], there is a strong call for accessible news reading technologies.

In this position paper we propose virtual reality (VR) as a promising solution to accessible news reading for low vision. Nowadays, with the introduction of budget headsets such as Google Cardboard©, Oculus Go© and Samsung GearVR©[1], the price of accessing this technology has lowered to the price of obtaining a cell phone, making VR available to the general public. Taking advantage of the freedom to visually arrange the 360 degrees visual space, VR solutions have been proposed and experimented in the context of low vision for: rehabilitation [4], navigation training [5], accessible architectural design [6], gaze pattern recording [7], and awareness raising [8]. Recent findings also show that VR offers controlled environments for conducting psychophysics user studies [9].

For low-vision reading, VR can provide the similar advantage of allowing the user to customize the look and feel of the reading content in the 3D environment. However, the development of reading applications in VR for all audiences is still in its early stage. A survey of existing VR reading applications is thus necessary to understand (1) what kinds of reading content or file formats are currently supported, and (2) whether the typography and layout of physical (e.g., newspapers) and digital (e.g., PDFs, e-books) of these documents can be easily adapted and visually customized to the user's preference. Moreover, few guidelines exist for visual accessibility design in VR environments, and none at all concerning applications with the primary goal for reading. As such, proposing design principles that are supported by evidence-based studies is crucial for the future design of low-vision applications in VR.

To address the challenge of providing an accessible news reading platform for low-vision users, this position paper has three goals:

1. Provide a thorough literature review on current assistive technologies and accessibility design for low-vision news reading

2. From the literature, outline the advantages of VR for low-vision news reading, and establish a set of design principles to serve as guidelines for developing accessible VR reading applications, coupled with a survey on the availability of content and low-vision accessibility features in existing reading applications for VR; and

3. Propose a proof-of-concept for designing an accessible news reading application based on the design principles established in 2.

The remainder of this paper begins with a literature review in Section 2 of the advances and challenges in current technology for low-vision news reading. Next, Section 3 provides an analysis and study of the advantages and design principles for low-vision reading in VR, coupled with a survey of existing VR-reading applications. In section 4 we provide a proof-of-concept for

[1] Official websites of the Google cardboard©:`https://vr.google.com/cardboard`, Oculus Go©: `https://www.oculus.com/go`, and Samsung GearVR©: `https://www.samsung.com/global/galaxy/gear-vr`

low-vision news reading in VR. Finally, Sections 5 and 6 offer discussions in the next steps for implementing learnability design and user evaluations, and conclusions.

2 Background: Accessible news reading

This section details the background and literature into assistive technologies and accessibility design for news reading. We first discuss how existing vision aids and news media are coupled to enhance accessibility for the low-vision audience. We comment on two kinds of solutions: (1) visual aids, that make visual information easier to perceive, and (2) sensory substitution devices (SSDs) that transform visual content into audio. We then discuss the limitations of existing solutions, and the challenges that current news reading media confronts to provide visual accessibility for low vision.

2.1 Print

Newsprint is the traditional way to read news. The physical paper is intuitive for most people to position, adjust, and globally navigate between pages and article. However, newsprint is designed primarily for normally sighted individuals, using small print and complex layouts that make them very hard to access for low-vision readers.

To accommodate the low-vision audience, one possibility would be to publish large print editions. However, whereas some publishers provide a selection of books with larger print and looser layouts (e.g., Barnes and Nobles), there are few similar initiatives for the press. The *New York Times* issues a large print edition of their newspapers weekly: A 40-page publication in 16-type print, summarizing the previous week's Times. This singular example highlights the difficulty of producing accessible versions of newsprint, requiring additional effort from news designers to adapt content, select news source, and customize visual elements.

As a consequence, magnification equipment is in general necessary for low-vision people. Most commercialised reading aids take the form of magnifiers, and can be optical or electronic, portable or desktop. Electronic aids usually offer display options to personalize scale, polarity, and color inverting. Relatively recently, visual aids adopting head mounted displays or VR headsets have also been developed (e.g., OxSight, eSight, Helios, IrisVision, Relumino), although these tools are not solely dedicated to reading.

Overall, these magnification tools have been shown to increase reading ability of low-vision patients for standard news print [10, 11]. However, there is a strong trade-off between portability (i.e., whether the user is required to sit at a desk) and screen space (i.e., how much content can be seen through the magnifier). Desktop CCTVs provide high quality magnification and large screens, but are too heavy to move around regularly. On the other hand, portable magnifiers have limiting screen size that raises the difficulty of both global (e.g., between articles, sections, media content) and local (e.g., line to line) navigation [12, 13, 14]. Most portable electronic magnifiers also require the document to be on a flat surface to function well.

2.2 Digital devices

The transition of news from print to digital, from local to online has transformed journalism, bringing about faster updates, multimedia embedding, and wider selection of content. From the perspective of news accessibility, online news introduces fresh opportunities for people with visual impairment, making news accessible from most mobile devices. Studies have shown that reading activities on digital devices such as e-readers or iPads is at least no different from printed material

for normally sighted people [15, 16], and often significantly better for low vision [17, 18, 19]. This later observation results from the emergence of applications (i.e., ZoomText, SuperNova) that provide various types of embedded visual aids, such as magnification and color scheme optimization, associated with intuitive touch screen gestures (e.g., pinch-to-zoom).

Nonetheless, a review of visual aids usage on digital devices [20] have outlined a number of disadvantages, namely (1) the limited screen space to show magnified content ending with local/global navigation problems similar to newsprint, (2) fatigue due to screen glare after continued use, (3) contradicting gestures when using multiple aids simultaneously, and (4) the lack of training resources.

2.3 Audio

Audio-based news reading activities can come in two forms: curated audio news, and use of text-to-speech aids.

Accessibility versions of newspapers have been proposed by companies, who provide "talking" audio versions containing weekly summaries of news for select outlets, such as the Talking News[2], or the Newsline service[3] provided by the National Federation of the Blind. However, availability of content is limited to few publishers or organizations, and are at most provided weekly.

Another kind of solution is called sensory substitution, commonly known as text-to-speech, which aims at transforming the textual information into audio, which can exist for both traditional newsprint and digital devices.

For traditional newsprint, text-to-speech aids are based on optical character recognition methods (OCR). MyEye is an example of such a system, consisting of a small camera that can be clipped to the glasses, a processing unit to analyse the text, and a speaker to render the information as an audio stream. Its main feature is the ability to read aloud selected text by jointly orientating the head towards the target text and pointing at it with the finger. It is most efficient in reading linear text passages such as books or single articles. However, the reading experience with complex document layouts such as newspapers is prone to errors when navigating between complex visual elements such as columns, captions, and images.

