Autofocals: Evaluating Gaze-Contingent Eyeglasses for Presbyopes

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Fig. 1. We present Autofocals, a hardware and software solution for presbyopes (those with an age-related loss of accommodation) that externally mimics the natural accommodation response. With eye trackers and a depth sensor, the system estimates the vergence and gaze direction (left), and scene depth (middle). A sensor fusion algorithm combines these inputs to estimate the fixation distance of the wearer, then brings it into focus using focus-tunable lenses. In contrast to current presbyopia corrections, which either require head movement or reduce visual quality at near distances, our study shows that a user wearing Autofocals (right) can intuitively look to any distance, while maintaining 20/20 acuity.

Presbyopia, the loss of accommodation due to the stiffening of the crystalline lens, affects nearly 20% of the population worldwide. Traditional forms of presbyopia correction use fixed focal elements that inherently trade off field of view or stereo vision for a greater range of distances at which the wearer can see clearly. However, none of these offer the same natural refocusing enjoyed in youth. In this work, we built a new presbyopia correction, dubbed Autofocals, which externally mimics the natural accommodation response by combining data from eye trackers and a depth sensor, and then automatically drives focus-tunable lenses. We evaluated the Autofocals on 24 users (ages 51–81) across a set of visual and task performance metrics: visual acuity, contrast sensitivity, and letter matching. We observed that the Autofocals exhibit significantly better visual acuity at nearer distances when compared to both monovision and progressive lenses, while not sacrificing 20/20 visual acuity at any other distance. No significant difference was observed with respect to contrast sensitivity or task performance. When asked to compare the Autofocals against their own correction in terms of being able to effectively see at all distances, 7 out of 11 participants rated Autofocals higher, with another 2 rating them equivalent.

CCS Concepts: • **Human-centered computing** → **User studies**; **Accessibility technologies**; • **Hardware** → *Sensor applications and deployments*;

Additional Key Words and Phrases: presbyopia, computational optometry

ACM Reference Format:

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1 INTRODUCTION

Vision is one of the most, if not the most, important senses that humans use to navigate their everyday worlds. Unfortunately, as people age, their ability to accommodate, or refocus the crystalline lenses in their eyes to near distances, steadily decreases until most cannot view anything within arms' reach in sharp focus [Duane 1912]. This loss in range of clear vision is known as presbyopia and affects over a billion people worldwide [Holden et al. 2008], with the number guaranteed to grow as the population ages [UN DESA 2017]. People are typically diagnosed with presbyopia by their late 40s. Furthermore, despite impairment, vision gains even more importance in old age, as people rely more on their vision to compensate for degradation of the vestibular or somatosensory system, leading to an increase in falls [Newton 2003].

The problem of presbyopia is understandably not a new one, and people have used various solutions to help them perform tasks at near distances (Figure 2). For example, a simple solution is to carry an extra pair of reading glasses that allow for near vision. In order to avoid the inconvenience of carrying a second set of glasses, many people opt for corrections that can support multiple distances of focus. Bifocals, trifocals, or progressive addition lenses achieve this by assigning different parts of the field of view to different distances. Monovision lenses achieve this by assigning each eye to a different distance. Another option is simultaneous vision lenses, which involve presenting near- and far-corrected visual information superimposed via multifocal lenses. This can be achieved, for example, with concentric or diffractive contact lenses directly over the pupil. Charman [2014] provides a detailed overview of these and other approaches to presbyopia correction.

Despite the variety of vision correction options available to presbyopes, these all fall short of restoring the quality of vision they once enjoyed in their youth. Reading glasses, besides the relative inconvenience, can also be forgotten or misplaced, rendering the wearer incapable of performing near tasks for an extended period. Bifocals, trifocals, and progressives restrict the field of view at any

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given desired focal distance and introduce distortions in regions where the refractive power transitions. Lord et al. [2002] showed that these types of glasses impair depth perception and edge-contrast sensitivity, leading to an increased risk when navigating unfamiliar environments or stairs, and recommend using single focal length glasses in such situations – a recommendation which, if followed, negates the convenience of these glasses. As for monovision and the various simultaneous vision approaches, studies consistently show that they too fall short of reading glasses for visual acuity or stereoacuity, with some prospective wearers rejecting them entirely due to poor or unnatural vision [Back et al. 1992; Erickson and Schor 1990; Harris et al. 1992; Sheedy et al. 1991, 1988].

The common thread across these methods is that they use fixed focal elements to approximate vision that was once achieved by varifocal lenses in the wearer's eyes. A natural response when presented with this fact is to consider using a varifocal element in the corrective eyewear. An early implementation of lenses with tunable power was the Alvarez lens, which required mechanical shifting [Alvarez 1967]. Since then, people have developed prototypes of electronically tunable eyewear using liquid-crystal diffractive lenses or liquid-filled membranes, controllable via either manual input or a depth sensor [Hasan et al. 2017b; Li et al. 2006; Wang et al. 2014]. However, none of these solutions emulate accommodation in a way that matches the behavior that younger people are accustomed to: simply looking around and having focus just work. A system capable of meeting this ideal would require both a depth camera and robust, affordable eye trackers. For example, despite having a depth sensor, Hasan et al. [2017b] omit eye tracking and therefore force the focus to the object directly in the center of the user's vision, which can be less than ideal. Furthermore, none of these solutions have been evaluated or verified as outperforming traditional fixed-focus methods of correction.

