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Abstract: Low-vision conditions resulting in partial loss of the 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 paper positions virtual reality as the next step towards accessible and enjoyable news reading for the low vision. We first conduct an extensive review into existing research on low-vision reading technologies and accessibility 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 study of eight reading applications in virtual reality to evaluate how accessibility design is currently implemented in existing products. Finally, we present a framework that integrates the design principles resulting from our analysis and study, and implement a proof-of-concept for this framework 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 inaccessible to low-vision readers, and a burden for news publishers to create accessible versions. Yet news reading has become an essential activity in the 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 paper we investigate how virtual reality (VR) could serve as a basis to conceive an accessible news reading platform. 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. As a result, VR is emerging as a promising platform in the low-vision context. Although the technology is still considered to be in its early stages for low-vision applications, a new trend is developing around VR applications for low vision, acknowledging its use for rehabilitation [4], navigation training [5], simulating low-vision conditions for the purpose of architectural design [6], extraction of gaze patterns [7], and raising awareness [8]. Finally, recent findings also show that VR offers controlled environments for conducting psychophysics user studies [9].

Virtual reality as a platform for low-vision reading is still in its early stages of development. Currently there are very few guidelines for accessibility design in VR environments, and none at all concerning applications with the primary goal for reading. Moreover, there is currently no framework for automatically adapting content from other media sources such as print or web, which would require additional effort from content designers to customize the look and feel of all objects in the 3D environment.

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

1. Establish a set of design principles derived from literature, to serve as guidelines for the design of accessible VR reading applications;

2. Study accessibility features in existing reading applications for VR; and

3. Propose a framework for designing an accessible news reading application for VR headsets, with a proof-of-concept of such a system.

The remainder of the paper begins with a literature review of the advances and challenges for low-vision reading. Next we provide 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. We then propose a framework and demonstrate the first prototype of our application in VR targeting low-vision users. Finally, we offer discussions in the next steps for implementing learnability design and user evaluations, and conclusions.

[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`

2 Background: Accessible news reading

This section outlines the background and literature into accessibility design for news reading. We first discuss how existing vision aid tools 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 current 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. 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 have large print editions. However, whereas some publishers provide a selection of books with larger font and looser layouts (e.g., Barnes and Nobles), there are very few similar initiatives for the press. Up to our knowledge, only the New York Times issues a large print edition of their newspapers weekly: A 40-page publication in 16-type font, 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 (e.g., Prodigi by Humanware). Electronic aids usually offer display options to personalize scale, contrast, and color inverting. Relatively recent, 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 newsprint font [10, 11]. However, they have a strong trade-off between portability (i.e., whether the user is required to sit at a desk or read from a flat surface) and screen space (i.e., how much content can be seen through the magnifier). Particularly, when using portable magnifiers, limitations in the screen space raise the difficulty of both global (e.g., between articles, sections, media content) and local (e.g., line to line) navigation [12, 13, 14].

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], and often significantly better for low-vision users [16, 17]. 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 [18] 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) the lack of flexibility in adjusting the

colors and layout of applications, (3) contradicting gestures when using multiple aids simultaneously, and (4) the lack of training resources.

2.3 Audio

Another kind of solution is called sensory substitution and aims at transforming the textual information into speech.

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.

For digital devices and digital content can 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)[2] 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 [19] 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.

These tools provide ways to have access to reading content, but this is not reading anymore. Indeed, for both for normal vision and low vision readers, there is a strong preference for text news over audio [20, 21], and low-vision people also prefer visual reading to text-to-speech aids [18]. This seems to be due to several psychological factors that have not yet, to our knowledge, been clearly quantified, but would deserve to be. One important psychological factor is that visually impaired people are not blind and do not feel blind. For example, people with age-related macular degeneration (AMD) can still see through a large part of the visual field and effectively use this "residual" vision for daily tasks. They also know that they can read isolated words when they are sufficiently enlarged. The greatest challenge appears when it comes to reading several lines of text in cluttered layouts such as newspapers. Other factors concern audiobooks in general [22], specifically (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 reading-aid solutions, it appears that designing accessible newspapers for the low-vision audience remains an ongoing challenge for a number of reasons [1].

