Optimizing VR for All Users Through Adaptive Focus Displays

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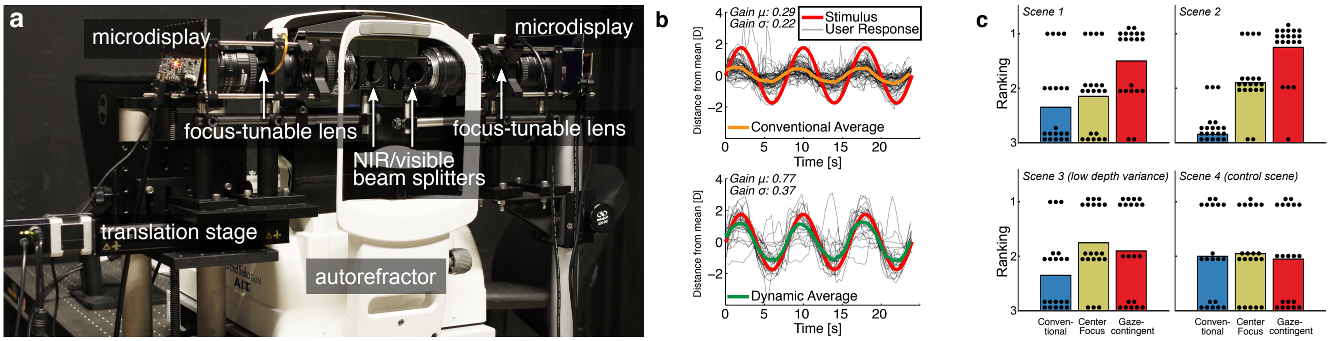

Figure 1: (a) Our benchtop setup incorporating adaptive focus via focus-tunable lenses and an autorefractor for accommodation measurement. (b) Accommodative responses to a sinusoidal target were recorded. The stimulus (red), individual responses (gray), and the average response (green, orange), are shown (mean subtracted per user). (c) Preference rankings for each display mode, with varying scenes. Circles indicate individual responses. A clear preference for the adaptive modes is seen.

ABSTRACT

Personal computing devices have evolved steadily, from desktops to mobile devices, and now to emerging trends in wearable computing. Wearables are expected to be integral to consumer electronics, with the primary mode of interaction often being a near-eye display. However, current-generation near-eye displays are unable to provide fully natural focus cues for all users, which often leads to discomfort. This core limitation is due to the optics of the systems themselves, with current displays being unable to change focus as required by natural vision. Furthermore, the form factor often makes it difficult for users to wear corrective eyewear. With two prototype near-eye displays, we address these issues using display modes that adapt to the user via computational optics. These prototypes make use of focus-tunable lenses, mechanically actuated displays, and gaze tracking technology to correct common refractive errors per user, and provide natural focus cues by dynamically updating scene depth based on where a user looks. Recent advances in computational optics hint at a future in which some users experience better vision in the virtual world than in the real one.

CCS CONCEPTS

• **Computing methodologies → Virtual reality**; *Perception*;

KEYWORDS

virtual and augmented reality, vision correction, computational optics

SIGGRAPH '17 Talks, July 30 - August 03, 2017, Los Angeles, CA, USA

ACM ISBN 978-1-4503-5008-2/17/07.
https://doi.org/10.1145/3084363.3085029

ACM Reference format:
Nitish Padmanaban Robert Konrad Emily A. Cooper Gordon Wetzstein. 2017. Optimizing VR for All Users Through Adaptive Focus Displays. In *Proceedings of SIGGRAPH '17 Talks, Los Angeles, CA, USA, July 30 - August 03, 2017,* 2 pages.
https://doi.org/10.1145/3084363.3085029

1 INTRODUCTION

Virtual and augmented reality (VR/AR) systems have promising applications spanning education, communication, training, behavioral therapy, and basic vision research. However, the basic optics of commercial systems are largely unchanged since their conception in the 1800s. In front of each eye, a small physical display is placed behind a magnifying lens, creating a virtual image at a fixed distance from the viewer, with small differences in the images displayed to each eye creating a perception of depth, called stereopsis.

But this simple optical design lacks a critical aspect of 3D vision: changes in stereoscopic depth are also associated with changes in focus. When viewing a near-eye display, users' eyes can change their vergence angle to a range of stereoscopic depths, but to focus on the virtual image, the eyes must accommodate to a single, fixed distance. For users with normal vision, this creates an unnatural condition known as the vergence–accommodation conflict (VAC) [Kooi and Toet 2004; Lambooij et al. 2009], which may lead to double vision (diplopia), compromised visual clarity, visual discomfort, and fatigue [Kooi and Toet 2004; Shibata et al. 2011].