Digital devices and digital content can also be converted into an audio stream using text-to-speech software (e.g., Jaws, VoiceOver, TalkBack). For text-to-speech to function properly, the W3C Web Accessibility Initiative (WAI)[4] provides principles for creating navigable and comfortable visual design, as well as sufficient alternative text support for non-text content. Internet design and hosting services such as Shorthand (2017) are also becoming more aware to help their users integrate accessibility features early on, and authoring tools [21] can help designers visualize and evaluate the accessibility of their website design. Though these standards and tools target the design of web content, they address universal accessibility issues where non-digital content cannot–such as customizing style, layout, and providing additional context for visual media. However, because these recommendations are not always properly implemented, screen readers may encounter some difficulties to deal with cluttered website design and advertisements, which are very common in news websites.

Though these tools allow easy access to text and alleviate visual stress, both for normal and low-vision readers, low-vision patients still have strong preference for text news over audio [22, 23], and they also prefer visual reading to text-to-speech aids [20]. This seems to be due to several psychological factors that have not yet, to our knowledge, been clearly quantified, but would deserve to be. Several of these factors have been identified, concerning audiobooks in general

[2] `https://sites.google.com/site/talkingnewsatnni/brief-history-of-TNs`
[3] `https://www.nfb.org/programs-services/nfb-newsline`
[4] `https://www.w3.org/WAI/`

[24], namely (1) the pleasure of listening to an audiobook depends on the voice of the narrator, (2) the rhythm of listening to an audiobook is imposed by the narrator, (3) stopping or pausing the audio involves pressing a button which is already in itself a source of discomfort, especially if it must be repeated regularly, and (4) navigating through an audiobook (e.g., searching for a specific position in the book) or mapping the audio to the text is not at all intuitive.

2.4 Challenges

From this analysis of current visual aids and devices, it appears that designing accessible newspapers for the low-vision audience remains an ongoing challenge for a number of reasons [1]. First, the complex and small print layout of news media makes local navigation (e.g., going from one line to the next, moving between columns) a great challenge, even with handheld and desktop magnifiers due to the limits in screen space. Second, the non-linear format of newspapers demands efficient global navigation (e.g., following references across pages, locating articles of interest) that is impossible for simple screen readers or text-to-speech aids. Third, the variety of formats and layouts produced between various publishers hinders algorithmic techniques from automatically processing the content and adapting it to the low-vision audience. And finally, creating accessibility versions of the news requires additional effort from design and editing, is time consuming, and goes against the timely nature of news which can occur, develop, and be reported and updated in real time.

This ongoing transition to the production and distribution of news in a digital form calls for web content design to be accessible, and for suitable accessibility tools to be designed for various users. Striking a balance between preserving the free navigation format of printed newspapers, while avoiding crowding effects [25] within the space and navigation limits of digital screens is the immediate challenge for accessibility [26, 27]. Experiments in developing interactive newsprint [28] automatic reformatting to tablets [29] offer insight on how printed newspapers can be adapted to the format and comfort different digital media.

Another direction of work involves creating customized reading applications dedicated to low vision. Note that such applications can also benefit from the accessibility tools and principles available for large public applications. One illustration of this idea is the web application called EV News[5] designed for people with macular degeneration. This application automatically transforms articles from a number of online news outlets into a scrolling interface where the print size, color, typography, scrolling speed, etc. could be customized. The design was based on eccentric viewing studies of low-vision reading, about reading dynamic horizontally scrolling text [30]. However, this format does exclude image and video content, and also imposes a continuous reading pace on user.

3 Methods: Analysis and study of VR design principles for low-vision reading

In Section 2, we have highlighted the limitations of current reading-aid platforms and solutions, in particular for news reading. In this section we move on to positioning VR as the next platform to develop novel solutions which could better fit low-vision user needs. First, we explain the advantages of VR for low vision as a whole, independently of the application. Then, we propose a set of design principles, based on low-vision research, that should be considered in a reading application. Finally, we conduct a survey on existing VR reading applications for accessibility features and design in their usage.

[5] EV News: `http://www.mdevreader.rhul.ac.uk/ev-news/#.ev-feeds`

Table 1: **Comparison of news reading media:** This table compares print, digital devices, and audio for low-vision news reading on the types of reading aids that are compatible with these media, and the advantages and limitations of each.

Medium	**Compatible vision aids**	**Advantages**	**Limitations**
Print	handheld or desktop magnifiers, text-to-speech	maneuverable: paper is easy to flip through, fold and handle global view: navigating between pages or different articles in the page is intuitive	fixed layout: print size, font and contrast polarity are not adjustable portability: the newspaper is not portable with a handheld or desktop magnifier
Digital devices	screen magnifiers/readers, touch gestures	mobility: devices are portable with visual aids integrated as applications gestures: intuitive gestures to pinch-to-zoom and to activate audio and vibration feedback content: freedom to choose and access almost unlimited quantity of content	screen space: small screens can only fit a limited number of magnified characters fatigue: screen glare and brightness can cause fatigue with extended use navigation: there is no concept of a newspaper page, instead hyperlinks are used to navigate between articles training: training resources are limited, and some gestures may be contradicting or not intuitive
Audio	N/A	mobility: usually can be worn or carried in a mobile device comfort: no visual fatigue	accuracy: word recognition and pronunciation is prone to errors navigation: rigid linear reading makes it difficult to browse and select content content: curated audio versions of the news are limited to very few publishers, and at most available weekly

3.1 The advantages of VR for low vision

As a whole, VR is a great candidate to go beyond current technological solutions such as monitors with larger screens, which are limited with respect to most of the properties mentioned above. Its unique advantages for low vision as compared to existing reading aids includes:

Comfort. Users can sit comfortably in their sofa, with no obligation to sit at a desk (e.g., with CCTV), bent toward their text (e.g., using handheld magnifiers), or fight with lighting conditions and ambient light since the environment can be fully controlled.

Mobility. Headsets can be used in various reading poses for indoor environments without additional cables, as compared to most magnifiers and text-to-speech aids that require the document to be on a flat surface like a desk.

Wide visual field of view (FOV). The FOV of modern VR headsets is between 90 to 110 degrees, which would allow magnification of up to 25 times normal reading print[6] for the MNREAD visual acuity charts [31] without exceeding the visual field, as compared to less than 10 times magnification on a 15-inch screen. Head and eye movements can further expand this field of view.

Multi-functional. Where low-vision aids usually have only a single functionality (magnification, text-to-speech), modern VR headsets all come with web browsers, online capabilities, and downloadable applications.