Therefore, we ask the question of whether or not this class of focus-tunable glasses solutions can match or outperform traditional fixed-focus correction along both visual and task-based performance metrics. To test this, we build our own focus-tunable glasses implementation; we incorporate both a wide field of view depth sensor and vergence measurements from eye tracking to estimate the best focal setting for the tunable lenses (Figure 2). With this system, we compare our performance against that of commonly prescribed treatments. Our contributions are therefore that

- we developed a complete hardware and software solution that externally simulates an accurate accommodation response by intelligently driving a focus-tunable optic;
- we developed a sensor fusion algorithm for integrating data from an eye tracker and depth camera and for vergence estimation; and
- we verify that Autofocals are preferred over the traditional methods of treating presbyopia and identify critical areas for technological improvement with a user study.

2 RELATED WORK

2.1 Focus-Tunable Optics

The class of technologies that make true presbyopia correction a tangible possibility is focus-tunable lenses. One of the earlier works

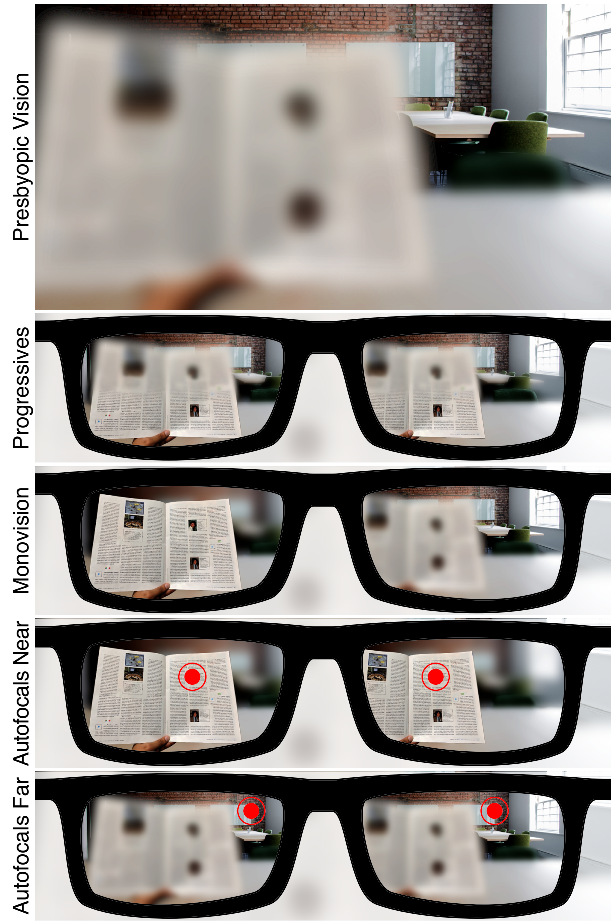

Fig. 2. Typical vision for a presbyope through various methods of correction. Without any correction, near distances are blurry. Progressives and monovision allow focus to both near and far distances by either splitting up the field of view, or using different eyes for each distance, as illustrated. The Autofocals use information from each eye's gaze to dynamically update the focus to near or far.

in this space was the Alvarez lenses [Alvarez 1967]. These lenses consist of a pair of cubic phase lenses that have complementary correction to one another – when overlapped, they have no refractive power, and shifting one relative to the other can introduce both positive or negative powers. However, this design is not ideal since mechanical components tend to wear down faster, and more extreme powers inherently reduce field of view as the overlapping region of the lenses is reduced.

Since then, there has been much effort made to develop wide field-of-view lenses for use in presbyopic correction. Two main categories that these lenses fall into include liquid-crystal lenses and liquid-filled membrane lenses. In the space of liquid lenses, there have been proposals such as using a liquid lens mounted on a polydimethylsiloxane (PDMS) contact lens [Jiang and Kanhere 2015], but also work put into creating functional larger lenses for eyeglasses-based correction [Hasan et al. 2017a]. Liquid-crystal lenses, on the other hand, may be more flexible in that they can directly address phase across the field of view, allowing for more varied corrections with a single element, with much recent work on making them a more viable option for eyeglasses, improving focusing time and addressable range [Chen et al. 2014; Lin and Chen 2013; Lin et al. 2014]. Another possible approach involves using a deformable mirror. Papadatou et al. [2016] for example used one to create and test simultaneous vision correction.

Focus-Tunable Glasses. Some have taken these lenses one step further and incorporated them in eyeglasses. For example, Wang et al. [2014] developed a set of liquid lenses that they tested on a single observer. Unfortunately, their system had a response time on the order of seconds, and was partially table-mounted. Using a liquid-crystal diffractive lens, Li et al. [2006] created a wearable prototype that had a response time of under a second. However, they did not have any method of focus control that depended on the viewer, making the solution somewhat incomplete. Finally, there is the prototype from Hasan et al. [2017b] which uses a time-of-flight sensor pointing directly ahead of the user to close the control loop and update the liquid lenses. While an important step, this is somewhat limiting and requires the wearer to move their head around to focus to different distances. Integrating an eye-tracker into the refocusing pipeline would remove this requirement. There have been steps made to address this, but without integration into a system with focus-tunable lenses [Li and Li 2016]. Finally, it is important to note that none of these have been evaluated and verified to be more preferable or to improve task performance relative to traditional fixed-focus methods of correction.

