

Optimizing virtual reality for all users through gaze-contingent and adaptive focus displays

Nitish Padmanaban^a, Robert Konrad^a, Tal Stramer^a, Emily A. Cooper^{b,1}, and Gordon Wetzstein^{a,1}

^aDepartment of Electrical Engineering, Stanford University, Stanford, CA 94305; and ^bDepartment of Psychological & Brain Sciences, Dartmouth College, Hanover, NH 03755

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From the desktop to the laptop to the mobile device, personal computing platforms evolve over time. Moving forward, wearable computing is widely expected to be integral to consumer electronics and beyond. The primary interface between a wearable computer and a user is often a near-eye display. However, current generation near-eye displays suffer from multiple limitations: they are unable to provide fully natural visual cues and comfortable viewing experiences for all users. At their core, many of the issues with near-eye displays are caused by limitations in conventional optics. Current displays cannot reproduce the changes in focus that accompany natural vision, and they cannot support users with uncorrected refractive errors. With two prototype near-eye displays, we show how these issues can be overcome using display modes that adapt to the user via computational optics. By using focus-tunable lenses, mechanically actuated displays, and mobile gaze-tracking technology, these displays can be tailored to correct common refractive errors and provide natural focus cues by dynamically updating the system based on where a user looks in a virtual scene. Indeed, the opportunities afforded by recent advances in computational optics open up the possibility of creating a computing platform in which some users may experience better quality vision in the virtual world than in the real one.

virtual reality | augmented reality | 3D vision | vision correction | computational optics

Emerging virtual reality (VR) and augmented reality (AR) systems have applications that span entertainment, education, communication, training, behavioral therapy, and basic vision research. In these systems, a user primarily interacts with the virtual environment through a near-eye display. Since the invention of the stereoscope almost 180 years ago (1), significant developments have been made in display electronics and computer graphics (2), but the optical design of stereoscopic near-eye displays remains almost unchanged from the Victorian age. In front of each eye, a small physical display is placed behind a magnifying lens, creating a virtual image at some fixed distance from the viewer (Fig. 1A). Small differences in the images displayed to the two eyes can create a vivid perception of depth, called stereopsis.

However, this simple optical design lacks a critical aspect of 3D vision in the natural environment: changes in stereoscopic depth are also associated with changes in focus. When viewing a near-eye display, users' eyes change their vergence angle to fixate objects at a range of stereoscopic depths, but to focus on the virtual image, the crystalline lenses of the eyes must accommodate to a single fixed distance (Fig. 2A). For users with normal vision, this asymmetry creates an unnatural condition known as the vergence–accommodation conflict (3, 4). Symptoms associated with this conflict include double vision (diplopia), compromised visual clarity, visual discomfort, and fatigue (3, 5). Moreover, a lack of accurate focus also removes a cue that is important for depth perception (6, 7).

The vergence–accommodation conflict is clearly an important problem to solve for users with normal vision. However, how many people actually have normal vision? Correctable visual impairments caused by refractive errors, such as myopia (near-

sightedness) and hyperopia (far-sightedness), affect approximately one-half of the US population (8). Additionally, essentially all people in middle age and beyond are affected by presbyopia, a decreased ability to accommodate (9). For people with these common visual impairments, the use of near-eye displays is further restricted by the fact that it is not always possible to wear optical correction.

Here, we first describe a near-eye display system with focus-tunable optics—lenses that change their focal power in real time. This system can provide correction for common refractive errors, removing the need for glasses in VR. Next, we show that the same system can also mitigate the vergence–accommodation conflict by dynamically providing near-correct focus cues at a wide range of distances. However, our study reveals that this conflict should be addressed differently depending on the age of the user. Finally, we design and assess a system that integrates a stereoscopic eye tracker to update the virtual image distance in a gaze-contingent manner, closely resembling natural viewing conditions. Compared with other focus-supporting display designs (10–18) (details are in *SI Appendix*), these adaptive technologies can be implemented in near-eye systems with readily available optoelectronic components and offer uncompromised image resolution and quality. Our results show how computational optics can increase the accessibility of VR/AR and improve the experience for all users.

Results

Near-Eye Display Systems with Adaptive Focus. In our first display system, a focus-tunable liquid lens is placed between each eye and a high-resolution microdisplay. The focus-tunable lenses allow for adaptive focus—real-time control of the distance to the virtual image of the display (Fig. 1A, green arrows). The lenses are driven by the same computer that controls the displayed images, allowing for precise temporal synchronization between the

Significance

Wearable displays are becoming increasingly important, but the accessibility, visual comfort, and quality of current generation devices are limited. We study optocomputational display modes and show their potential to improve experiences for users across ages and with common refractive errors. With the presented studies and technologies, we lay the foundations of next generation computational near-eye displays that can be used by everyone.

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¹To whom correspondence may be addressed. Email: emily.a.cooper@dartmouth.edu or gordon.wetzstein@stanford.edu.

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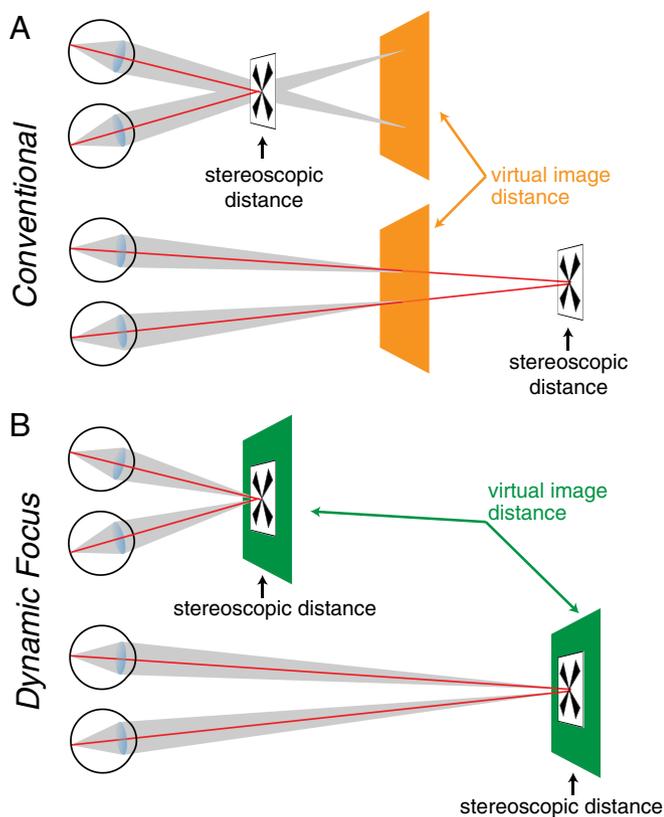


Fig. 2. (A) The use of a fixed focus lens in conventional near-eye displays means that the magnified virtual image appears at a constant distance (orange planes). However, by presenting different images to the two eyes, objects can be simulated at arbitrary stereoscopic distances. To experience clear and single vision in VR, the user's eyes have to rotate to verge at the correct stereoscopic distance (red lines), but the eyes must maintain accommodation at the virtual image distance (gray areas). (B) In a dynamic focus display, the virtual image distance (green planes) is constantly updated to match the stereoscopic distance of the target. Thus, the vergence and accommodation distances can be matched.

inaccurate corrections or modest changes in clarity that were not noticeable in the virtual scene (*SI Appendix* has additional discussion). Future work can incorporate the refractive testing directly into the system by also using the focus-tunable lenses to determine the spherical lens power that results in the sharpest perceived image and then, store this information for future sessions.