Multimedia. Text, image, audio, video, and even 3D content can be presented on headsets.

Interaction paradigms. Interaction methods can be customized, with technical capabilities encompassing controller, voice, head movement, and multiple possibilities for customized hand gestures and controllers depending on the application.

Immersion. Perhaps, rarely mentioned is how virtual environments are immersive and separate from the outside world, allowing people to do as they wish. This is particularly important for many people who hesitate to use vision aids or hold text very close to their face due to privacy issues or concern for public perception, even when it could ease their stress [20].

Affordability. Compatible with most modern smartphones, a Google Cardboard© costs as low as $15, and an Oculus Go© $200, where common visual aids (e.g., handheld magnifiers, text-to-speech, CCTV) have a usual range from $600 to $3000 depending on quality and function.

3.2 Accessibility design principles for VR reading applications

Nowadays, with the rising popularity of VR headsets due to the lower cost and commercialization, the question of accessible design in virtual environments and VR is posed. However, studies of the accessibility of VR to low-vision users is still in its early stages. A number of systems have proposed principles of accessible virtual environment design for games [32], and general application and interface design [23, 33]. Most notably, [33] have proposed the SeeingVR toolbox for the Unity3D environment that can integrate accessibility tools both into the development workflow, or added-on for pre-existing applications. Many of these tools were inspired by existing low-vision aids, multimedia accessibility standards, and limited work on accessibility in virtual environments, and were subsequently evaluated with low-vision users. Nevertheless, SeeingVR applies mainly to the general design of VR environments, not specific to low-vision reading.

[6] 12-pt print held at a reading distance of 40 cm, as defined by [31]

From the previous understanding of the design of reading aid systems, VR applications for low vision, and of news reading activities, we propose a number of accessibility design principles for VR applications targeting reading activities based on the previous survey.

Global and local navigation. Properly using the large visual space in VR in order to provide an intuitive navigation scheme for complex and multi-page documents is at the heart of designing an enjoyable reading experience, and stands out from existing text-to-speech reading aids. This involves allowing quick global navigation between different article sections on a page or between pages and chapters (e.g., skimming through a document to find interesting content) as well as easing line-to-line local navigation (e.g., by parsing and enlarging text content) [12, 14, 13].

Adjustable print and text layout. As mentioned through the review of [25], a number of print-related variables concern reading efficiency for low-vision people, including flexibility to adjust (1) print size: reasonably up to 100 times the size of news print, (2) font type: a number of fonts such as Tiresias or Eido have been developed with accessibility in mind, and animated fonts such as livefont[34] can also increase improve text legibility on digital screens, and (3) spacing: mainly word and line spacing, but not letter spacing to avoid crowding the visual field.

To adjust the perceived size of the print, text objects in 3D can be easily enlarged or even arranged closer in the virtual environment, reducing the need for a magnifier. Similarly, one aspect that has not been addressed at all is conforming to medical standards for evaluating low-vision reading ability. This involves adjusting print size based on visual degrees, and line width based on number of characters [35]. The possibility to flexibly change text layout based on these medical standards has not been addressed at all in any applications we reviewed, but would be crucial to evaluating the effectiveness of a reading platform, and adapting text content based on professional diagnosis.

Smart text contrasting. The benefits of providing intelligent color adjustments to increase the polarity of text (e.g., common configurations for low-vision aids are white text on a black background and yellow on blue) without affecting non-text media (e.g., images and color scheme of the document) has been outlined numerous times, indicating possibly an improvement of 10 - 40% in reading speed [25]. However, it should be offered as an option to the user instead of being a fixed setting, since some users still prefer reading text on white backgrounds. Inverted text has been integrated into numerous digital and VR applications, including 3D environments [32, 33].

Currently, many browsers and phone applications do offer inverted color functions for electronic content, and some electronic desktop magnifiers can also invert colors of printed documents. However, these current reading aids do not differentiate between text and media content, resulting in photos and design elements also being inverted, detracting from the reading experience [20]. The ability to detect and invert only the text and not other multimedia items is essential.

Accessibility menu. A menu to adjust all visual and environmental parameters should be provided to allow personalization of the virtual reading environment [32, 33].

Hands free (voice) control. In addition to text menus, the reading preferences should offer some form of non-text, and preferably hands-free control such as voice commands. This would accommodate less technologically capable users, avoid overcrowded menu options, and simplify the user experience to allow quick adjustments to the visual space or switch between different visual settings.

Image enhancement. Similar to how augmented reality displays can adjust the brightness and polarity of visual elements, or create semantic overlays on the environment [36, 37, 38, 39, 40, 41],

image enhancement techniques to sharpen text and media content can be provided to the users as an option.

3.3 Survey of existing VR reading applications

VR reading is in its early stages and only a few applications are available. VR is used as a reading interface that can provide advantages such as improved immersion and atmosphere. Virtual environments can be personalized to be distraction free, or tailored to the story for stronger immersion. In the latter, we are more at the boundaries of reading and games, and there is a lot of promise here, both for readers and writers. But are these applications accessible for the low vision?

We conducted a survey of low-vision accessibility features listed above in existing VR reading applications. An overview of the applications we surveyed can be found in Table 2. Some of these applications only support a specific genre or file type. A number of other applications that only contain one book or game were not considered here.

Our survey has found that very limited features for accessibility are present in current VR reading applications, as shown in the right portion of Table 2, though it is important to note that none of these applications were designed with low-vision users as a primary target. The screenshots of some of these applications can be seen in Fig. 1. As we can observe, the goal of many of these applications is to replicate the reading experience of physical books and comics, and existing e-readers by introducing similar formatting and navigation. In terms of content, many applications either provide a selection of reading content from their application markets, while others may allow uploading of user content in limited formats. Moreover, these applications were not designed to read documents with complex page layouts, dense text, limits in print size or zoom due to image resolution, and mix of text and media content. Thus, a fully accessible VR reading experience is still missing and nothing has been done yet for news reading.

