CLEVR: A Customizable Interactive Learning Environment for Users with Low Vision in Virtual Reality

Adrian H. Hoppe
Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
adrian.hoppe@kit.edu

Julia K. Anken
Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
julia.anken@student.kit.edu

Thorsten Schwarz
Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
thorsten.schwarz@kit.edu

Rainer Stiefelhagen
Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
rainer.stiefelhagen@kit.edu

Florian van de Camp
Fraunhofer Institute of Optronics, System Technologies, and Image Exploitation (IOSB), Karlsruhe, Germany
florian.vandecamp@iosb.fraunhofer.de

ABSTRACT

Technological advances enable the development of new low vision aids. One such new technology is virtual reality (VR). Existing VR applications offer a variety of adjustments to the content and the user's environment to support people with low vision. Yet, an interaction concept to conveniently activate and control these aids is missing. Therefore, we designed and implemented an interaction concept based on user and expert feedback and evaluated it in a user study. Our application offers various aids to support residual vision and a radial menu for intuitive use of these aids. The results of the user study show that the VR application allows simple task solving comparable to a desktop computer. Furthermore, the user study gives an insight into the effects of different visual impairments on the usage of VR, since the field of view has a larger impact than visual acuity. Overall, our results indicate that VR is a suitable aid to support the individual needs of users with low vision.

CCS CONCEPTS

• **Human-centered computing** → Accessibility; Accessibility technologies.

KEYWORDS

Virtual reality, Visual impaired, Low vision, Accessibility, Learning environment, Assistive systems

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1 INTRODUCTION

Human perception strongly focuses on one sense – vision. The real world as well as the use of technologies and virtual environments (VE) therefore often rely on visual aspects. Even people with low vision prefer visual information when using computers, smartphones, and tablets [1] [2]. Yet, their experience of VEs is not directly comparable to other technologies. Zhao et al. [3] show that the visual acuity determined by standard vision tests does not allow any conclusion about the visual acuity when using AR glasses. According to the basic idea of ability-based design by Wobbrock et al. [4], technologies should be accessible for everyone and optimally adapted to users' respective abilities. VR applications provide new possibilities as the application can fully control the VE and adapt to support the requirements of users with low vision. VR overcomes physical constraints such as the size of screens and allows to utilize large or multiple displays. With a VE colors, contrast, and the brightness of the virtual content and surroundings can be freely adjusted.

Several systems exist that support users with low vision. Some systems aim to support users with everyday tasks by enhancing the real world [5] [6] [7]. For this, a camera image is scaled, color adjusted, or otherwise modified. The image is then displayed to the user e.g. with augmented reality (AR) glasses. Other systems provide aids within a VE and adjust the virtual content [8] [9] [10]. All these systems provide helpful tools to increase the readability of real or virtual content. However, none of them offer a holistic interaction concept that is applicable to a wide range of visual impairments. The presented systems use swipe and tap [7] or hand gestures [5], gaze [9], or mouse and keyboard [8] to control a menu, or present no user interface, but use a Wizard of Oz-based speech input setup to change settings [6] [10]. A study on the accessibility of VR [11] highlights the lack of adaptability as one of the major problems of systems. Since every disability and limitation is individual, it is crucial to ensure maximum flexibility and adaptability of the VR environment. Zolyomi et al [12]found that the question of whether and how assistive technology is integrated into everyday life depends crucially on an understanding of the personal value of what is seen.

The presented work targets to supply a Customizable interactive Learning Environment for low vision users in Virtual Reality

(CLEVR). CLEVR leverages the full control over the virtual world to offer diverse adaptation possibilities for people with a wide range of clinical pictures and requirements. CLEVR supports any desktop application by using screen capturing. The main contribution of this work is the development of an interaction concept that includes a radial menu which allows users to adjust the adaptations easily and provides feedback using multiple stimuli.

2 CLEVR: DESIGN AND IMPLEMENTATION

Three CLEVR prototypes were implemented using Unity and a Pimax 5K+ VR system with HTC Vive controllers and iteratively evaluated with users and experts. In order to be capable of accessing a broad range of applications and content a screen capture feature was integrated. The capture software is based on Windows GDI[1] id="fn1"> https://docs.microsoft.com/en-us/windows/win32/gdi/windows-gdi </fn> and allows to capture whole screens or single windows and to display the content within the VE. A user can interact with the virtual screens by using a ray-cast interaction [13].

As a first prototype, the user's workspace (i.e. desk) was replicated within VR. Physical objects (e.g. a magnifying glass) were placed on the desk to allow the user to enable certain aids. The aids' settings were controlled using a virtual screen and a ray-cast interaction. The interaction concept was examined with the help of four experts from the Study Centre for the Visually Impaired Students (SZS) at the KIT. The experts concluded that the desk is a hindrance to use because it does not allow the user to move freely. A second prototype therefore used virtual screens controlled by touch. However, a user study with three low vision users showed that touch interaction is unsuitable because functions were often selected unintentionally or unnoticed. Additionally, multiple screens were arranged in a circle around the user to provide an overview and to increase work productivity [14] [15] [16]. The participants could not benefit from this overview because the screens were placed too far away. A reduction to one screen and the addition of a thicker border, allowing users to distinguish between content and environment, was suggested. The aspect ratio of the screens was also addressed. The lateral edges and upper region of the enlarged screens are too far away and therefore not readable. As a result, users suggested that the screens should be movable. Also, they found the vibration feedback used for some elements, such as grasping and activating an element, helpful. Haptic feedback should be integrated into all settings and interactions to prevent unnoticed selection.