Driving the Eyes' Natural Accommodative Response Using Dynamic Focus. Even in the absence of an uncorrected refractive error, near-eye displays suffer from the same limitations as any conventional stereoscopic display: they do not accurately simulate changes in optical distance when objects move in depth (Fig. 2A). To fixate and fuse stereoscopic targets at different distances, the eyes rotate in opposite directions to place the target on both foveas; this response is called vergence (red lines in Fig. 2A). However, to focus the displayed targets sharply on the retinas, the eyes must always accommodate to the virtual display distance (gray lines in Fig. 2A). In natural vision, the vergence and accommodation distances are the same, and thus, these two responses are neurally coupled. The discrepancy created by conventional near-eye displays (the vergence–accommodation conflict) can, in principle, be eliminated with an adaptive focus display by producing dynamic focus: constantly updating the virtual distance of a target to match its stereoscopic distance (Fig. 2B) (19, 20).

Using the autorefractor integrated in our system (Fig. 1B), we examined how the eyes' accommodative responses differ

between conventional and dynamic focus conditions and in particular, whether dynamic focus can drive normal accommodation by restoring correct focus cues. Users ($n = 64$, ages 22–63 y old) viewed a Maltese cross that moved sinusoidally in depth between 0.5 and 4 D at 0.125 Hz (mean = 2.25 D, amplitude = 1.75 D), while the accommodative distance of the eyes was continuously measured. Users who wore glasses were tested as described previously with the NETRA, and their correction was incorporated. In the conventional condition, the virtual image distance was fixed at 1.3 m; in the dynamic condition, the virtual image was matched to the stereoscopic distance of the target. Because of dropped data points from the autorefractor, we were able to analyze 24 trials from the dynamic condition, which we compare with 59 trials for the conventional condition taken from across all test groups.

The results are shown in Fig. 3A and B. Despite the fixed accommodative distance in the conventional condition, on average, there was a small accommodative response (orange line in Fig. 3A) (mean gain = 0.29) to the stimulus. This response is likely because of the cross-coupling between vergence and accommodative responses (24). However, the dynamic display mode (green line in Fig. 3B) elicited a significantly greater accommodative gain (mean = 0.77; partially paired one-tailed Wilcoxon tests, $p < 0.001$), which closely resembles natural viewing conditions (25). These results show that it is indeed possible to drive natural accommodation in VR with a dynamic focus display (*SI Appendix* has supporting analysis).

The ability to accommodate degrades with age (i.e., presbyopia) (26). Thus, we examined how the age of our users affected their response gain. For both conditions, accommodative gain was significantly negatively correlated with age (Fig. 3C) (conventional $r = -0.34$, dynamic $r = -0.73$, $ps < 0.01$). This correlation is illustrated further in Fig. 3C, *Inset*, in which average gains are shown for users grouped by age (≤ 45 and > 45 y old). Although the gains are much greater for the dynamic condition than conventional among the younger age group, the older group had similar gains for the two conditions. From these results, we predicted that accurate focus cues in near-eye displays would mostly benefit younger users and in fact, may be detrimental to the visual perception of older users in VR. We examine this question below.

Optimizing Optics for Younger and Older Users. A substantial amount of research supports the idea that mitigating the vergence–accommodation conflict in stereoscopic displays improves both perception and comfort, and this observation has been a major motivation for the development of displays that support multiple focus distances (3, 5, 7, 12–15, 27). However, the fact that accommodative gain universally deteriorates with age suggests that the effects of the vergence–accommodation conflict may differ for people of different ages (28–30) and even that multifocus or dynamic display modes may be undesirable for older users. Because presbyopes do not accommodate to a wide range of distances, these individuals essentially always have this conflict in their day to day lives. Additionally, presbyopes cannot focus to near distances, and therefore, using dynamic focus to place the virtual image of the display nearby would likely decrease image quality. To test this hypothesis, we assessed sharpness and fusibility with conventional and dynamic focus in younger (≤ 45 y old, $n = 51$) and older (> 45 y old, $n = 13$) users.

For the younger group, sharpness was slightly reduced for closer targets in both conditions. However, for the older group, perceived sharpness was high for all distances in the conventional condition and fell steeply at near distances in the dynamic condition (Fig. 3D). A logistic regression using age, condition, and distance showed significant main effects of distance and condition. The distance odds ratio was 0.56 ($ci = 0.46$ – 0.69), and the ratio for the dynamic condition was 0.60 ($ci = 0.48$ – 0.75 ; $ps < 0.001$),

placed in a vertical orientation (according to Optotune) is 0.3λ (measured at 525 nm). No noticeable pupil swim was reported. Two additional camera lenses provide a 1:1 optical relay system that increases the eye relief so as to provide sufficient spacing for a near-IR (NIR)/visible beam splitter (Thorlabs BSW20R). The left one-half of the assembly is mounted on a Zaber T-LSR150A Translation Stage that allows interpupillary distance adjustment. A Grand Seiko WAM-5500 Autorefractor records the accommodation state of the user's right eye at about 4–5 Hz with an accuracy of ± 0.25 D through the beam splitter. The wearable prototype is built on top of Samsung's Gear VR platform with a Samsung Galaxy S7 Phone (field of view = 96° , resolution = $1,280 \times 1,440$ per eye). A SensoMotoric Instruments (SMI) Mobile ET-HMD Eye Tracker is integrated in the Gear VR. This binocular eye tracker operates at 60 Hz over the full field of view. The typical accuracy of the gaze tracker is listed as $< 0.5^\circ$. We mount an NEMA 17 Stepper Motor (Phidgets 3303) on the SMI Mobile ET-HMD Eye Tracker and couple it to the focus adjustment mechanism of the Gear VR, which mechanically changes the distance between phone and internal lenses. The overall system latency is

approximately 280 ms for a sweep from 4 to 0 D (optical infinity). For reference, a typical response time for human accommodation is around 300–400 ms (discussion is in *SI Appendix*) (37).

Experiments. Informed consent was obtained from all study participants, and the procedures were approved by the Stanford University Institutional Review Board. Details are in *SI Appendix*.

Data Availability. *Dataset S1* includes the raw data from both studies.

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Supporting Information (SI)

Review of Related Display Technologies.

A comprehensive overview of 3D displays in general and related perceptual issues can be found in the recent survey by Banks et al. (1). In the following, we briefly review display technologies that are aimed at enhancing 3D information via focus cues.