2.2 Comparison of Presbyopia Treatments

When it comes to the traditional forms of correction, each tends to fall short on some metric. In terms of acuity, the standard to beat is the correction afforded by simply carrying multiple pairs of single-vision glasses for each desired viewing distance – which is also the least convenient solution by far, giving us ample motivation to improve upon this solution. While bifocals at first glance seem like a reasonable fix – they are in some sense two stacked single-vision lenses – they, along with progressives and trifocals, have a decreased field of view at any given distance. This has been shown to impair contrast sensitivity and depth perception when walking, increasing risk of injury [Lord et al. 2002]. Furthermore, progressives have been shown to perform worse in tasks requiring lateral head movement than those wearing single-vision lenses [Selenow et al. 2002].

Monovision and simultaneous-vision contacts (both diffractive or concentric lenses) offer both a wider field of view as well as clear vision over a range of distances without requiring head motion. While monovision performs better than diffractive and concentric lenses in terms of visual acuity and contrast and tends to be preferred by wearers over concentric lenses, it tends to perform worse on stereoactuity [Harris et al. 1992]. Neither of these corrections, however, outperform reading glasses, or even bifocals. Studies show that monovision [Sheedy et al. 1988] and concentric lenses [Sheedy et al. 1991] are worse than reading glasses for near-distance tasks and acuity at the reading glasses' correction distance. Also, in terms of contrast and stereoacuity, reading glasses [Back et al. 1992; Papas et al. 1990] and bifocals [Erickson and Schor 1990] outperform both monovision and concentric lenses.

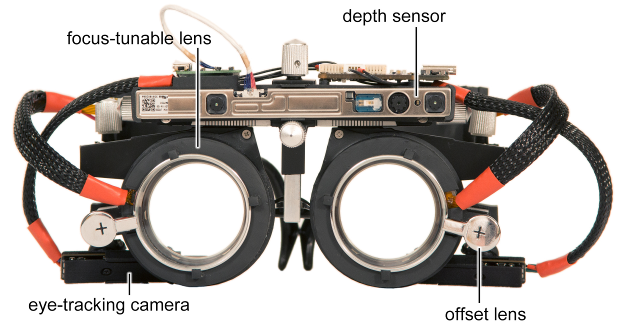

Fig. 3. A photo of the prototype, showing the focus-tunable lenses, depth sensor, eye-tracking cameras, and offset lenses mounted on a universal optometrist trial lens frame.

What the Autofocals and other focus-tunable lens solutions aim to do is provide corrected vision that has comparable field of view to reading glasses, monovision, and simultaneous vision contacts, while also providing acuity and task performance that outperforms them in tasks requiring focus at various distances. The wider field of view should improve safety outcomes, while providing overall better vision based on acuity and task performance.

2.3 Vision Correction in Computer Graphics

Over the last few years, a number of interactive techniques related to vision correction have been discussed in the graphics community. For example, Pamplona et al. [2012], Huang et al. [2014], and Montalto et al. [2015] explore different display technologies that have the potential to correct the eyesight of myopic, hyperopic, or presbyopic users when using digital displays. Focus-tunable lenses, in particular, have also become very popular to address the lack of focus cues in virtual and augmented reality [Dunn et al. 2017; Johnson et al. 2016; Konrad et al. 2016; Liu et al. 2008; Love et al. 2009; Padmanaban et al. 2017]. None of these approaches, however, aim at restoring a users' vision in the real world.

3 AUTOFOCAL EYEGLASSES DESIGN

3.1 Hardware Components

Our prototype (Figure 3) is a tethered system built largely from commercially available components. The frame is built around universal optometrist trial lens frames, with 3D printed components mounted on top to accommodate our measurement devices and lenses. The two measurement devices are used to obtain depth information about the surrounding, and gaze information from the wearer. A Realsense R200 (rated for 0.5–3.5 m indoors) supplies depth maps at a 30 fps, using a pair of infrared stereo cameras with a structured illumination source. The gaze information is provided by eye trackers from Pupil Labs [Kassner et al. 2014]. There is one 120 Hz eye tracker for each eye, allowing us to also estimate vergence. Finally, there are the focus-tunable lenses themselves: a pair of Optotune EL-30-45 liquid lenses, with a 30 mm aperture. Their supported

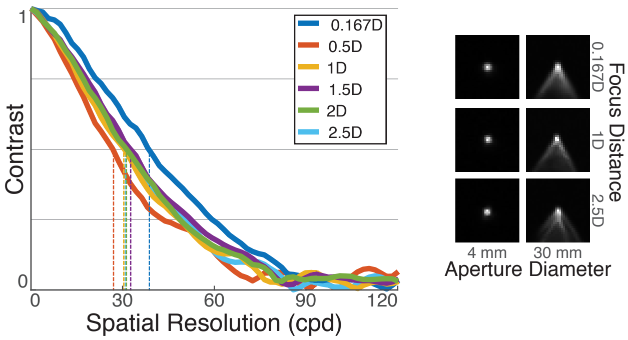

Fig. 4. Optical characteristics of the Optotune EL-30-45 focus-tunable lenses. *Left:* The MTF curves of the lenses, focused at different distances. Dashed lines indicate the MTF50 for each distance. The lenses perform close to 20/20 acuity, with the MTF50 at most distances above 30 cpd. *Right:* Point spread captured through the lenses with different distances and apertures. When the optical axis is horizontal, gravity causes the liquid in the focus-tunable lenses to pool to the bottom, leading to coma using the widest aperture (right column). However, little coma is observed in the Autofocals system where the aperture is constrained by human pupil sizes (left column).

range of focus was measured to be −2.25 to 2 D (diopters, 1/meters), with a 100 ms settling time. To allow the Autofocals to work in the 0–4 D range for a wide variety of wearers, we also fit a spherical or cylindrical offset lens for each focus-tunable lens, with the exact lens power chosen based on the wearer's prescription.