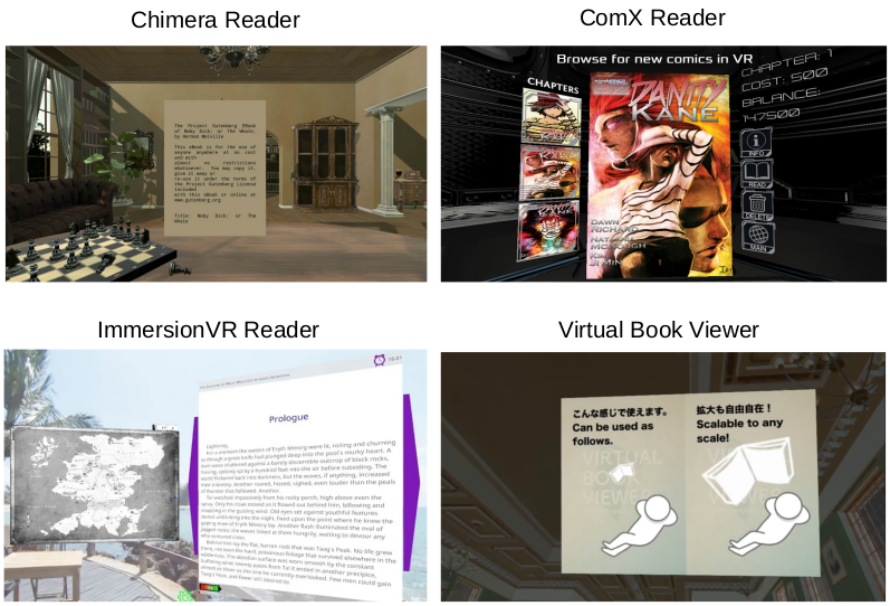

Figure 1: **Screenshots of selected VR reading applications:** Popular applications for reading in virtual reality often aim to maintain the layout and formatting of the original text.

Table 2: **Comparison of reading applications for VR headsets:** This table provides an overview of reading applications for VR headsets that we included in our survey, and the accessibility features they supported. Compatible devices, genres, and file formats are summarized on the left. Accessibility features include magnification and zoom (**MZ**), print size adjustment (**PS**), and audiobook support (**AB**). Other accessibility features were not found to be available in any application, and were thus excluded from the table. We found that accessibility was rarely considered in the application design, and only limited features were available.

Application	**Device**	**Genre**	**Content**	**Accessibility**		
				MZ	**PS**	**AB**
Bedtime VR	Gear VR Cardboard	books	app limited			
Chimera	Gear VR	books	epub		•	
ComX VR	Cardboard	comics	app limited	•		
ImmersionVR Reader	Gear VR Oculus Go	books	epubs & pdf	•		•
Madefire Comics	Gear VR Cardboard Daydream	comics	app limited			•
Sphere Toon	Vive	comics	app limited			•
Virtual Book Viewer	Oculus Go	books	pdfs & images	•		
Vivepaper	Vive Cardboard	books	app limited			

4 Results: Framework and proof of concept

We designed a proof-of-concept VR news reading application based on the design principles and survey. Its purpose is not to provide a full-functioning product for end users, but to demonstrate how VR achieves the essential accessibility features outlined in Section 3 that were previously strong limitations of existing assistive technologies for reading complex news documents, as listed in Table 1. We first present the framework for our proof-of-concept, then describe the implementation of our application.

4.1 VR news reading framework

For the design of a news reading platform in VR, we propose a framework that adapts original news content from PDFs to a customised reading interface with accessibility features. This framework is comprised of three steps: (1) representation of original content to a universal, intermediary, format that captures the structure and hierarchy of the documents, (2) transforming complex layouts into a linear navigation, and (3) customization of visual space in VR. We explain each element of the framework as follows:

4.1.1 Representation of source material

News reading content can come in a variety of formats including scanned images of physical newspapers, PDFs or electronic images, and websites that combine text, image, video, hyperlinks, and other interactive content.

At this step, content should be transformed from its original format to an intermediary format

that can represent the hierarchy of the news content (e.g., *pages* → *articles* → *headline* → *text*, etc.) and how media content is associated to text content (e.g., image captions or video headings). Techniques to do this would include document segmentation and image classification techniques, as well as OCR when text cannot be extracted directly from the original source. The completeness of this intermediary format would be directly affected by the amount of information provided in the original source material: limited and error prone for image files, while more rich and understandable for PDFs with selectable text or websites. Current work in this area shows initial results to the structural and semantic parsing of complex document images [42, 43, 44, 45]. An example hierarchical analysis of a model newspaper is shown in Figure 2.

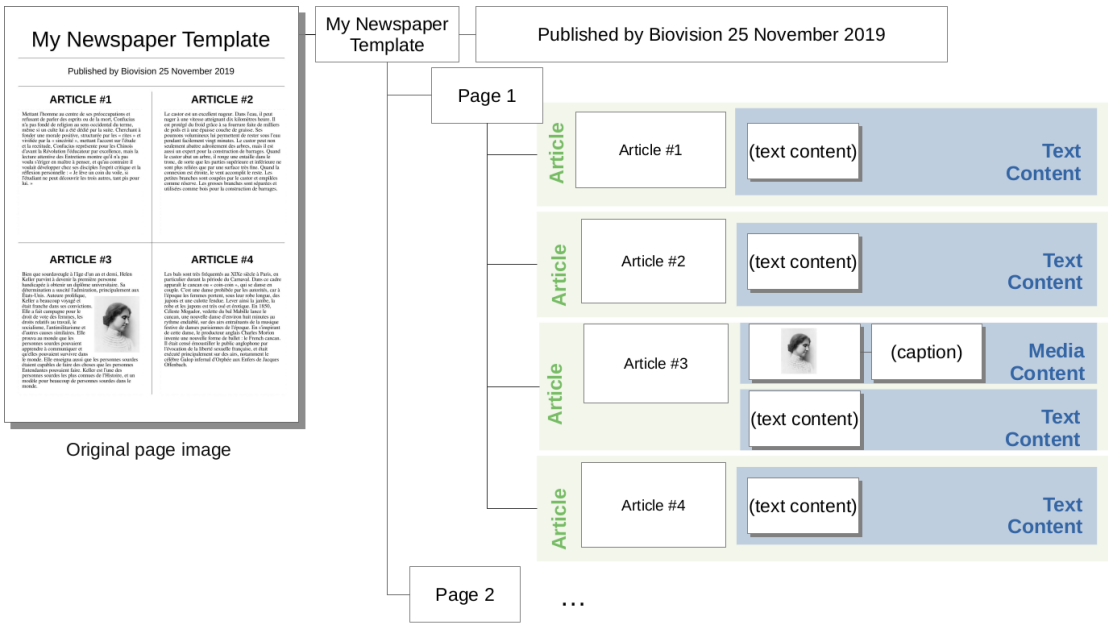

Figure 2: **Hierarchical structure of newspaper content:** Newspaper navigation is not linear, but newspaper documents can be represented in a hierarchical structure from pages, to articles, to individual text and media content. Text and images in this example are from Wikipedia and for demonstrating common newspaper layout.