[2]Official website: https://www.w3.org/WAI/

Table 1: **Comparison of news reading media:** This table compares print, mobile, and e-ink devices for news reading on the types of reading aids that are compatible with these media, and the advantages and disadvantages 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 mobility: the newspaper is not portable with a handheld or desktop magnifier audio: text-to-speech on news documents is error-prone
Digital Devices	screen magnifiers, screen readers, touch screen gestures	mobility: device and accompanying aids are portable audio: direct access to audio aids within the device to read text out loud	screen space: small screens can only fit a limited number of 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
Audio	N/A	mobility: usually can be worn or carried in a mobile device comfort: no visual fatigue	content: content is not timely and limited based on providers navigation: rigid sequential reading makes it difficult to browse and select content

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 considering the space and navigation limits of digital screens is the immediate challenge for accessibility [23, 24]. Customized interactive news prints developed by [25], and the adapting of printed newspapers to tablets by [26] show how the style of the newspaper can be taken from printed newspapers, with a much less crowded arrangement, which would also be important to avoiding crowding effects [27].

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[3] designed for people with macular degeneration. This application automatically transforms articles from a number of online news outlets into a scrolling interface where the font 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 [28]. The reading experience is purely text based, though, and thus image and video content are left out.

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 proposing VR as a new 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 study on existing VR reading applications for accessibility features and design in their usage.

3.1 The advantages of VR for low vision

VR headsets have a number of unique advantages for low vision as compared to existing reading aids:

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.

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

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[4] for the MNRead visual acuity charts [29] 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 [18].

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 between $600 to $3000 depending on quality and function.

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.

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 [30], and general application and interface design [21, 31]. Most notably, [31] 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 reading activities, and does not address the specific issue of low-vision reading.

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

[4] 12-pt font held at a reading distance of 40 cm, as defined by [29]

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 font and text layout. As mentioned through the review of [27], a number of font-related variables concern reading efficiency for low vision people, including flexibility to adjust (1) font size: reasonably up to 100 times the size of newsprint font, (2) font type: a number of fonts such as Tiresias or Eido have been developed with accessibility in mind, 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 font, 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 font size based on visual degrees, and line width based on number of characters [32]. 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.

Contrast and brightness. The benefits of providing inverted text reading environments (e.g. white text on dark background) has been outlined numerous times, indicating possibly an improvement of 10 - 40% in reading speed [27]. 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 [30, 31].

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 [18]. 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 [30, 31].

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 contrast of visual elements, or create semantic overlays on the environment [33, 34, 35, 36, 37, 38], 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

Table 2: **E-readers for VR headsets:** This table provides an overview of reading applications for VR headsets that we included in our survey for accessibility features. Compatible devices, genres, and file formats are summarized here.

Application	Device	Genre	Content
ImmersionVR Reader	Gear VR, Oculus Go	all books	epubs & pdf
Chimera	Gear VR	all books	epub
Vivepaper	Vive, Cardboard	all books	app limited
Virtual Book Viewer	Oculus Go	all books	pdfs & images
Bedtime VR	Gear VR, Cardboard	children's books	app limited
Madefire Comics	Gear VR, Cardboard, Daydream	comics	app limited
Sphere Toon	Vive	comics	app limited
ComX VR	Cardboard	comics	app limited

Table 3: **Accessibility features of existing VR reading applications:** we surveyed the accessibility features of applications listed in Table 2 by directly installing and using the applications (when available) and studying the user manuals. We found that accessibility was rarely considered in the application design, and only limited features were available.

Feature	Applications with feature
Zoom / Magnification	Virtual Book Viewer, ComX VR, Reader
Font size	Chimera (2 sizes)
Text-to-speech	Reader (audiobook support)

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 e-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 Table 3, though it is important to note that none of these applications were designed with low-vision users as a primary target. For complex documents like newspapers, these applications are still challenging for low-vision users due to the complex page layouts, limits in font size or zoom due to image resolution, and mix of text and media content. 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.

Thus, a fully accessible VR reading experience is still missing and nothing has been done yet for news reading.

4 Results: Framework and proof of concept

Based on the indices and study conducted in Section 3, we are able to propose a framework and visual design for a VR reading application for complex news documents, accompanied by a working prototype as a proof of concept.

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 customizable reading interface with accessibility features.

This framework is comprised of three steps: (1) representation of original content to a universal, intermediary format, (2) personalizing 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 [39, 40, 41, 42].An example hierarchical analysis of a newspaper is shown in Figure 1.