To ensure that the lenses provide enough fidelity for vision correction purposes, we evaluated their optical characteristics. We measured the modulation transfer function (MTF) of the optical system at different distances using the slanted-edge algorithm based on the ISO 12233 standard (Figure 4, left). During measurements, a 4 mm aperture was set 2 cm away from the lens, mimicking the typical pupil size for photopic vision amongst presbyopes [Cardona and López 2016] and distance of the lenses from the eyes. The dashed lines indicate the MTF50 for each of the focusing distances, with the smallest MTF50 of 26.79 cpd occuring at the 0.5 D focusing distance. All other focusing distances had an MTF50 greater than 30 cpd, which corresponds to typical human visual acuity. We do not expect the optical system to be the limiting factor for the visual acuity study in system evaluation.

In addition to MTF measurements we evaluated the the system's coma. With the optical axis oriented in the horizontal position, gravity causes the lens' liquid to pool towards the bottom, leading to significant coma when imaging through the full 30 mm aperture (Figure 4, right). However, at any given time, humans only look through a subset of the lens due to their small pupil/aperture and observe minimal coma. In this scenario, the non-uniform distribution of the liquid is instead perceived as a spatially varying focal power across the lens. The measured power of the region 10 mm above the center of the lens adds a +1.5 D shift while the region 10 mm below the center adds a −1.5 D shift. These shifts are consistent across all focusing distances and could theoretically be corrected with a static coma corrector, assuming the glasses will be worn in a predominantly upright position. We did not implement the coma corrector, and instead carefully adjusted the Autofocals' frame so that the eyes were behind the centers of the lenses.

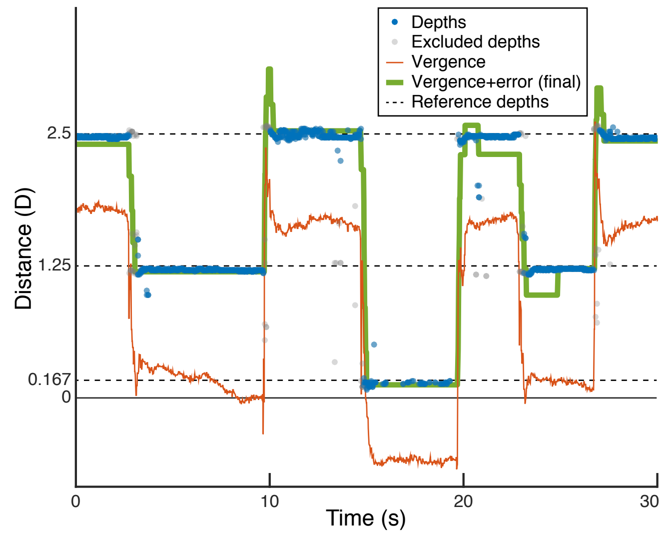

Fig. 5. An example recording of the sensor fusion algorithm. The raw vergence (red) has the right trends, but is noisy and has an offset from the actual fixated depths. Depth values from the R200 (dots) are filtered to valid values (blue). The depth informs an error estimate, which is used to obtain the final lens output powers (green).

Hardware Limitations. The Pupil Labs eye trackers have an average accuracy of 0.6° per eye, which for a wearer with an interpupillary distance of 64 mm, limits the accuracy of accommodation estimates to about 0.25 D in ideal conditions. The accuracy can only get worse as the glasses shift on a wearer's head. This limits accuracy of vergence measurements.

Our prototype does not currently support more than one offset lens, which limits our ability to correct for both spherical and cylindrical aberrations within the eye. This often means that we left a small amount of astigmatism unaccounted for in the prototype. This can be accounted for simply by adding space for another offset lens that corrects the cylindrical power in a future iteration.

3.2 Fixation Depth Estimation Sensor Fusion

We have four "raw" inputs: the gaze point of the left eye, the gaze point of the right eye, a scene-facing depth camera, and the wearer's interpupillary distance (IPD). We then process these into a vergence estimate and a single depth estimate, which are the inputs to the sensor fusion algorithm.

The gazes are given as (x, y) coordinates normalized to a range of 0 to 1 relative to the field of view of the R200 – this is done via Pupil Labs' calibration software. Since the geometry of the calibration scene relative to the wearer is set ahead of time, the wearer's IPD and the separation distance of two gaze points is sufficient to determine the wearer's vergence distance. Though not necessary, this estimate can then be refined by calibrating the vergence at two known distances and scaling the geometric estimate accordingly.

Furthermore, we discard any values outside the −1 to 4 D range. These limits are based on the depth extremes in our study setup.

For the depth estimate, we first inpaint the depth map using a Navier-Stokes alogrithm [Bertalmio et al. 2001]. Then, we use the left eye's gaze coordinate to index into a 5×5 neighborhood of depth map, from which we take the median depth. We use the left eye because it is approximately aligned with the camera of the R200; if the left eye is not available, we fall back to the right eye.

Given these processed values, the high level operation of the sensor fusion algorithm can be described as vergence plus an error term (estimated as the difference between the vergence and depth). We choose this approach since vergence updates much faster and is not affected by depth discontinuities at edges. However, it is sensitive to inaccuracies in calibration, which manifests itself as a nearly constant offset in the range of operation (Figure 5). Since the depth map itself is accurate, this offset is corrected for with the gaze-indexed depth estimate.