4.1.2 Navigation

Once the media and text content have been analyzed, the next step is to improve the reading experience by exploiting this hierarchy. Newspaper navigation is not linear, and people seldom read every word on a page, from cover to cover. Instead, people are attracted by images, browse through article headings to find keywords, follow references to related stories, and go directly to pages with specific types of news stories they are interested in [46]. When an article of interest is found, the reader would then go deeper to read the text content.

This leads to two types of navigation: (1) *global navigation*: the browsing of pages and articles in the overall document for content that attracts the user, and (2) *local navigation*: reading actual article content line-by-line, word-by-word. Global navigation allows efficient progression throughout the newspaper and more control over the content one decides to read, whereas local

navigation allows a more intimate reaction with content that is appealing to the audience. For the low-vision audience, easing the reading of individual words and sentences through magnification should not come at the expense of the possibility to browse and select interesting content through global navigation. Thus, from the raw content, it is necessary to provide rules to help the reader navigate the document, allowing multi-levels of hierarchical navigation by page, article, and article content. The goal of this is to address the challenge of providing an intuitive global navigation for complex news documents such that the user can quickly search, browse, and access the news content.

By separating the navigation from the document layout, this framework would relieve the task of segmenting and processing the complex visual information in each page. The hierarchical navigation level of pages, articles in the page, and article content allows the user to get a rough idea of the flow of the newspaper, quickly locate articles of interest or leave halfway, all the while not getting lost in the complex layout.

In the long term, we hope to develop a system that can further personalise the reading flow according to the user's personal habits and preferences. Instead of proposing the same reading flow to everyone, articles and content that the user prefers regularly can be proposed upfront to save effort.

4.1.3 Custom visual space

Finally, the aspect that concerns accessibility the most is the customization of visual parameters of the text and image content, such as polarity, as well as integrating accessibility features discussed in Section 3.

Most prominently, visual presentation of text must be fully customizable, including how sentences are segmented, the amount of text to present at once, the print size and style, and size and distance of the reading area. These features would ease the local navigation of text (i.e., navigation between words, lines, and columns) for low-vision users.

4.2 Implementation

Here we provide a design and its implementation as a proof-of-concept based on the framework and design principles proposed. We pair a card-reading metaphor with a global view of the newspaper preserving its original layout. It is important to note that we do not seek to replicate the reading experience of the original book or document, as most existing applications do (Figure 1), but instead, rearrange the visual and textual elements in order to provide a reading experience that is comfortable and easy to navigate.

Prototype of this design has been implemented in WebGL, which can be run on any computing device with a modern browser. Our prototype has been tested on the GearVR, Oculus Go, and Firefox and Chrome browsers on laptops and mobile phones. The implementation of the prototype provides technical verification of the feasibility of the design principles proposed in Section 3.

We use a json representation of the newspaper containing the content and hierarchy of the newspaper document, and parsing the text content based on upper and lower limit constraints to the number of characters. Additional rules can be added, such as to ignore specific types of content (e.g., advertisements), parse by word or sentences, and sequence in which to show content in a page (e.g., headlines come before subheadings).

In this prototype, text is presented segment-by-segment using a card-deck navigation metaphor in the middle of the visual space, and users can use remote control gestures to browse backwards or forwards between each card, or select a card for in-depth reading (e.g., selecting an article heading to see the article content).

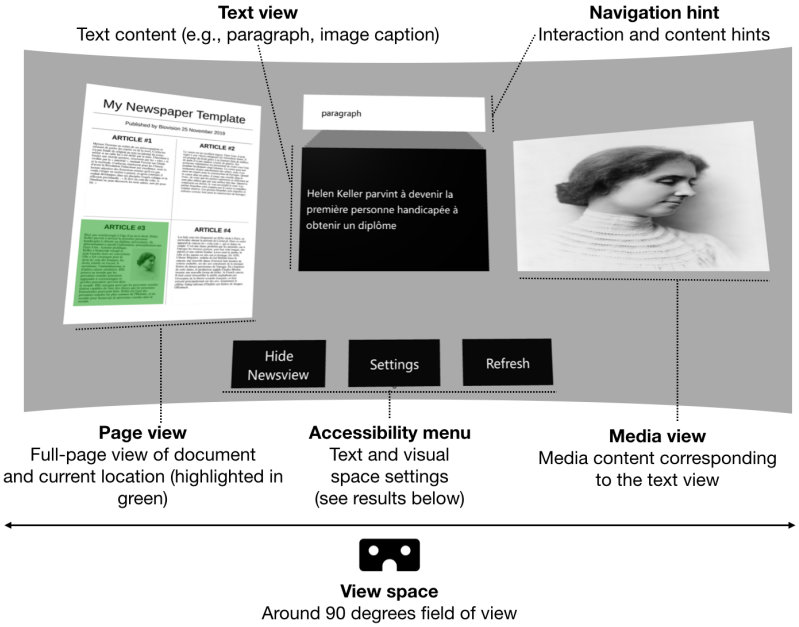

Figure 3: **Application prototype:** The global overview of the newspaper page is shown side-by-side with the enlarged text and images of the highlighted region. Navigation hints above the card show what type of content is displayed (e.g., photo, heading, paragraph) and whether the card can be selected (i.e., highlighted in light blue) to reveal further content. Text and images of the newspaper are purely for demonstrating a proof-of-concept.

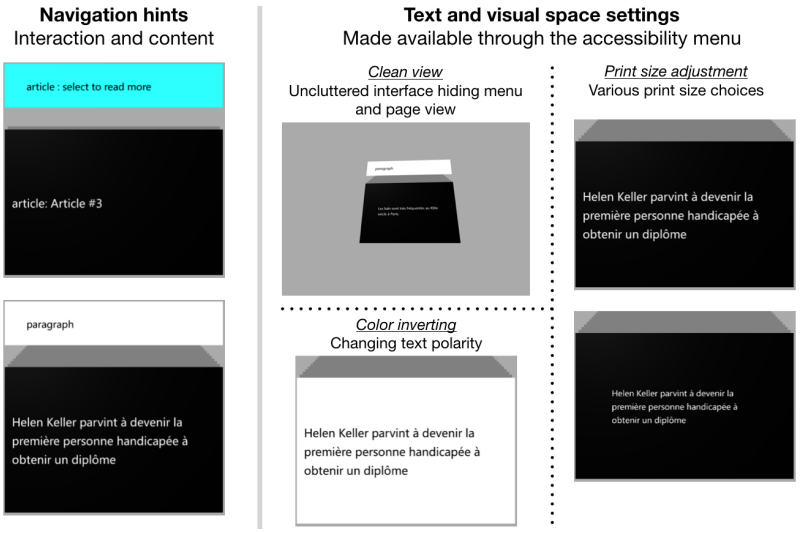

Figure 4: **Visual accessibility:** Navigation hints indicate interaction possibilities and inform the user of the nature of the displayed text. The accessibility menu provides a number of functions including (1) showing/hiding the page and menu view to personalize the view space, (2) invert foreground and background color for text content, and (3) change the print size.