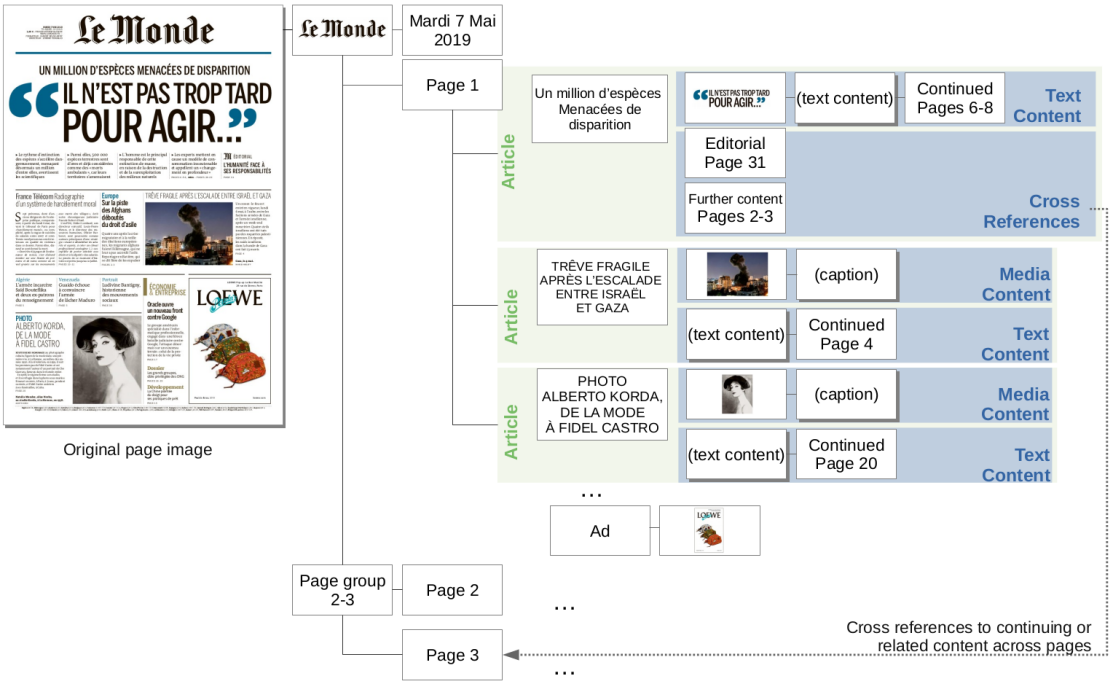

Figure 1: Newspaper navigation is not linear, but newspaper documents can be represented in a hierarchical structure from pages, to articles, to individual text and media content. Text and images in this example ©Le Monde

4.1.2 Navigation

Once the media and text content have been organized, the next step is to personalize the reading experience. 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, click on hyperlinks to related stories, and go directly to pages with specific types of news stories they are interested in [43]. When an article of interest is found, the reader would then go deeper to read the text content.

This difference is what we call *global navigation*–the possibility of browsing articles in the overall document for content that attracts the user–and *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 navigate the document, including but not limited to filtering content based on keywords, and 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 customize the news document content to their own reading preferences.

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.

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 contrast, as well as integrating accessibility features discussed in Section 3.

Most prominently, visual presentation of text must be fully customizable, including how sentences are broken, the amount of text to present at once, the font 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.

We provide a preliminary example for this framework through the design and implementation of a VR reading application, presented in the next section.

4.2 Proof of concept prototype 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.

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).

The interface has a number of goals pertaining to important accessibility features discussed in Section 3. The visual design of the interface is shown in Figure 2.

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 contrast. A number of settings for the font can be adjusted through the accessibility menu (as shown in Figure 3).

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. A number of settings for font in the text view are also offered:

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

- *Inverting text*: options are given to invert text content 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 3.

As a proof-of-concept, this prototype 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. 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.