The details of this algorithm are in Algorithm 1. Since the vergence estimate, v, is noisy (Figure 5, red), it is first smoothed with an exponential average to obtain v_{filt} (line 5). Then, to correct for the offset in vergence, we check for a new filtered depth estimate, d_{filt} (Figure 5, blue). These two values are used to update the error estimate, v_{err}, with an exponential average, but such that fluctuations from depth discontinuities are not considered (line 8). We also allow error updates at either extreme of the depth range to control for initial conditions with large vergence error. Finally, the lens focal power (Figure 5, green) is set to the new error-compensated vergence estimate (line 13), with a minimum step size of 0.25 D to prevent jitter caused by limits of the eye tracking accuracy (Section 3.1).

The value for d_{filt}, used in Algorithm 1, is calculated as seen in Algorithm 2. The raw depth estimate, d, exhibited a tendency to drop by nearly a diopter for some frames (Figure 5, gray). We consider a drop of more than 0.5 D to potentially be an artifact. However, some drops are clearly the users looking to a new distance. Therefore, we reject depth estimates until an exponential filter starting from the last valid depth (line 11) "catches up."

ALGORITHM 1: Sensor fusion: vergence + error

1 $v_{\text{filt}} = v_{\text{err}} = 0$; $\alpha_v = 0.2$; $\alpha_e = 0.2$;
2 **while** *running* **do**
3   **if** `checkNewValidEyeTrackerVergence()` **then**
4     $v \leftarrow$ `getNewValidEyeTrackerVergence()`;
5     $v_{\text{filt}} \leftarrow \alpha_v v + (1 - \alpha_v) v_{\text{filt}}$;
6   **if** `checkDepthUpdated()` **then**
7       $d_{\text{filt}} \leftarrow$ `getLatestDepth()`;
8   **if** $|d_{\text{filt}} - (v_{\text{filt}} + v_{\text{err}})| < 0.5$ or $v_{\text{filt}}, d_{\text{filt}} < 0.75$ or $v_{\text{filt}}, d_{\text{filt}} > 2.0$ **then**
9         $v_{\text{err}} \leftarrow \alpha_e (d_{\text{filt}} - v_{\text{filt}}) + (1 - \alpha_e) v_{\text{err}}$;
10   **end**
11   **end**
12   **if** $|$`getLensPower()`$ - (v_{\text{filt}} + v_{\text{err}})| > 0.25$ **then**
13   `setLensPower(`$v_{\text{filt}} + v_{\text{err}}$`)`;
14   **end**
15   **end**
16 **end**

ALGORITHM 2: Depth denoiser

1 $d_{\text{denoiser}} = 0$; $\alpha_d = 0.2$;
2 **while** *running* **do**
3   `setDepthUpdated(False)`;
4   **if** `checkNewR200DepthMeasurement()` **then**
5     $d \leftarrow$ `getNewR200DepthMeasurement()`;
6   **if** $d_{\text{denoiser}} - d < 0.5$ **then**
7       $d_{\text{denoiser}} \leftarrow d$;
8   `setLatestDepth(`d`)`;
9   `setDepthUpdated(True)`;
10   **else**
11       $d_{\text{denoiser}} \leftarrow \alpha_d d + (1 - \alpha_d) d_{\text{denoiser}}$;
12   **end**
13   **end**
14 **end**

4 USER STUDY DESIGN

In order to evaluate the Autofocals and focus-tunable technology in general, we conducted a user study consisting of 26 participants (ages 51–81, mean age 63.6, 9 male, 17 female). All users had far vision corrected to 20/20. Two progressive wearers were excluded due to inability to simultaneously correct spherical and cylindrical aberrations using our prototype. Due to possible improvements in proficiency using presbyopic correction as a function of length of use, we only compare the Autofocals against the correction the users wear on a regular basis. This splits our study population into 6 people that typically wear monovison and 18 with progressives. All procedures were approved by the institutional review board of the home institution.

Our user study consisted of four phases, repeated once with their correction and once with the Autofocals (correction order alternated between participants): first, we measure their required prescription using the Grand Seiko WAM-5500 autorefractor; second, we evaluate their visual performance using acuity and contrast eye charts; then we evaluate their performance on a task requiring changing focus distance; finally, we let them freely observe a natural scene with several objects on and beyond a table. All eye charts were displayed using monitors with approximately 190 cd/m^2 of output when white, and with high enough resolution to support at least 20/10 vision at their chosen distance (at 2.5 D and 1.25 D, a 5.98″ display with at a 1440p resolution, and at 0.167 D a 24″ display at 1080p). The monitors were all calibrated with measurements of light output at all gray levels with the SpectraScan PR670, a spectroradiometer. All eye charts used the Sloan font [Pelli et al. 1988]. For the eye chart and task performance tests the users were asked to rest their chin on a chin rest to fix their distance to the monitors.

It should be noted that for most of the tasks, we make a slight modification to the operation of the lenses. While for the natural scene evaluation, we use the sensor fusion algorithm as described in subsection 3.2, the other tasks instead use a version that is set to the known distances of the displays. Acuity and contrast are set to the distance of the currently visible eye chart, and the task performance is set to the display distance nearest to the user's current vergence. The rationale for the decision to use these alternative modes of operation is twofold: first, our purpose is to evaluate the acuity and contrast at specific working distances as compared to traditional corrections, and second, we wished to reduce the latency and jitter as much as possible when distances are known. These both stem from a desire to evaluate the underlying technology, which is in its infancy, as opposed to limiting ourselves to our current prototype.