The interface has a number of features pertaining to the accessibility design principles discussed in Section 3. The visual design of the interface is shown in Figure 3 with details on accessibility features in Figure 4. Our accompanying video[7] provides a demo of the main features and usage of the prototype.

View space contains the page view, text view, media view, and accessibility menu, all of which can be flexibly moved around, hidden, or summoned at the user's preference.

Page view displays the full page image of the current page. A global navigation indicator highlights the part of the newspaper that is currently displayed in the text and media views so that the user can immediately know their current reading position. The color of the highlight indicates whether the current content has been seen before by the user. A global highlighting of all readable content on the page is also available, allowing the user to track overall reading progress.

Text view shows the text content, which can be a heading, caption, paragraph, or other text content in the newspaper. Foreground and background color of text is displayed in high polarity. The text print size and color can be adjusted through the accessibility menu (indicated in Figure 3 and example outcomes shown in Figure 4).

Media view shows any media content associated with the current text snippet. Usually, the text snippet would be the caption of the image or slogan of an advertisement. All media items also support additional alternative text.

Navigation hint indicates to the reader what type of content is currently being displayed in the text and media views (e.g., photo, heading, paragraph). When the card is interactive, it is highlighted in light blue, meaning the user can "select" the article card to reveal further content (e.g., text inside the article).

Accessibility menu provides the functions to adjust the visual space, such as hiding the page view. Settings for print in the text view are also offered:

- *Print size*: options to change the print size and style to the user's most comfortable reading print. Print size can be changed in terms of total width of the text view, distance of the text view, and number of characters per line.

- *Smart text inversion*: options are given to invert text content with high polarity without also inverting the colors of media content

The menu can be revealed or hidden using the controller to provide an uncluttered "clean" reading view to the user, as shown in Figure 4.

Our proof-of-concept shows that almost all of the design principles discussed in Section 3 can be implemented, also accounting for the flexibility to turn on or off features that the user does not want. Furthermore, it globally demonstrates that VR affords a level of personalization of visual parameters and wide spacial arrangement that surpasses any other existing news media, device, or assistive reading technology. As the next step, we expect to integrate other accessibility aids such as text-to-speech, voice control, or brightness adjustment, and bring in both content providers and end users into the design process to provide feedback for improving the user experience.

[7] Please see supplementary material.

5 Discussion

From the analysis and study of design principles, to the design of a proof-of-concept, we have demonstrated the potential of VR to become the next platform for accessible news reading for low vision. In this section, we discuss two crucial next steps in this work: (1) integrating learnability into system design for non-technology oriented users, and (2) conducting evidence-based studies and clinical trials for complex reading activities, and on new media like VR.

5.1 Integrating learnability

Low vision is strongly associated with older people because the risk of most eye diseases increases with age. Examples of common age-related eye diseases are age-related macular degeneration, glaucoma and diabetic retinopathy. Because the elderly today did not grow up during the era of computers and internet, a legitimate concern is to understand their relationship with technology. Currently, there is still a digital gap between the elderly and younger adults even if this gap will become smaller over time, since the rate of elderly users familiar with technology is growing. Privacy concerns, and the perception that new technologies are difficult to approach or use correctly can be a decisive barrier to the elderly [47].

Meanwhile, it has been shown in many studies that the elderly are eager to adopt new technology when they discover its convenience, and when sufficient support and guidance is provided to ease its usage [48, 49]. This outlines the importance of integrating learnability into system design. It is important to realize that many technologies have an initial learning curve that can be hard to overcome without proper training or help [50].

As far as VR is concerned, the same observations hold [51]. Beyond psychological barriers that may exist, there is no physical or cognitive barrier in using it; however, they need a period of time to gradually familiarize themselves with the technology, which may be longer for more elderly audiences. Once a good impression of the technology is established through regular usage, the convenience and even enjoyment that it brings can encourage the elderly to adopt a more positive attitude towards this technology [52]. Thus to ease the introduction of our platform, the next immediate step is to incorporate learnable design into our system, by using familiar and easy-to-learn interaction mechanisms (e.g., voice, point and click), and deliver guidance either through in-application tutorials, or designing training procedures that can be delivered, for example, by close family or experienced low-vision service community, to the end users of our systems.

5.2 Need for evaluations

Evaluating the efficacy of low-vision reading aids is in itself a research question that requires deeper survey and experiments that can measure user experience (e.g., usability, comfort, personalization), design (e.g., ease of use, flexibility), and performance (e.g., reading speed, accuracy). For example, standardized reading test have been developed for measuring reading speed, notably the MNREAD acuity chart [35] and the iRest test [53]. However, these reading tests are simplified reading scenarios, not accounting for realistic complex reading task like news reading, which requires increased mental engagement to browse and select articles within documents with cluttered layouts. To our knowledge, measuring reading performance for complex documents has not yet been properly addressed in the literature.

Taking inspiration from [54], who took a first step in the direction of validating a reading-aid system for complex documents, we also envision a user study on our VR application by both quantifying existing metrics for measuring speed and efficiency of low-vision reading, and

qualifying ease, comfort, and enjoyability of usage through task-based directed reading and in-depth surveys and interviews. This feedback would not only benefit the continued design and improving of our proposed application, but also, moreover, set the stage for formalizing accessibility design principles of reading applications and virtual environments.

6 Conclusion

In this position paper, we have reviewed the accessibility of low-vision reading, with a focus on finding a solution for news reading. We have found that VR holds high potential due to the wide availability of VR devices as well as the flexibility of arranging and changing visual variables in a 3D environment. To this end, we have a proof-of-concept news reading platform in VR for low vision using browser-based graphics. Our implementation emphasizes the ease of adjusting visual features and layout in the visual space, as well as personalize the navigation flow of complex news documents.

As a rising platform, virtual reality opens as many possibilities as it does challenges in trying to establish itself into the mainstream media. However, its strong advantages in its mobility, affordability, immersion, and flexibility for arranging the wide visual space set it apart from traditional print and other digital devices for reading. These advantages would allow designers and content providers to propose accessible reading solutions on VR that make use of a personalisable, 360 degrees space that is otherwise unavailable for other reading media. It is thus in this vein that we call for the study of virtual reality as a reading media early on, to (1) better understand the benefits of the medium for low vision, (2) establish design principles for visual accessibility, and (3) explore novel applications have the potential to help low-vision population better navigate their everyday life.