Building on the feedback from the first two prototypes, an interaction concept was developed that focused on enabling perception via multiple senses. The challenge was to define easy to learn controls that support a variety of adjustments. Also, a kind of "blind" operation should be offered for experienced users. It should be possible to observe the effects of adjustments made directly and indirectly, while at the same time, the menu is visible and usable. To achieve this, two radial context-sensitive menus were introduced for convenient operation and adaptations of the aids. Each radial menu contains four buttons which select a function or open a submenu. The radial menu is operated using the round touchpad (or joystick) of the controllers and is attached right above it. Upon touch, the position of each thumb is used to highlight the closest button within the respective menu in a different color and haptic feedback is triggered. To select an option, the touchpad must be pressed like a button. An unnoticed selection is thereby avoided. As there are several sub-menus, the controller's grip button closes the current submenu and opens menu above it. A long press of the grip button closes the radial menu at any time. To ensure readability, the size of the radial menus can be scaled and the fore- and background colors can be adjusted. Also, we included a text-to-speech feature for all controls. The advantage of attaching the menu to the controller is that the menu can be brought closer with a simple hand movement and thus further enlarged. In addition to that, the fixed menu structure allows users to access a functionality blindly using a combination of key presses. The functionalities are divided between both hands. The dominant hand controls all settings and

[1] https://docs.microsoft.com/en-us/windows/win32/gdi/windows-gdi<fn



Figure 1: CLEVR application with the radial menu attached to the controllers including a title for the current menu (left) and the VE with surroundings and the virtual screen showing the captured desktop (right).

adjustments that directly affect the screen. With the non-dominant hand, aids are controlled, and supporting actions are carried out. This includes the adaptation of the entire VE, e.g. to reduce brightness. Also, one-click shortcuts were introduced to use frequently used functionalities i.e. magnification tool and virtual screen positioning. While using one of these functions, the controller touchpad can be pressed to open the corresponding menu directly. See Figure 1 for the final setup. The CLEVR application contains the following functionalities: magnification (on/off, zoom levels, fixed to head, hand, or bifocal), virtual pointer (on/off , size, color), radial menu, virtual keyboard, and controller tooltips (different sizes and colors), text-to-speech (on/off), customizable environment (different colors, brightness and surroundings), virtual screen adjustment (position with individual axis lock, size and curvature), and virtual screen content adjustment (color filters, brightness, contrast, etc.).

3 EVALUATION

We performed a user study with 18 unpaid people with low vision and various clinical pictures. Retinal diseases are represented by e.g. macular degeneration, Retinitis pigmentosa and cone rod dystrophy. Diseases of the optic nerve, such as optic atrophy and glaucoma, were distinguished. Additionally, subjects with albinism and aniridia were included. Visual acuity ranged from 25% residual vision to FC (finger counting). 50% of the participants stated to have an impaired field of view. Four different tasks were first performed with CLEVR and then on a desktop computer for comparison. The tasks are assumed to be representative tasks that are performed on a daily basis. Users were asked to fill out a questionnaire, search for information within articles of a wikipedia-style website, find a diagram within a book and gather information, and compare values within a multi-table excel sheet. Prior to usage, users learned to use the VR system with an interactive tutorial as well as adjusted the aids to fit their requirements.

No participant discontinued the study, but 5 of the 18 participants could not complete all VR tasks, all 5 had an impaired visual field. Users who were able to complete all tasks with VR took between 13:46 and 44:29 min (M = 29:45, SD = 10:56). By grouping the users according to their symptoms, we found that visual acuity is not decisive for the task completion times. Yet, task completion times for the participants with an un- or slightly impaired visual field (M = 18:59, SD = 04:09) are lower than those of users with an impaired visual field (M = 37:56, SD = 06:53). A Welch test confirms that difference is significant, $t(8.217) = -5.763$, $p < 0.001$, Cohen's $d = -3.327$. To assess the workload of the CLEVR system compared to a desktop computer, we asked users to fill out NASA TLX questionnaires (see Figure 2). A paired t-test shows that the overall workload ratings for VR is significantly higher than for desktop, $t(15)=5.909$, $p < 0.001$, Cohen's $dz = 1.477$. The mental and physical demand are significantly higher when working with VR, $t(12) = 4.702$, $p = 0.001$, Cohen's $dz = 1.304$., and $t(12) = 2.371$, $p = 0.035$, Cohen's $dz = 0.658$ respectively. The user's effort is significantly higher when working with CLEVR, $t(12) = 2.368$, $p = 0.036$, Cohen's $dz = 0.657$. There is no significant difference in temporal demand, performance, or frustration.