Retinal Blur and Disparity Rendering Software-only approaches for attempting to provide focus cues have been explored in the past. For example, dynamic depth of field rendering is a software-only approach that renders the fixated object sharply while blurring other objects according to their relative distance in the virtual environment (2–4). There are no optical changes to the display in this mode—the distance of the virtual image remains fixed as in the conventional mode, only the displayed images change. In all studies (2–4), this technique has not been found to be perceptually beneficial, most likely because human accommodation may be driven by the accommodation-dependent blur gradient. Specifically, in natural conditions, changes of perceived retinal blur with respect to changes in the accommodative state of the crystalline lens would drive a user's accommodation to the distance of the fixated object. The retinal blur gradient in a digital display drives accommodation to its virtual image, no matter how the displayed content is altered.

Gaze-contingent disparity rendering (5) is another software-only approach that is effective in retaining the relative disparity cues between rendered objects by shifting the the entire 3D scene in depth such that the fixated object appears at the zero-disparity plane (i.e., the virtual image distance).

Limitations: Neither of these software-only approaches provide natural focus cues nor do they make near-eye displays accessible for users with refractive errors.

Volumetric and Multi-plane Displays Three-dimensional volumetric and multi-plane displays represent the most common approach to focus-supporting near-eye displays. Instead of using 2D display primitives at some fixed or adaptive distance to the eye, volumetric displays either mechanically or optically scan out the 3D space of possible light emitting display primitives in front of each eye (6).

Multi-plane displays approximate this volume using a few virtual planes that are generated by beam splitters (7, 8) or time-multiplexed focus-tunable optics (9–15). According to Campbell (16), the depth of focus, the change in focal distance that is just noticeable, under normal viewing conditions is roughly 0.3 D, which could be used to determine the spacing between the presentation planes. Interestingly, MacKenzie et al. (17, 18) recently used multi-focal displays to determine that a spacing of 0.9 D between discrete focal planes is sufficient to create accurate and natural accommodation responses in a multi-plane display. Our study does not evaluate multi-plane displays—both of our prototypes allow for continuous focus adjustment in the adaptive display mode. However, our prototypes could easily be adapted to offer a limited set of

directly addressable focal planes. In this case, the insights of MacKenzie et al.'s study would also apply and can be used as a guideline.

Limitations: Implementations with beam splitters make small device form factor for wearable near-eye displays difficult, temporal multiplexing can introduce perceived flicker and requires display refresh rates beyond those offered by current-generation microdisplays. Without significant improvements in refresh rates of displays commonly used for VR/AR applications, volumetric and multi-plane displays do not seem practical.

Light Field and Holographic Displays Other displays, such as light field and holographic displays, aim to synthesize the full 4D light field in front of each eye. Conceptually, this approach allows for parallax over the entire eye box to be accurately reproduced, including monocular occlusions, specular highlights, and other effects that cannot be reproduced by volumetric displays.

Limitations: Current-generation light field displays provide limited resolution (19–21) whereas holographic displays suffer from speckle and have extreme requirements on pixel sizes that are not afforded by near-eye displays also providing a large field of view.

Virtual Retinal Displays Direct stimulation of the retina, for example with scanned laser projectors, has been proposed. By focusing the laser through a small region of the user's pupil, the retinal blur is basically non-existent and can be controlled in software. This display mode renders the accommodative system into an open loop condition.

Limitations: Retinal displays in open loop do not drive human accommodation and they suffer from a very small eye box. Users of such systems often perceive visual artifacts, caused by shadows of small particles or aberrations in their own eyes. These and other limitations have prevented widespread use of virtual retinal displays.

Optical See-through Augmented Reality (AR) Displays AR displays are closely related to but different from virtual reality (VR) displays. In VR, the user's visual field is only stimulated by digital content created by a near-eye display. AR displays provide similar stimuli, but optically superimpose these on the physical stimuli of the real world. Most commonly, AR displays use optical combiners similar to those used in Pepper's Ghost illusion to combine digital and physical stimuli.

The goal of focus-supporting displays is somewhat different for VR and AR displays. In VR, the goal for non-presbyopes is to drive accommodation so as to provide natural viewing conditions and mitigate the vergence-accommodation conflict and its symptoms. In AR applications, there are two goals. The first is the same as for VR: one would like to be able to drive accommodative user responses with the digital content. Second, one would also like to ensure consistent focus cues between physical and digital content. The first goal for AR is adequately addressed with our VR-centric study. Evaluating

consistency of focus cues in AR is an interesting avenue of future research.

Benchtop Focus-tunable Display System.

Hardware An additional image of this prototype is shown in Fig. S1. The optical system for each eye comprises three Nikon Nikkor 50-mm f/1.4 camera lenses and a focus-tunable lens (Optotune EL-10-30-C with 10 mm diameter and a focal range of 5 to 10 diopters (D)). The Nikon lens closest to the screen is mounted at its focal distance to create a virtual image at optical infinity. The focus-tunable lens abuts the Nikon lens closest to the screen, and is offset with a -10 D lens. Without current applied, the focus-tunable lens places the virtual image at 5 D (0.2 m), but with increasing current the curvature of the liquid lens is increased, thereby placing the virtual image at a farther distance from the observer. Hence, the other two camera lenses provide a 1:1 optical relay system that increases the eye relief to about 4–5 cm. Without this relay, the eyeball of the observer would have to be placed right on the focus-tunable lens, which is mechanically difficult and would also not be comfortable. The eye relief also provides space for a visible/near-infrared beam splitter (Thorlabs BSW20R) in front of the eyes, so as to allow the autorefractor to function.

A Grand Seiko WAM-5500 autorefractor is integrated into the near-eye display system. The autorefractor uses built-in near infrared illumination (NIR) and a NIR camera to determine the user's accommodative state. The illumination pattern is close to invisible to the user. Accommodation measures are directly transmitted to the computer that controls the visual stimulus. The accuracy of the autorefractor is verified using a Heine Ophthalmoscope Trainer model eye (C-000.33.010).

Software All software driving the prototype is implemented in C++. The OpenGL application programming interface is used for 3D rendering.

Calibration. The prototype is calibrated in several steps to ensure that the images presented to the users exhibited no vertical parallax and are displayed with the right optical parameters. At each of the following steps, a bubble level is used to ensure that all parts are level. First, a digital single-lens reflex camera (DSLR) is used to verify that the screen is indeed placed at infinity by the lens mounted closest to the screen. Then, once the left and right assemblies are completed, a set of 4 calibration targets are used to ensure that the VIS/NIR mirror is placed at a 45° angle in each optical path. Two of the targets are placed right after the screen, and two in the perpendicular direction relative to the screen after the VIS/NIR beam splitters. The beam splitter positions and rotations are adjusted such that the full field of view from the lenses is reflected, and all 4 calibration targets are aligned in the optical axis. With just the calibration targets at the screen in place, the position of the 600 px square viewport on the LCDs is adjusted such that the onscreen targets are centered through the calibration targets when they are displayed at infinity. We then verify that the viewport is roughly equal in size to the circular field of view.