4.1 Acuity

The acuity tests were administered using a logMAR (minimum angle of resolution) chart based on the ETDRS chart [Ferris et al. 1982] at 99% contrast. One line of five random letters (from the 10 Sloan letters) was shown at a time, with each subsequent line smaller by 0.1 logMAR. This continued until the user identified three or more letters incorrectly within the same line. The final reported acuity was the acuity of that line, minus 0.02 logMAR per letter answered incorrectly during that trial. Acuity corresponding to 20/20 vision is defined as 0.0 logMAR. The acuity tests were conducted at distances of 0.167, 1.25, and 2.5 D (6 m, 80 cm, and 40 cm), with three repeats at each distance, and with the order randomized across all trials.

4.2 Contrast Sensitivity

For the contrast test, we construct a chart based on the Pelli-Robinson contrast chart [Pelli et al. 1988], using Sloan letters at a size corresponding to 20/120 acuity. Again, one line was displayed at a time, but with 3 Sloan letters in each line. Starting with 0.05 logCS (Weber contrast sensitivity) for the first line, each subsequent line had contrast reduced by 0.15 logCS until the user incorrectly identified two letters in a single line, or until the user got to 1.7 logCS, which was the limit of the display. The final contrast sensitivity was the contrast of the last line with a majority of letters identified correctly. The contrast test was conducted only at the intermediate distance of 1.25 D, a distance supported by all forms of correction considered.

4.3 Task Performance

Next, for the task performance test, we place in front of the user two displays, one at 0.167 D, and the other at 2.5 D (image in Supplemental Material). We display a single letter on each monitor, with 50% probability of them being the same letter. In this case, we use the full extended Sloan alphabet (with the exception of the letters 'G' and 'W' which had unusual shapes compared to typical fonts), and at a size corresponding to 20/40 acuity. The task is then to indicate whether or not the letters match, using a keyboard. The user would perform this task for two minutes, at the end of which we calculate their accuracy and speed. Users were prompted to focus on accuracy while maintaining speed with the following prompt, "We are recording both speed and accuracy, so try to get as many correct as you can while still going quickly." Users were given a training period of 20 pairs ahead of the timed portion to get accustomed to the controls. When wearing the Autofocals for this task, the user was asked to move their head as little as possible to avoid losing eye tracker calibration. One monovision wearer and three progressive lens wearers were excluded from the task performance data due to inability to calibrate the eye trackers after repeated attempts (leaving 5 monovision, 15 progressives).

4.4 Natural Scene Preference

Finally, we allow the users to freely view a natural scene (image in Supplemental Material) for roughly a minute each with their correction and with the Autofocals. We also add a second mode of operation to the Autofocals that uses only the depth from the center of the R200's field of view to evaluate the benefits afforded by incorporating eye trackers. This center-depth mode is made to imitate Hasan et al.'s system [2017a] and is only used during the natural scene evaluation. After the users evaluate the scene, we have them rank the three conditions on physical comfort and "how effectively they allowed [them] to see to all distances," allowing ties, as well as recording any general feedback that they gave. A rank of 1 indicated that a correction was the best, and 3 the worst.

The first 10 users consistently noted jitter in the focus state as unacceptable when ranking the corrections. Since the natural scene viewing is the only portion that implemented the sensor fusion algorithm, we treated these first users as a pilot to refine the sensor fusion algorithm. In particular, we traded off some precision and latency in exchange for reducing the amount of refocusing jitter – for example, by increasing the smoothing on vergence, and only updating the lens power for changes in distance of 0.25 D or more (as described in Section 3.2).

Three progressive lens wearers were excluded from the task performance data due to inability to calibrate the eye trackers after repeated attempts (leaving 1 monovision, 10 progressives).

5 RESULTS

5.1 Acuity

The average acuity using each correction at each of the three distances can be seen in Figure 6. From the figure, it is clear that while the Autofocals maintain at least 20/20 vision at all distances, the tradeoffs involved in having higher near add powers (positive correction added for near vision) in traditional correction result in reduced acuity at the closest distance. The two groups of users (monovision and progressives) were analyzed separately with a 2×3 two-way repeated measures ANOVA, with independent variables of correction (their correction vs. Autofocals) and distance. Greenhouse-Geisser sphericity correction was applied. Post-hoc tests were conducted as pairwise t-tests only between the corrections at each distance (due to lack of interpretability of other comparisons), with Bonferroni correction applied to the p-values.

For monovision, the ANOVA shows significant main effects of correction ($F(1, 5) = 7.26,\ p < 0.05$) and distance ($F(1.72, 8.61) = 7.24,\ p < 0.05$). There is also a significant interaction of correction and distance ($F(1.24, 6.21) = 22.7,\ p < 0.01$). Since the interaction is significant, we conduct followup t-tests for the post-hoc analysis. The Autofocals show a significant improvement over monovision at a distance of 2.5 D ($p < 0.01$), with monovision faring worse than 20/20 acuity on average at this distance (0.117 logMAR).