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References

[1] M. Hersh and M. Johnson, *Assistive Technology for Visually Impaired and Blind People*. London: Springer, 2010.

[2] C. Kulkarni and E. Chi, "All the news that's fit to read: A study of social annotations for news reading," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, (New York, NY, USA), pp. 2407–2416, ACM, 2013.

[3] J. Garden-Robinson, S. Stastny, and C. Kjera, "How to teach people with low vision," 2017. Accessed: 2019-10-15.

[4] M. Raphanel, G. Shaughness, W. H. Seiple, and A. Arleo, "Current practice in low vision rehabilitation of age-related macular degeneration and usefulness of virtual reality as a rehabilitation tool," *Journal of Aging Science*, vol. 6, no. 2, 2017.

[5] S. Maidenbaum, S. Levy-Tzedek, D.-R. Chebat, and A. Amedi, "Increasing accessibility to the blind of virtual environments, using a virtual mobility aid based on the "eyecane": Feasibility study," *PLOS ONE*, vol. 8, 08 2013.

[6] G. Stewart and R. J. McCrindle, "Visual impairment simulator for auditing and design," in *Proceedings of 11th International Conference on Disability, Virtual Reality & Associated Technologies*, ICDVRAT '16, (Los Angeles, California, USA), pp. 139–148, ICDVRAT, Sep 2016.

[7] J. Gutiérrez, E. David, Y. Rai, and P. L. Callet, "Toolbox and dataset for the development of saliency and scanpath models for omnidirectional/360° still images," *Signal Processing: Image Communication*, vol. 69, pp. 35–42, 2018. Salient360: Visual attention modeling for 360° Images.

[8] Y. Boumenir, A. Kadri, N. Suire, C. Mury, and E. Klinger, "When sighted people are in the skin of visually impaired ones:perception and actions in virtual reality situation," in *Proceedings of 9th International Conference on Disability, Virtual Reality & Associated Technologies*, (Laval, France), pp. 111–119, ICVRAT, Sept. 2012.

[9] B. de Gelder, J. Kätsyri, and A. W. de Borst, "Virtual reality and the new psychophysics," *British Journal of Psychology*, vol. 109, 03 2018.

[10] T. H. Margrain, "Helping blind and partially sighted people to read: the effectiveness of low vision aids," *British Journal of Ophthalmology*, vol. 84, no. 8, pp. 919–921, 2000.

[11] K. Latham, "Benefits of low vision aids to reading accessibility," *Vision Research*, vol. 153, pp. 47 – 52, 2018.

[12] C. Aguilar and E. Castet, "Evaluation of a gaze-controlled vision enhancement system for reading in visually impaired people," *PLOS ONE*, vol. 12, p. e0174910, 04 2017.

[13] P. J. Beckmann and G. E. Legge, "Psychophysics of reading—XIV. The page navigation problem in using magnifiers," *Vision Research*, vol. 36, no. 22, pp. 3723 – 3733, 1996.

[14] E. Roberts, S. Kinneir, and C. McGinley, *Design and Low Vision Aids — a YouthPerspective*. UK: Thomas Pocklington Trust, 2016.

[15] D. Zambarbieri and E. Carniglia, "Eye movement analysis of reading from computer displays, ereaders and printed books," *Ophthalmic and Physiological Optics*, vol. 32, no. 5, pp. 390–396, 2012.

[16] M. Köpper, S. Mayr, and A. Buchner, "Reading from computer screen versus reading from paper: does it still make a difference?," *Ergonomics*, vol. 59, no. 5, pp. 615–632, 2016.

[17] S. A. Haji, K. Sambhav, S. Grover, and K. V. Chalam, "Evaluation of the ipad as a low vision aid for improving reading ability," *Clinical ophthalmology*, vol. 9, p. 17–20, 2015.

[18] K. Gill, A. Mao, A. M. Powell, and T. Sheidow, "Digital reader vs print media: the role of digital technology in reading accuracy in age-related macular degeneration," *Eye*, vol. 27, p. 639–643, 2013.

[19] A. Calabrèse, L. To, Y. He, E. Berkholtz, P. Rafian, and G. E. Legge, "Comparing performance on the mnread ipad application with the mnread acuity chart," *Journal of Vision*, vol. 18, 01 2018.

[20] S. F. A. Szpiro, S. Hashash, Y. Zhao, and S. Azenkot, "How people with low vision access computing devices: Understanding challenges and opportunities," in *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '16, (New York, NY, USA), pp. 171–180, ACM, 2016.

[21] H. Takagi, C. Asakawa, K. Fukuda, and J. Maeda, "Accessibility designer: Visualizing usability for the blind," in *Proceedings of the Sixth International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS'04)*, (Atlanta, GA, USA), pp. 177–184, Association for Computing Machinery,, October 2004.

[22] A. Mitchell, "Americans still prefer watching to reading the news–and mostly still through television," Dec 2018. Accessed: 2019-06-28.

[23] M. Teófilo, V. F. Lucena, J. Nascimento, T. Miyagawa, and F. Maciel, "Evaluating accessibility features designed for virtual reality context," in *2018 IEEE International Conference on Consumer Electronics (ICCE)*, (Las Vegas, NV, USA), IEEE, Jan 2018.

[24] C. Vandendorpe, *Du papyrus à l'hypertexte. Essai sur les mutations du texte et de la lecture.* Sciences et société, France: La Découverte, 1999.

[25] G. Legge, "Reading digital with low vision," *Visible language*, vol. 50, no. 2, pp. 102–125, 2016.

[26] M. Ajita, "Why can't i read a newspaper on my phone!?," Nov 2015. Accessed: 2019-06-28.

[27] C. Ihlström Eriksson, M. Åkesson, and S. Nordqvist, "From print to web to e-paper - the challenge of designing the e-newspaper," in *Proceedings of ICCC 8th International Conference on Electronic Publishing*, (Sweden), pp. 249–260, International Council for Computer Communication (ICCC), 2004.

[28] D. M. Frohlich, P. Ely, H. Moore, C. Golsteijn, P. Egglestone, J. Mills, J. Rogers, T. Metcalf, K. Stone, and M. Menicou, "Designing interactive newsprint," *International Journal of Human-Computer Studies*, vol. 104, pp. 36 – 49, 2017.