To set the height of the two assemblies, we first adjust the right assembly's height until a representative user's eye is vertically centered in the autorefractor's display as they look through the beam splitters. The left assembly is then adjusted to the same height (verified by connecting a cage rod

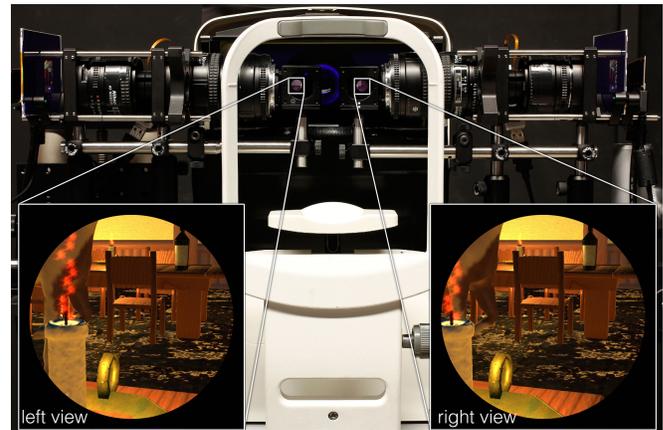


Fig. S1. Prototype stereoscopic near-eye display with focus-tunable lenses and adjustable interpupillary distance via a translation stage. The system includes an autorefractor that is capable of recording the accommodative state of the user's right eye continuously at 4–5 Hz. Insets show example stereoscopic views.

across the two assemblies and a bubble level). Here the cage rod also serves to verify that the two assemblies are parallel to each other. While displaying the Maltese cross target on both screens, we use a camera and adjust the forward tilt of the beam splitters until the two targets are at the same vertical position. Any small amount (a pixel or two) of vertical parallax remaining is fixed by moving the viewports on screen. Lack of vertical parallax is then verified with a human user.

Finally, we calibrate the power of the Optotune lenses and the position of the Zaber stage so that the lens power and interpupillary distance (IPD) can be programmatically controlled. For the Optotune lenses, we place a DSLR at the user's viewing position, set its focal distance at each of the marked distances on its lens, and for each distance measure the focal powers output by the driver. The offset to apply in software is calculated using a best fit linear regression between Optotune driver and DSLR focal powers in diopters. The Zaber stage is calibrated by setting its maximum position where the two assemblies are at their nearest possible distance, then recording the distance between the optical axes (identified as above using 4 calibration targets).

Gaze-contingent Near-eye Display System.

Hardware Fig. S2 shows a schematic view of this hardware setup. The system provides a 96° field of view, a significant improvement over the benchtop variant. The NEMA 17 stepper motor mounted on the Samsung Gear VR is coupled via a 2" pulley and an O-ring to the focus adjustment mechanism, which mechanically changes the distance between phone and internal lenses. The motor offers a 1.8° step angle, with a 0.1125° micro-step angle, and 4.24 kg-cm torque by drawing up to 2.5 A of current. The driver board (Phidget 1067 Phidget-Stepper Bipolar HC) is controlled by a Raspberry Pi 3 Model B that is connected to the Gear VR phone via bluetooth. Overall system latency, including rendering, data transmission, and motor adjustments, are approx. 280 ms for a sweep from 4 D (25 cm) to 0 D (optical infinity) and 160 ms for a sweep from 3 D (33 cm) to 1 D (1 m). The system's latency can be noticeable for a user who knows what to look for, even though the response time of the human accommodative re-



Fig. S2. A conventional near-eye display (Samsung Gear VR) is augmented by a gaze tracker and a motor that is capable of adjusting the physical distance between screen and lenses.

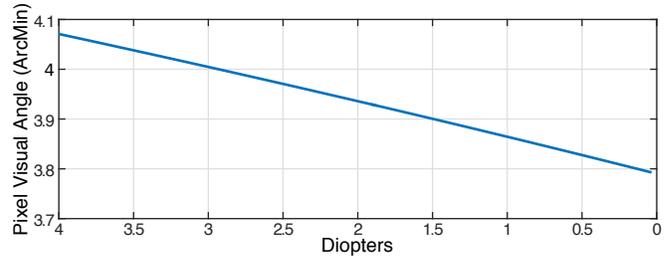


Fig. S3. The visual angle of one pixel of a Samsung Galaxy S7 as perceived by a user with 2 cm eye relief, as a function of the distance to the virtual image.

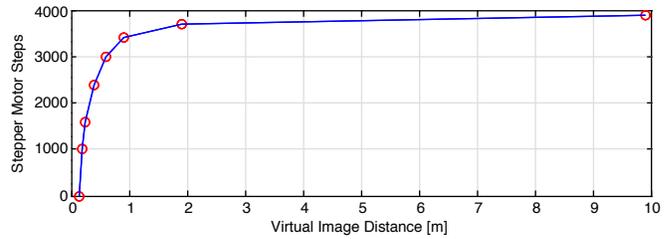


Fig. S4. We measure the mapping between stepper motor micro-steps, each corresponding to a 0.1125° rotation, to distances of the virtual image (red circles). A high-resolution lookup table is then computed by linearly interpolating between the measurements (blue line).

sponse is also on the order of hundreds of milliseconds (22). Nonetheless, the user study with this system indicates that the system latency does not remove the benefits of adaptive modes for user preferences. Indeed, reducing the latency to a point at which it was unobtrusive was one of the engineering challenges posed by designing this system.

Due to the user's eye being spaced a small distance away from the lens, some amount of magnification change necessarily occurs when changing the distance to the virtual image. To determine how large this change is, we calculated the visual angle subtended by one pixel as a function of the virtual image distance (Fig. S3). Over a 4 D range, the visual angle of one pixel changes by less than 0.3 arcminutes. These changes can be compensated for in software, at the cost of potentially introducing aliasing artifacts, or optically, at the cost of introducing a tunable lens into the system. However, given how small the magnification change is in the current system, we decided to evaluate it without compensation.

Software All applications are written in Unity version 5.4.1. SMI provides a Unity plugin for their eye tracker, which allows for control of all components from a single application. Unity is connected to the Raspberry Pi via bluetooth, but only a single metric distance value needs to be transmitted per rendered frame which is easily possible at the available bandwidth. The Raspberry Pi uses Python code and a Python-based software development kit provided by Phidgets to drive the stepper motor to the desired distance.