In a subsequent interview, the users stated that the habituation factor plays a particularly important role. VR offers the potential that already at the first use a similar performance can be achieved as in the daily work on the desktop computer. "There is a potential to become as fast as on the PC and still have a better body posture and really take advantage of VR." (participant 12). "It was just so unfamiliar with the 2 controllers and the menus. But I think if you get used to it, it works well." (participant 16). Each participant mentioned different problems of usage in everyday life. Many of

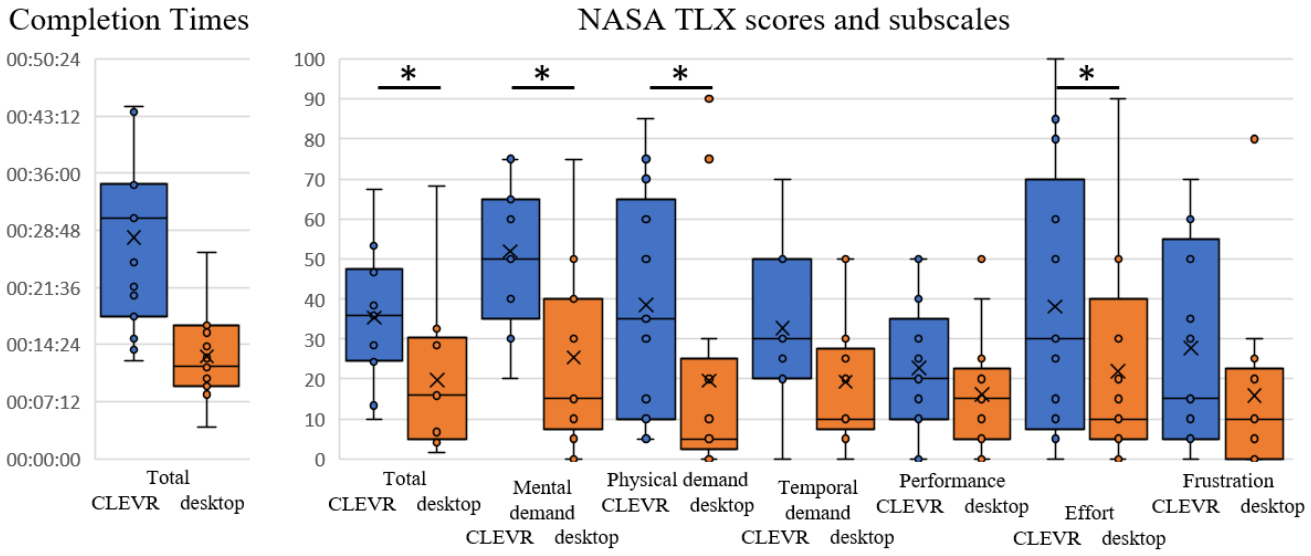


Figure 2: Boxplots of Completion Times and NASA-TLX measurements for CLEVR vs. desktop computer for the participants who have completed all tasks. * indicate significant differences.

them already considered the application as an improvement. "I like the settings, it makes much more sense to do things with the button, rather than with a floating menu. It shows me where to click, that's very user experience oriented and well designed. [...] you already get used to routines." (participant 12). "Up to now, I have always thought that VR is unsuitable for people who see nothing or very badly like me. But because you can get so close to everything, I am really extremely enthusiastic. And I enjoyed it very much. I could imagine that this is something that I can simply use at home." (participant 16).

4 DISCUSSION

Most participants (72,22%) were able to complete all tasks. The results showed that participants with an unimpaired visual field needed significantly less time for the tasks. The visual field seems to be an important factor for users to be able to use VR. Visual acuity on the other hand has no influence on the capability of task fulfillment. Even participants with a visual acuity < 2% (legally blind in Germany) were able to perform the tasks. The participants of the preliminary study also indicated, that the revised interaction system is much more suitable and provides reliable control over the aids and screens. The workload of the participants is low to medium. Most users (except one) rate CLEVR as more demanding than using a desktop computer. However, a higher physical and mental strain of the VR application is expected, since the controls required some learning effort and the HMD is still quite heavy and most users sweat during longer user sessions. However, the participants liked the fact that they could physically move while working with CLEVR.

5 CONCLUSION AND FUTURE WORK

At present, people with low vision have to adapt to the rigid conditions of a desktop computer (e.g. limited screen size) or other aids. By using VR, physical limitations can be overcome as the virtual world offers great control over the content displayed (e.g. reducing the overall brightness of the room). By using the possibilities offered by VR as a technology, people with low vision can adapt their virtual environment to their needs and requirements. Also, users are not tied to a desk, but can move around or choose a more comfortable body posture, as noted by the participants. The CLEVR system provides an intuitive and easy-to-use radial interaction menu to activate or adjust a variety of aids. The radial menu addresses visual, acoustic, and haptic senses to ensure usability for a variety of users and even blind usage. Although the interaction is more demanding, participants could imagine using the VR system in the future. Furthermore, the user study revealed an interesting insight that the visual field of the users seems to have a greater influence than visual acuity when using VR.

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