For progressive lenses, the ANOVA shows a significant main effect of distance ($F(1.69, 28.65) = 16.0,\ p < 0.001$). There is also a significant interaction of correction and distance ($F(1.34, 22.81) =$

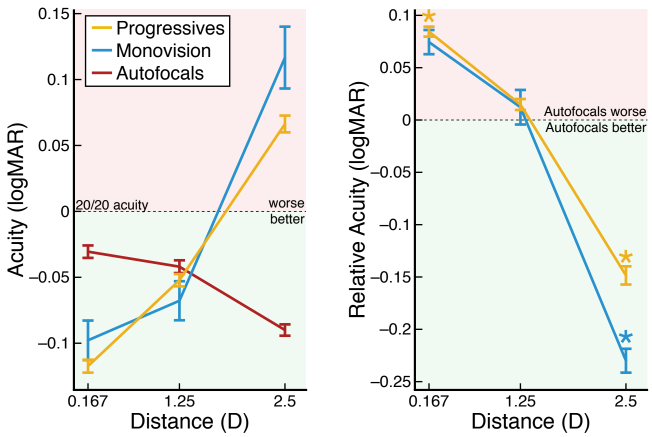

Fig. 6. *Left:* The average acuities for each correction and distance. The Autofocals are on average better than 20/20 at all distances, unlike the other corrections at the nearest distance. *Right:* Average acuity of the Autofocals relative to each user's correction (paired differences). Stars indicate that the Autofocals performed significantly better or worse for the given distance and correction ($p < 0.01$). Error bars represent standard error.

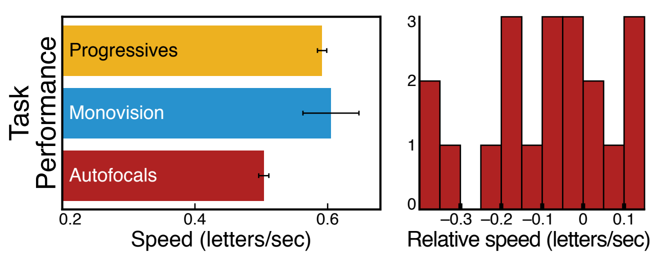

Fig. 7. *Left:* The average speeds of the users during the letter matching task. Error bars represent standard error. Autofocals perform the slowest on average. *Right:* However, a histogram of the speed of a wearer using Autofocals relative to their own correction shows that nearly a third of users were faster in Autofocals. This indicates that miscalibration, not latency, may have affected the speed for a subset of users.

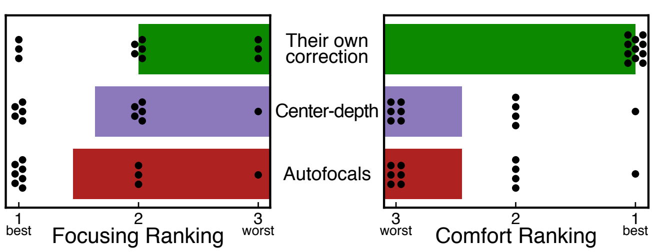

Fig. 8. *Left:* The average rankings for how effectively users were able to see to all distances (1 is the best rank). Individual rankings are shown as black circles. The trend favors the Autofocals over center-depth, and both modes over their own correction. This indicates that eye-tracked systems may be preferable despite their drawbacks in comfort, need for calibration, and familiarity. *Right:* Average comfort rankings show a clear and expected result in favor of their own correction. Users that ranked either mode of the prototype as tied for 1 cited not having to crane their necks back to look at near things higher in their visual field.

32.87, $p < 0.001$), and so we conduct followup t-tests. At a distance of 0.167 D, progressive lenses significantly outperform Autofocals ($p < 0.01$), whereas Autofocals significantly outperforms progressive lenses at 2.5 D ($p < 0.01$). It should be noted that progressive lenses were worse than 20/20 on average at the near distance (0.0663 logMAR). On the other hand, the Autofocals still supported at least 20/20 vision at the far distance (−0.033 logMAR), even though they performed worse than progressives.

In summary, the Autofocals performed significantly worse than progressives at the far distance, but significantly better, and by a wider margin, than both monovision and progressives at the near distance. Furthermore, only the Autofocals performed better than 20/20 acuity on average at every distance.

5.2 Contrast Sensitivity

The average contrast sensitivities are as follows: 1.56 logCS for Autofocals with monovision wearers, 1.62 for monovision, 1.62 for Autofocals with progressives wearers, and 1.66 for progressives. Several users were able to consistently read the lowest contrast line supported by the monitor (1.7 logCS): 3 using monovision, 12 using progressives, and 14 with the Autofocals (3 and 11 from the monovision and progressives groups, respectively). Since this clipping of values violates assumptions of normality, we run a Wilcoxon signed-rank test for each correction, which shows no statistically significant differences at the 0.05 level.

5.3 Task Performance

The speed of the users in each correction can be found in Figure 7. The mean accuracy in each correction is: 92.0% for Autofocals with monovision wearers, 92.1% for monovision, 95.7% for Autofocals with progressives wearers, and 93.9% for progressives. This indicates that users generally went slower to maintain accuracy, as desired. The speed is calculated only based on correctly identified matches. Comparing the speeds with paired t-tests for each correction shows no statistically significant differences at the 0.05 level.

5.4 Natural Scene Preference

The average rankings for physical comfort of the Autofocals using our sensor fusion and in center-depth mode were 2.45 for both. Their own correction on the other hand had a universal ranking of 1, which is understandably better (Figure 8). When looking at their rankings for effectiveness of vision at all distances, we see that on average our sensor fusion performed slightly better than center-depth, which was in turn slightly better than their own correction. A Friedman test of the rankings shows no statistically different differences in these rankings.

6 DISCUSSION

6.1 Acuity and Contrast Sensitivity

Traditional forms of correction, as expected, performed well for the intermediate and far distances (1.25 D and 0.167 D) and showed slight improvements in terms of visual acuity when compared to the Autofocals. While progressives show a statistically significant improvement at the far distance over the Autofocals, *only* users using the Autofocals were capable of reaching at least 20/20 acuity on average at each of the tested distances (2.5 D, 1.25 D, and 0.167 D). Observing acuity at the nearest distance, users wearing the Autofocals significantly outperformed both monovision and progressive wearers and were able to see better than 20/20 when previously, they could not with their correction. This is despite the spatially varying focal power across the lenses (Section 3.1). Therefore, these results can only improve with reduced aberration, such as a coma corrector. Each of the tested correction methods exhibited very similar contrast sensitivity results, at least within the range of contrasts tested.