Calibration As a one-time pre-processing step, we calibrate the mapping between stepper motor settings and metric distances of the virtual image. This calibration is done by focusing a DSLR camera at several distances through the Gear VR optics and adjusting the motor such that the virtual image appears at each of these distances. Linearly interpolating between the sparse set of calibrated distances, a high-resolution

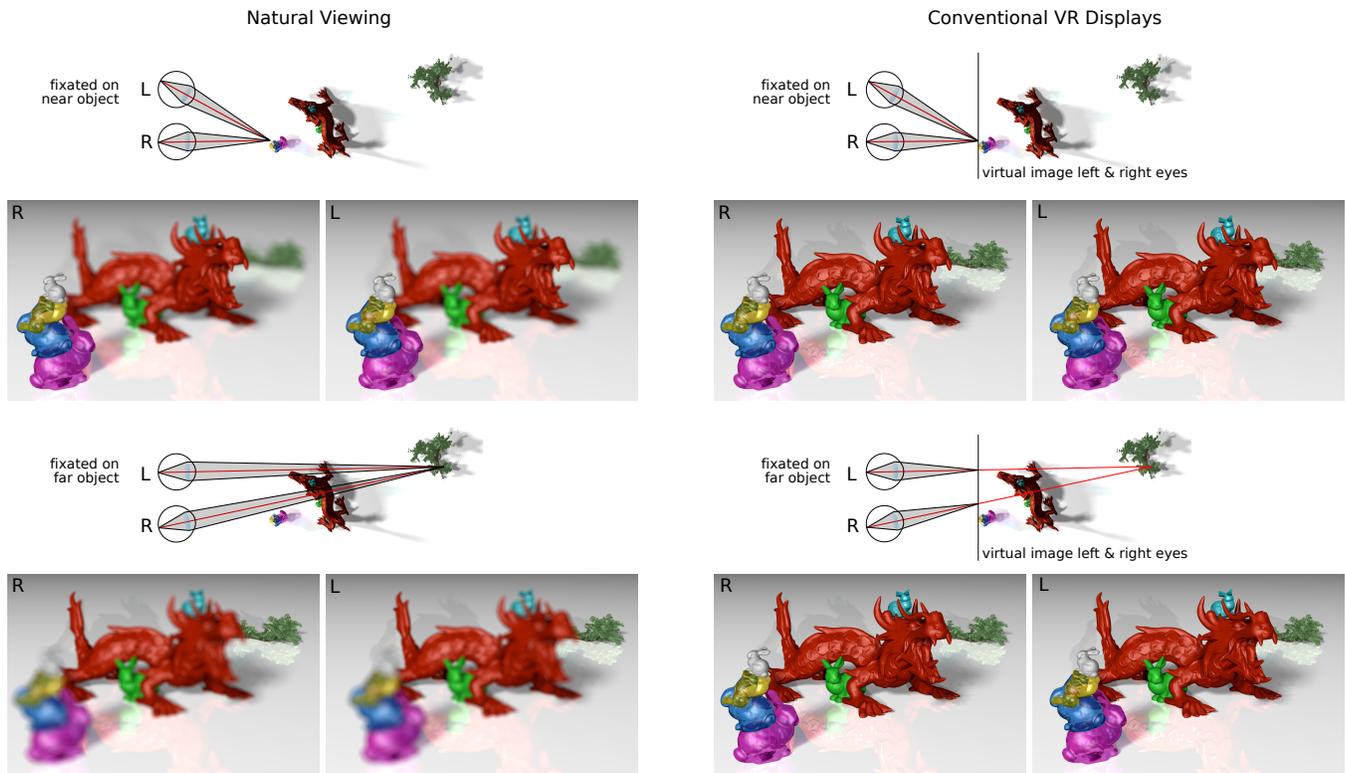


Fig. S5. Each panel includes a top down view of a fixation point and a cross-fusible stereo pair. In natural viewing conditions (left), the eyes verge (red lines) and accommodate (gray areas) at the depth of the fixated object. Current-generation near-eye displays (right) create a magnified virtual image to which the user accommodates. For virtual objects displayed at distances away from that virtual image, vergence and accommodation cues are in an unnatural state known as the vergence–accommodation conflict. Users whose accommodation range does not include the virtual image distance, e.g. due to myopia, hyperopia, or presbyopia, cannot see a sharp image in conventional VR displays at all.

lookup table is computed that maps virtual image distances to specific motor settings (Fig. S4). This lookup table is stored on the Raspberry Pi and used to drive the virtual image to a specific metric distance, as requested by the Unity application.

The eye tracker is calibrated using a per-user, per-use procedure that is partly provided by the manufacturer. In this procedure, the user is presented with several targets appearing at different locations within their visual field and asked to fixate on these targets. For the gaze-contingent focus display, we repeat this procedure three times and adjust the virtual image distance to either 0.67, 3, or 4 D for each of these runs. During runtime, we dynamically select the calibration setting that is closest to the set of pre-calibrated virtual image distances. This calibration makes gaze tracking more robust than calibrating only for a single virtual image distance when dynamically changing the virtual image distance.

Summary of display modes. The following summarizes the different display modes that were evaluated in this study.

Conventional mode is the display mode employed by current-generation near-eye displays. Simple magnifying lenses enlarge the image of a microdisplay and create a virtual image at some fixed distance to the viewer. Fig. S5 illustrates how conventional stereoscopic displays differ from natural viewing. Top-down views illustrate the vergence and accommodative distances when looking at objects at different distances in the physical world (left) and in a conventional stereoscopic display (right). Cross-fusible stereo pairs simulate the visual cues (binocular disparity and retinal blur) available during

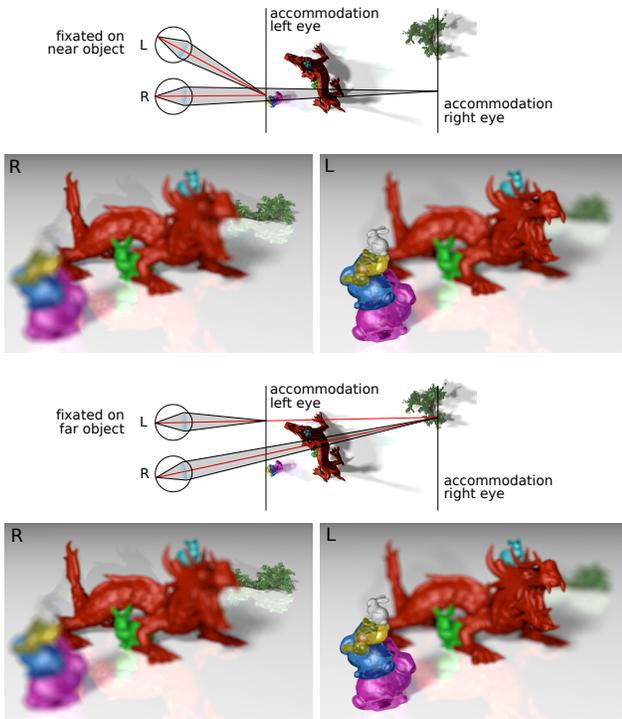
each fixation. In natural viewing, the accommodation state of the eye also creates the perceived retinal blur or depth of field cue. This depth of field is different for near and far fixation distances (Fig. S5, left). For conventional VR, the accommodative state does not change and is fixed on the virtual image. Hence, all displayed objects are equally sharp (Fig. S5, right), unless the depth-dependent blur is rendered into the image.