The VAC is clearly an important problem to solve for users with normal vision. However, correctable visual impairments caused by refractive errors, such as myopia (near-sightedness) and hyperopia (far-sightedness), affect approximately half of the US population [Vitale et al. 2008]. And essentially all people in middle-age and beyond suffer from a decreased ability to accommodate, called presbyopia. For people with these common impairments, additional or wholly different solutions are required for an optimal experience in VR.

2 METHODS

We ran a user study of 173 people to evaluate whether an adaptive focus mode (below) can adequately address the VAC. We assess accommodation response with an autorefractor, and subjective ratings [Padmanaban et al. 2017]. In addition, we also consider the effects of age (for presbyopia) and refractive errors. A summary of our hardware systems and implemented display modes follows.

Benchtop Focus-tunable Display System. Figure 1a shows a benchtop prototype built using focus-tunable lenses between the eyes and the microdisplays. The focus-tunable lenses allow for real-time control of the distance to the virtual image of the displays, independently for each eye. This allows them to be adapted to the current display mode and to the prescription of the user. This prototype has an autorefractor behind a NIR/visible beamsplitter, allowing simultaneous display of content and accommodation measurement.

Gaze-contingent Near-eye Display System. Our second system achieves adaptive focus via a mechanically adjustable display [Shiwa et al. 1996], built on the Samsung GearVR platform. While it sacrifices independence of the eyes' views, it has the advantage of having a wider field of view and an eye tracker. Using the eye tracker, the system shifts the virtual image in near-real time to stimulate the user's accommodation in a gaze-contingent manner.

Conventional. The display mode matching current-generation VR systems, with the virtual image fixed at a single plane.

Corrected. A display mode with a fixed virtual image, with the virtual image shifted per eye to match the user's prescription.

Adaptive Focus. An umbrella term for our various display modes that address the VAC by adaptively changing the distance of the virtual image. The benchtop system implements *dynamic* mode, where the virtual image moves to match the depth of a target [Johnson et al. 2016; Konrad et al. 2016; Liu et al. 2008], which is assumed to be fixated. The *gaze-contingent* mode is implemented with the aid of an eye tracker in the second system, adaptively moving the virtual image to match the depth of the object in the direction of the user's gaze. In addition, we also test a *center-focus* mode that uses the head orientation forward direction instead of gaze.

3 RESULTS

Correcting Refractive Error. We tested 70 users between 21 and 64 years old to determine the efficacy of the corrected mode, without prior knowledge of their prescriptions. We use a portable, smartphone-based eye test (NETRA; EyeNetra, Inc.) that allows users to self-measure their prescription. We then use this measurement and test sharpness and fusibility of a target in the conventional and corrected modes. We find that not only is the corrected mode better for both sharpness and fusibility, but it is comparable to the sharpness reported by users without refractive error in the conventional mode. This suggests that it is possible to customize VR to be comparable to vision with a user's own corrective eyewear.

Vergence–Accommodation Conflict. For another 64 users between the ages of 22 and 63, we compared the effect of using conventional vs an adaptive mode. Using the benchtop setup, we measure the accommodative gain of each user relative to a sinusoidal stimulus (Figure 1b). We find a significant improvement in gain in the dynamic mode (over twice as much), matching typical responses in real-world viewing conditions. The dynamic mode also improves performance in fusion tests. A preference test was conducted using the gaze-contingent system on 20 younger users, which provides a more typical VR experience than the benchtop system (e.g. head movement, field of view). Comparing the conventional, center-focus, and gaze-contingent modes, we find a preference for the adaptive modes in scenes with close objects (and therefore potential for VAC), especially the gaze-contingent mode (Figure 1c). These results show that adaptive modes, with eye tracking as a core component, can adequately restore focus cues in VR – until either light-field displays, which produce truly accurate focus cues [Huang et al. 2015], become widely available, or accommodation-invariant displays, which allow fully vergence-driven accommodation [Konrad et al. 2017], offer improved resolution.

Vergence–Accommodation Conflict for Presbyopes. When the accommodative gain data is viewed as a function of age for the adaptive mode, a trend familiar to most over age 45 appears. The ability to accommodate degrades with age, suggesting that the VAC may differ for older users [Watt and Ryan 2015]. This is reflected in sharpness ratings given by older users. Sharpness reported in dynamic mode dropped significantly at near distances, whereas conventional mode elicited no such decline. However, it must be noted that fusibility was slightly improved in the dynamic mode even for presbyopes. Presbyopes' eyes are fixed at a single focus, so they do not benefit from traditional solutions to the VAC. It may be best to allow for an adaptive mode which limits the nearest approach of the virtual image based on the user's degree of presbyopia, gracefully falling back to a fixed-focus system for the oldest users.

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