[29] T. Strecker and S. Albayrak, "Adaptive user-centric layout of news with aesthetic constraints," in *Proceedings of the 1st Workshop on Semantic Personalized Information Management*, (Malta), pp. 8–15, LREC, 2010.

[30] R. Walker, L. Bryan, H. Harvey, A. Riazi, and S. J. Anderson, "The value of tablets as reading aids for individuals with central visual field loss : an evaluation of eccentric reading with static and scrolling text," *Ophthalmic and Physiological Optics*, vol. 36, pp. 459–464, July 2016.

[31] G. E. Legge and C. A. Bigelow, "Does print size matter for reading? A review of findings from vision science and typography," *Journal of Vision*, vol. 11, 08 2011.

[32] S. Trewin, V. L. Hanson, M. R. Laff, and A. Cavender, "Powerup: An accessible virtual world," in *Proceedings of the 10th International ACM SIGACCESS Conference on Computers and Accessibility*, Assets '08, (New York, NY, USA), pp. 177–184, ACM, 2008.

[33] Y. Zhao, E. Cutrell, C. Holz, M. R. Morris, E. Ofek, and A. Wilson, "Seeingvr: A set of tools to make virtual reality more accessible to people with low vision," in *Proceedings of the ACM CHI Conference on Human Factors in Computing Systems*, (Glasgow, Scotland), ACM, May 2019.

[34] D. Bragg, S. Azenkot, K. Larson, A. Bessemans, and A. T. Kalai, "Designing and evaluating livefonts," in *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, UIST '17, (New York, NY, USA), p. 481–492, Association for Computing Machinery, 2017.

[35] G. Legge, J. A. Ross, A. Luebker, and J. Lamay, "Psychophysics of reading: Viii. the minnesota low-vision reading test," *Optometry and Vision Science*, vol. 66, pp. 843–853, 1989.

[36] H. Moshtael, T. Aslam, I. Underwood, and B. Dhillon, "High tech aids low vision: A review of image processing for the visually impaired," *Translational vision science & technology*, vol. 4, no. 4, 2015.

[37] H. Moshtael, L. Fu, I. Underwood, and B. Dhillon, "Evaluation of head-mounted displays for macular degeneration: A pilot study," in *Innovation in Medicine and Healthcare 2016* (Y.-W. Chen, S. Tanaka, R. J. Howlett, and L. C. Jain, eds.), (Cham), pp. 71–81, Springer International Publishing, 2016.

[38] M. R. Everingham, B. Thomas, and T. Troscianko, "Head-mounted mobility aid for low vision using scene classification techniques," *International Journal of Virtual Reality*, vol. 3, 09 1999.

[39] R. Harper, L. Culham, and C. Dickinson, "Head mounted video magnification devices for low vision rehabilitation: a comparison with existing technology," *British Journal of Ophthalmology*, vol. 83, no. 4, pp. 495–500, 1999.

[40] E. Peli, G. Luo, A. Bowers, and N. Rensing, "Augmented vision head-mounted systems for vision impairments," *SID Symposium Digest of Technical Papers*, vol. 38, no. 1, pp. 1074–1077, 2007.

[41] A. D. Deemer, C. K. Bradley, N. C. Ross, D. M. Natale, R. Itthipanichpong, F. S. Werblin, and R. W. Massof, "Low vision enhancement with head-mounted video display systems: Are we there yet?," *Optometry and Vision Science*, vol. 95, pp. 694–703, Sep 2018.

[42] H. Alhéritière, F. Cloppet, C. Kurtz, J.-M. Ogier, and N. Vincent, "A document straight line based segmentation for complex layout extraction," in *Proceedings of the 14th IAPR International Conference on Document Analysis and Recognition*, (Kyoto, Japan), pp. 1126–1131, IEEE, 2017.

[43] D.-T. Ha, D.-D. Nguyen, and D.-H. Le, "An adaptive over-split and merge algorithm for page segmentation," in *Pattern Recognition Letters*, vol. 80, (Amsterdam, Netherlands), pp. 137–143, Elsevier, 2016.

[44] P. E. Mitchell and H. Yan, "Newspaper document analysis featuring connected line segmentation," in *Proceedings of Sixth International Conference on Document Analysis and Recognition*, (Seattle, WA, USA), pp. 1181–1185, IEEE, 2002.

[45] H.-Y. Wu and P. Kornprobst, "Multilayered Analysis of Newspaper Structure and Design," Research Report RR-9281, UCA, Inria, July 2019.

[46] K. Holmqvist and C. Wartenberg, "The role of local design factors for newspaper reading behaviour – an eye-tracking perspective," *Lund University Cognitive Science*, vol. 127, 2005.

[47] B. Knowles and V. L. Hanson, "The wisdom of older technology (non)users," *Communications of the ACM*, vol. 61, no. 3, 2018.

[48] E. Vaportzis, M. G. Clausen, and A. J. Gow, "Older adults perceptions of technology and barriers to interacting with tablet computers: A focus group study," *Frontiers in Psychology*, vol. 8, Oct 2017.

[49] M. Heinz, P. Martin, J. A. Margrett, M. Yearns, W. Franke, H.-I. Yang, J. Wong, and C. K. Chang, "Perceptions of technology among older adults," *Journal of Gerontological Nursing*, vol. 39, no. 1, pp. 42–51, 2013.

[50] N. Roussel, "Looking forward," 2014. Accessed: 2019-10-08.

[51] B. Michel, R. Guerchouche, P.-D. Petit, E. Chapoulie, V. Manera, G. Chaurasia, G. Drettakis, and P. Robert, "Is it possible to use highly realistic virtual reality in the elderly? a feasibility study with image-based rendering," *Neuropsychiatric disease and treatment*, vol. 11, pp. 557–63, 2015.

[52] S. Syed-Abdul, S. Malwade, A. A. Nursetyo, M. Sood, M. Bhatia, D. Barsasella, M. F. Liu, C. C. Chang, K. Srinivasan, M. Raja, and Y. C. J. Li, "Virtual reality among the elderly. a usefulness and acceptance study from taiwan," *BMC Geriatrics*, vol. 19, no. 223, 2019.

[53] S. Trauzettel-Klosinski and K. Dietz, "Standardized assessment of reading performance: the new international reading speed texts irest," *Investigative Ophthalmology & Visual Science*, vol. 53, pp. 5452–5461, Aug 2012.

[54] J.-B. Bernard, É. Tlapale, G. Faure, E. Castet, and P. Kornprobst, "Navisio: Towards an integrated reading aid system for low vision patients," in *Workshop on Computer Vision Applications for the Visually Impaired*, (Marseille, France), James Coughlan and Roberto Manduchi, ECCV, Oct 2008.

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