Corrected mode is the simplest adaptive display mode. The virtual image is kept at a fixed distance, but this distance is corrected to account for the user’s refractive error, either hyperopia and myopia.

Dynamic mode is a software/hardware approach that adjusts the virtual image distance, either by changing the focal length of the lenses or the distance between the microdisplay and the lenses. No eye tracking is used in this mode, so the virtual image distance is either linked to some specific rendered object in the scene or to the principle direction of head orientation, as for example determined by an inertial measurement unit in a head mounted display. When we evaluate the latter approach in the primary text, we call it *center focus* to differentiate it from the former.

Gaze-contingent focus mode is a software/hardware approach that adjusts the virtual image distance based on the depth at which the viewer is fixated, either by changing the focal length of the lenses or the distance between the microdisplay and the lenses. With information from an eye tracker, this mode allows for the virtual image distance to be adjusted

Monovision for Presbyopic Viewers in the Physical World



Monovision for Non-presbyopic Viewers in VR?

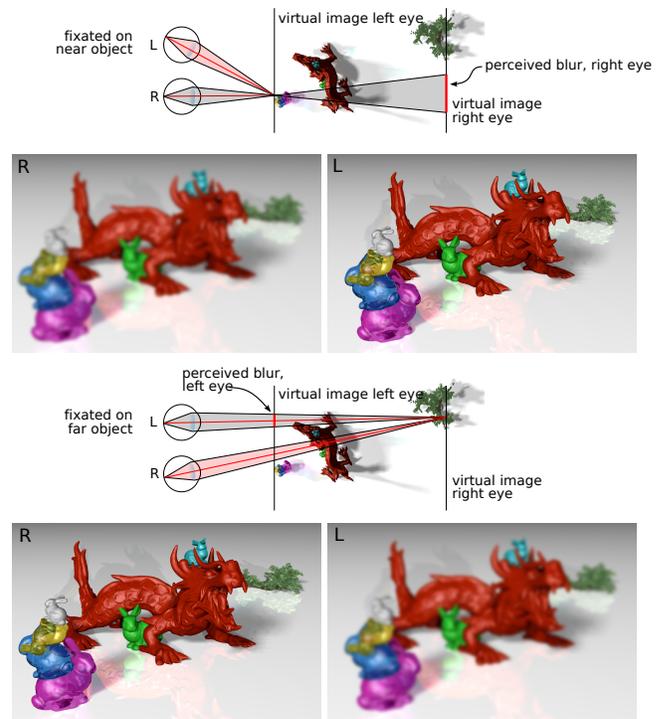


Fig. S6. Monovision is a common vision correction technique for presbyopic persons in the physical world. For this purpose, the dominant eye is usually corrected for far vision and the other eye for near vision, such that the presbyopic user is provided with sufficient visual acuity for different viewing conditions (left). It was recently hypothesized (4, 23, 24) that monovision integrated into near-eye displays may be able to allow non-presbyopic viewers to accommodate at two discrete distances (right). Assuming that the accommodation state of both eyes is coupled, for the VR monovision to work as intended the eye that drives accommodation for both eyes (red shaded area on the right) would have to switch depending on the vergence state of the eyes. Similar to monovision for presbyopic viewers, one eye would always see a blurry image whereas the other would see a sharp image; the order would switch when fixating on near or far objects. However, applied to these two applications, monovision has a very different goal and may only be useful for two disparate groups of people.

to either the distance where the viewer is verged (requires vergence tracking) or at the depth corresponding to their gaze direction (requires gaze tracking). In our study, we implement this mode with gaze tracking.

Monovision refers to a common treatment for presbyopia, a condition that often occurs with age in which people lose the ability to focus their eyes on nearby objects. To improve visual clarity, monovision places two lenses with different prescription values in front of each eye such that one eye dominates for distance vision and the other for near vision (Fig. S6, left). Monovision was recently proposed for VR/AR applications (4, 23, 24) and is evaluated in more detail in the following sections (Fig. S6, right).

Study design and details.

Users For the main study, data were collected from volunteers who participated as part of a public demonstration at the SIGGRAPH 2016 conference. The gender make-up of the users was 127 males, 25 females, and 1 not stated. All users filled out a questionnaire indicating their age, gender, familiarity with virtual reality, typical optical correction, and any other issues affecting their vision. Of the original study volunteers, eleven users indicated having ocular issues beyond the common target conditions and were thus excluded from the study. Another five users were excluded due to significantly incomplete questionnaires. Users were randomly assigned to one

of three groups: corrected versus uncorrected, conventional versus dynamic, or conventional versus monovision. Users who did not need optical correction or were wearing contact lenses were not assigned to the first group. Two more users were excluded due to incorrect assignment to conditions on the part of the experimenter.

A follow-up study was conducted at Stanford University. In the followup study, users were asked to perform a stereovision test to verify stereoacuity of at least 40 arcsec at 16 in (Randot test). They were also asked to perform a near point test in which we measured the nearest distance at which they could clearly and comfortably view a document to verify that they had a typical near point of 25 cm (4 D). They wore their corrective eyewear during the test. Three users were excluded prior to data collection due to not meeting the threshold in the random dot or near point tests. The remaining users were made up of 15 males and 5 females (age range 21–38 y old). All remaining users had corrected vision and viewed all three conditions (conventional, center focus, gaze-contingent focus). In all cases, the order of presentation of conditions was randomized per user and per task. One user from the follow up study also participated in the tasks for the main study.

Ocular Measurements In the main study, users had their near- and far-correction measured using the EyeNetra NETRA. The NETRA is a portable, cellphone-based autorefractor that measures spherical and cylindrical correction as well as interpupillary distance (IPD) (25).

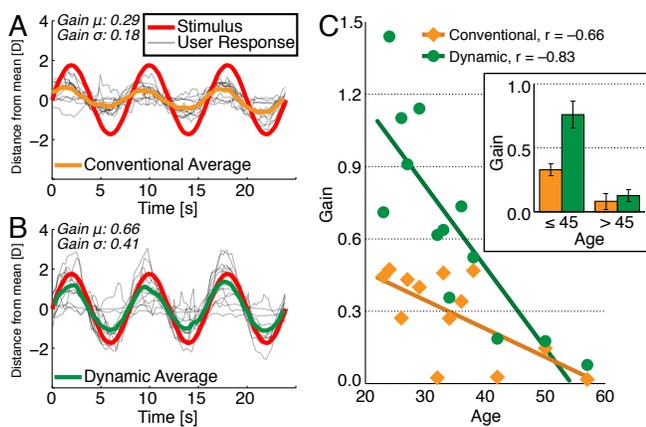


Fig. S7. Accommodative responses were recorded under conventional and dynamic display modes while users watched a target move sinusoidally in depth. Data are plotted in the same manner as Fig. 3, but only users with valid paired data for dynamic and conventional modes are shown. (A and B) The stimulus position (red), each individual response (gray), and the average response (orange indicates conventional and green indicates dynamic focus in all panels), are shown with the mean distance subtracted. (C) These gains plotted against the user's age show a clear downward trend with age, and a higher response in dynamic. Inset shows mean and standard error of the gains for users grouped into younger and older cohorts relative to forty-five years old.