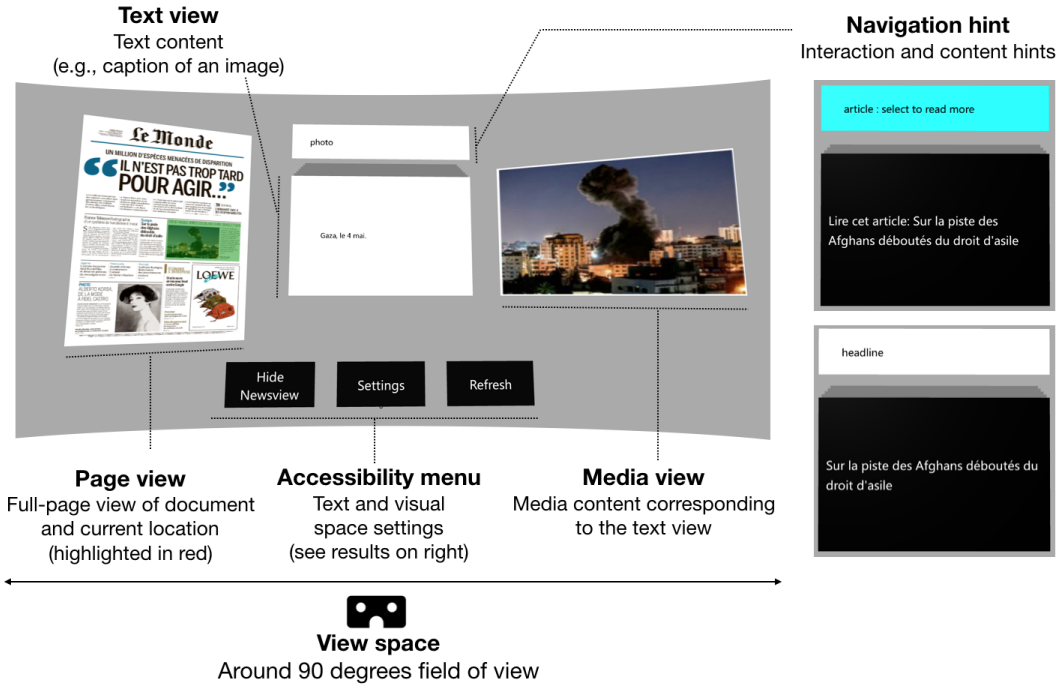

Figure 2: Application prototype: The global overview of the newspaper page is shown side-by-side with the enlarged text and images of the highlighted region. Navigation hints above the card show what type of content is displayed (e.g. photo, heading, paragraph) and whether the card can be selected (i.e. highlighted in light blue) to reveal further content.

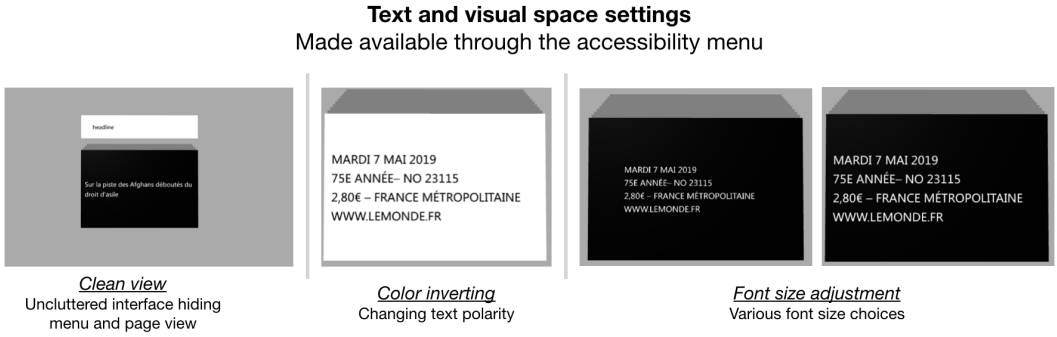

Figure 3: The accessibility menu provides a number of functions including (1) showing/hiding the page and menu view to personalize the view space, (2) invert foreground and background color only for text content, and (3) change the font size. Text and images in this example are copyright of ©Le Monde

5 Discussion

From the analysis and study of design principles, to the proposal of a framework and its implementation as 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 [44].

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 [45, 46]. 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 [47].

As far as VR is concerned, the same observations hold [48]. 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 [49]. 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 test [32] and iRest [50]. However, these reading tests are simplified reading scenarios, not accounting for realistic complex scenarios 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 [51], 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 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 proposed a framework of a reading platform in VR for low-vision news reading. Our framework emphasizes the ease of adjusting visual features and layout in the visual space, as well as personalize the navigation flow of complex news documents. One proof of concept prototype has been proposed that implements the framework and design principles.

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. It is also these advantages that could potentially allow VR to propose solutions to accessible reading that make use of a personalisable, 360 degrees space that is otherwise non-existent 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 better understand the benefits of the medium for low vision, to establish design principles for visual accessibility, and to explore novel applications have the potential to help low-vision population better navigate their everyday life.

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