For those wearing contacts, only the IPD was used. Users whose spherical equivalent (spherical + $0.5 \times$ cylindrical) measurement was less than ± 0.5 D were considered emmetropic and were not assigned to the corrected versus uncorrected condition. Of those not considered emmetropic, 114 were myopic, 11 hyperopic, and 2 were anisometric such that one eye was myopic and the other hyperopic. In the study comparing conventional and dynamic conditions, none of the users in the older age group indicated that they were wearing multifocal contact lenses.

Accommodation measures Users were presented with a Maltese cross target, which they were asked to follow with their eyes. The target was scaled to be 6.2 cm in height. When the users indicated readiness, the experimenter started the cycle for one condition, then repeated this process again for the other condition (randomized order), while simultaneously and manually starting measurement with the autorefractor each time.

Due to frequent erroneous data points from the autorefractor that manifested as large values or as time stamps with missing data points, several users' measurements were excluded from analysis, leaving data from 83 users. First, erroneous data points were identified as those that spiked to more than twice the stimulus amplitude from the median of the user's response for that mode. These were verified to not have removed any points from users that may have had a large voluntary accommodation. Any measurements in which 15% or more data points were removed as erroneous were excluded entirely. The remaining measurements were viewed without display mode labels, and any measurements containing spikes characteristic of the autorefractor's errors were excluded in their entirety as well. Finally, measurements with fewer than 6 data points were automatically excluded.

A gain value was calculated for each of the remaining measurements using Fourier analysis. First, we extracted the first 3 cycles of measurement data, following the first 0.5 cycles

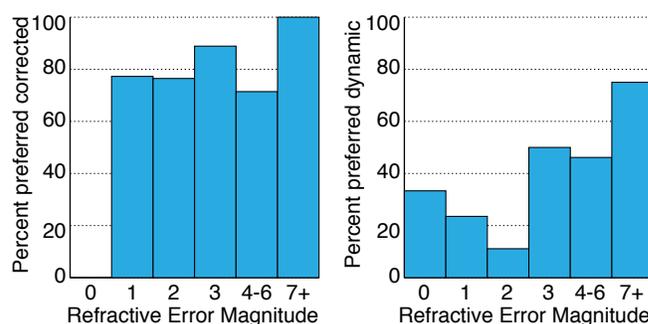


Fig. S8. The reported preference data for users is shown for users that experienced the corrected and uncorrected conditions (left), and those that experienced the conventional and dynamic conditions (right), as a function of the magnitude of their highest refractive error (between eyes). Each bar indicates the percent of users that preferred the condition hypothesized to be more preferable (i.e., corrected and dynamic on the left and right, respectively). Note that the histogram bins for the corrected/uncorrected preferences are chosen to start at 0.5 D because users with lower measured errors were considered emmetropic and not placed in this condition.

which were a buffer region, then subtracted the mean for these 3 cycles. We applied a Hamming window and projected the data points onto an 0.125 Hz exponential sinusoid at the time points provided by the autorefractor (which has non-uniform sampling times). The magnitude of the projection was then scaled according to the stimulus amplitude to give the gain. Due to excluded measurements, we use a partially paired analysis to pool the paired and unpaired data between the conventional and dynamic conditions (26), calculated using Wilcoxon signed-rank and rank-sum tests, respectively. The weights for pooling were calculated using the size of the smaller dataset.

Because some data were excluded, the subsequent gain analysis comparing conventional and dynamic conditions included both paired and unpaired measures. To confirm that the differences we see between these two conditions are not attributable to between-subjects differences, in Fig. S7, we consider the data for only the subset of users for whom both conditions were analyzed. Data are plotted in the same manner as Fig. 3 in the main paper, and the patterns in these data are the same as for the full analysis. In fact, within these users, the accommodative gain elicited by the dynamic condition was always greater than that elicited by the conventional condition, further supporting the finding that the dynamic mode elicits higher accommodative responses.

Although not reported in the main paper, accommodative gains were also measured for users in the corrected vs. uncorrected study. The average gain for users in the uncorrected was 0.27, as compared to the gain in the corrected/conventional mode of 0.29 as stated in the main paper. This difference was not statistically significant.

Sharpness and fusion tests To measure sharpness and fusion, users were instructed to focus on the Maltese cross target displayed at a fixed distance of 1, 2, 3, or 4 D and try to fuse it into a single image (it was on-screen for 4 s, with a 4 s delay before appearing). The target was always displayed such that it subtended 3.45° of the visual field, and all trial types (condition and distance) were randomized. A response screen appearing after each trial prompted the user to respond as to whether the target was fused, and to rate it as blurry, medium, or sharp.

Data were analyzed using mixed effects logistic regressions, with user modeled as a random effect. To evaluate the correction condition, we used a 2×4 model (condition \times distance). To evaluate the dynamic condition, we used a $2 \times 2 \times 4$ model (condition \times age group \times distance).

Preference test The users were presented their assigned two conditions in a random order, the first with a target labeled “A,” and the second with a target labeled “B.” They were asked to freely toggle between the two modes as they fixated on the target, then choose the one that they found more comfortable to observe. The targets were 6.2 cm tall and moving at 0.125 Hz sinusoidally in depth. The first 84 users were shown targets that moved between 25 and 75 cm (4 and 1.33 D), while the later users saw the targets move between 33.3 and 83.3 cm (3 and 1.2 D).

The results were analyzed using a binomial test. The results were first analyzed separately for the first 84 and the remaining users. For the uncorrected vs corrected condition preference, 81% of the first cohort preferred corrected and 79% of the second cohort preferred corrected (both $ps < 0.001$). Since the proportions were similar, we pooled all data before analysis. For the dynamic vs conventional preferences, within group differences were also highly similar so all users were pooled.

We also examined the potential effect of refractive error on preferences. For instance, because the conventional condition places the virtual image at a distance of 1.3 m, or 0.77 D, a user with myopia of -1 D would effectively see a clear image even without refractive correction. For the two studies, Fig. S8 shows the percent of users that preferred the corrected over the uncorrected condition (left) and the percent of users that preferred the dynamic over the conventional condition (right). Although not conclusive, this analysis suggests that users with only a small amount of correction were slightly closer to chance in their preferences for corrected versus uncorrected, whereas users with large refractive corrections were more likely to prefer the corrected condition. Interestingly, the analysis also suggests that users with larger refractive errors may be more likely to prefer the dynamic condition. However, the reason for this difference is unclear.

Gaze-contingent preference test In the follow-up study using the wearable prototype, users were presented with 4 different VR scenes and asked to rank the display modes in each. This study focused on image quality rather than comfort based on the hypothesis that the study duration was likely too short to affect comfort. The user was again free to toggle through the conditions repeatedly before ranking them. They were not given a specific fixation target and could explore the scene visually and move their head. In order to reduce the user’s ability to differentiate the conventional mode based on motor movement, the motor was used to move the screen imperceptibly back and forth, while still being audible. Panoramic renderings of all four scenes are shown in Fig. S9.

After conducting a Friedman test on the rankings, pair-wise follow up tests were conducted using the Wilcoxon signed rank test and corrected for multiple comparisons.

Monovision Presbyopes use monovision (and other treatments like bifocal or multifocal lenses) to extend the range of distances over which they experience clear vision. In monovision, a different power lens is placed in front of each eye, affording one eye clear vision for near distances and the other

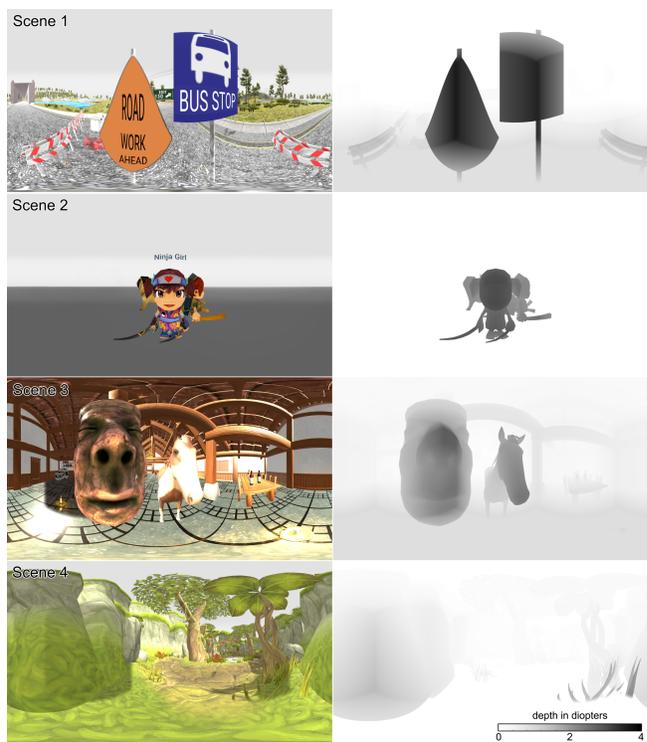


Fig. S9. Images of all four scenes used for the gaze-contingent preference test. These views show 360° panoramas using an equirectangular projection for both the color images (left column) and the depth maps (right column).

clear vision for far distances. Typically, the dominant eye is focused at 0 D (infinity), and the other eye at a nearer distance, usually at 1–2 D (0.5–1 m) (27, 28). The visual system then fuses the images together, with the acuity of the fused image being nearly equivalent to the better monocular acuity of each eye (29).

Monovision displays apply a similar principle to VR systems, but in this case with the goal of minimizing the vergence–accommodation conflict for non-presbyopes (4, 23, 24). A monovision-based VR system uses lenses of different focal power for each eye to place the virtual image of the display for each eye at a different distance (Fig. S6). Due to the fact that the accommodation for both eyes is linked and driven to the same distance (30), the hypothesis is that both eyes will accommodate to the virtual image plane closer to the distance that the user verges to, effectively mitigating the vergence–accommodation conflict one eye at a time. The downside is that one eye would always see a blurred image, but it is expected that the brain retains high frequency information from the eye with clearer vision for any condition (29). Such a scheme is attractive because it theoretically allows the user to accommodate to two planes, without requiring dynamic focal adjustments in the near-eye display.

As part of the study using the benchtop system, 16 users identified as not needing corrective eyewear (or wearing contacts) were tested in the monovision display mode (12 males, 4 females, age range 22–42 y old). When monovision correction is used for presbyopia, the dominant eye is usually assigned to far focus. In our study, we always assigned the farther accommodative plane to the right eye, which is more commonly dominant (31, 32). For examining accommodative gain, we

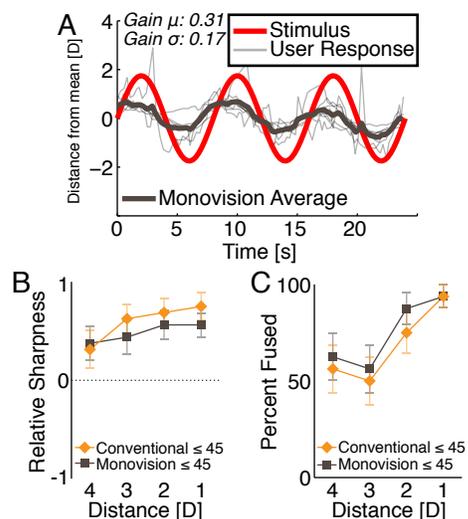


Fig. S10. Using the benchtop system to display a sinusoidal stimulus from 0.5–4 D (mean 2.25 D, amplitude 1.75 D), each user’s accommodative response was recorded with monovision (A). The stimulus (red), each individual response (gray), and the average response (dark gray), are shown with the mean subtracted. These users also reported sharpness (B) and fusibility (C) with a stimulus displayed at four fixed depths from 1–4 D. The x-axis is reversed to show nearer distances to the left. Error bars indicate standard error.

only kept 7 measurements from the monovision condition due to dropped data points (Fig. S10A). The average accommodative gain of users in monovision was similar to the users in conventional mode aged 45 y old and younger (0.31 and 0.32, respectively). This difference was not statistically significant.

We see in Fig. S10 B and C that perceived sharpness and binocular fusion in monovision are comparable to the conventional condition. The user responses for monovision suggest that the target was slightly less sharp, and slightly more fusible. However, these differences were not statistically significant. Logistic regressions on the sharpness and fusibility reveal only a significant main effect of distance. The odds ratios for distance were 0.51 ($ci = 0.32\text{--}0.79$) and 0.17 ($ci = 0.067\text{--}0.42$), respectively ($ps < 0.01$).

The preference results also did not indicate substantial differences between monovision and conventional conditions. In this task, 6 of the 16 users chose monovision (not significantly different from chance). The results therefore do not suggest any improvement in perception or preference with monovision. Furthermore, the accommodative gains for monovision and conventional do not support the idea that users switch between accommodating to the two virtual image planes in monovision; the planes were 1.5 D apart, and that would correspond to a gain of 0.43. On the other hand, users were only given a few minutes to experience and evaluate monovision. It is possible that perceptual performance may be improved with extended experience of monovision in VR. For example, presbyopes who are prescribed monovision correction report a period of adjustment over days or even weeks (33). Interestingly, this subjective improvement over time does not seem to correspond to changes in objective visual measures (33, 34). Further studies will be necessary to investigate long-term effects of monovision-based VR/AR systems, both in terms of whether experience might improve perceptual performance, and whether there are negative effects of viewing monovision displays for non-presbyopes.

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