An interesting trend is the improvement in visual acuity for users wearing the Autofocals at nearer distances. This can be attributed to the near triad, which is the oculomotor response when viewing a near target resulting in binocular convergence, increased accommodation, pupil miosis (i.e. constriction, images in Supplemental Material). When the users look to a far distance, their pupils naturally dilate, resulting in an effectively larger aperture through the focus-tunable optic. In Section 3.1 we show that a larger aperture leads to increased aberrations, which could explain the slight reduction in visual acuity at far distances. With better focus-tunable optics, visual acuity should remain similar to the near acuity at farther distances.

It should also be noted that there is a fundamental tradeoff in the near add power for progressive and monovision corrections. For monovision, higher add powers may decrease comfort and stereoacuity; many monovision wearers that entered our study reported also wearing reading glasses for near vision. Though powers for progressive lenses can get much higher, this requires more precise head movements. The Autofocals system has no physiological tradeoff on the nearest focusing distance.

6.2 Task Performance

We see that people on average perform slower using Autofocals in the task performance study. This seems to imply that the lag in the lenses and processing pipeline makes a measurable impact on refocusing speed. However, the data (Figure 7) shows that 6 users actually performed faster using the Autofocals than their correction. In fact, the second-fastest trial across all participants with a speed of 0.8 letters/sec was using the Autofocals, as compared to 0.76 letters/sec in their progressives (the fastest trial was a different participant wearing monovision). This implies that rather than inherent latency, other factors were involved. Observation of the gaze estimates during trials showed that they sometimes become less accurate as the users moved their heads – the slower performance is therefore likely due to miscalibration from movement of the Autofocals relative to the users' eyes. Another confounding factor is that traditional presbyopia corrections sometimes do not require any refocusing at all: multiple participants did not move their heads while wearing progressive lenses, and one stated that they placed their focus between the two distances when performing the task, allowing both displays to be slightly blurry but still legible; this method is one not possible with Autofocals or non-presbyopic vision, since that would require vergence to not be at either display distance.

6.3 Preference Rankings

Finally, our preference ranking after the natural viewing study points gives us at least one obvious conclusion: comfort is important, and the Autofocals are heavy; every user consistently rated their usual correction as more comfortable. Much of the weight is in the lenses themselves, which means that focus-tunable lens technology targeting presbyopia correction has to focus on reducing its weight, especially since these devices will be worn all day. On the other hand, most users felt that they were able to see more effectively to all distances with the Autofocals. This shows that the technology itself has distinct advantages to user experience over fixed focus methods. Furthermore, some that chose their own correction said that they liked their own best because it was what they were used to now. Others pointed to the fact that the Autofocals were great when they worked – such as during the task performance, when it was clamped to two distances and they were instructed to move their heads as little as possible – but they felt unpredictable at times during the natural viewing.

This brings us to the most important point outside of form factor: predictability. The key with adapting to traditional corrections such as progressives or monovision is that the fixed focus lenses provide predictability. The wearer does not have to guess if the glasses will work or not. In this respect, the center-depth mode, made to imitate a system like that of Hasan et al. [2017a] works quite well; a single depth sensor pointing straight ahead of the wearer is a lot more predictable than an eye-tracked system that is dependent on calibration. However, that many still preferred having the eye trackers means that a depth sensor–only system is not the best possible correction, just one that performs well with the current state of technology. The limiting factor in current technology, based on our reading of user accounts, is the eye tracking, specifically for vergence tracking. An ideal system using focus tunable lenses need only know the vergence state of the wearer, since that alone gives the intended focus distance, but it also needs to be able to accurately track and self-calibrate the vergence regardless of removal or adjustment of the eyewear. Though there have been great strides in making robust and affordable eye tracking systems for head-mounted displays in virtual and augmented reality [Stengel et al. 2015], the problem presbyopic corrections face is inherently more difficult due to the aforementioned issues, and the relatively higher cost of failure.

6.4 General Observations

A potential benefit that we explored relates to the potential for *exceeding* visual performance of younger people. Accommodation has a response time of around 370 ms [Campbell and Westheimer 1960] for externally modulated stimuli. Our system on the other hand theoretically responds within around 125 ms (average processing time per update plus lens settling time), which should allow for faster performance than natural accommodation. A pilot study indicated that the limiting factor in task performance between younger and older users was likely not accommodation speed.

Another thing to note is that nobody complained about the field of view of the focus-tunable lenses – interestingly, one user remarked that they enjoyed having "full field vision." This may be because many of them were used to small field of view on their progressive lenses, but the 30 mm aperture is also comparable in vertical extent to typical corrective eyewear. This is important since larger focus-tunable lenses often come with hard tradeoffs in response time or quality. It seems that retaining the current size and instead looking to improve speed may be sufficient for most people.

Finally, some users claimed their corrections could be out of date. An added benefit of having a focus-tunable correction is that it can be updated on-the-fly in software, removing the need for constantly buying new glasses as prescriptions change.

7 CONCLUSION

Presbyopia, despite being a nearly universal problem in old age, still does not have an ideal commercially-available solution. Focus-tunable lens technology shows promise and may enable technologies closer to the ideal of youthful vision. We built a prototype system, Autofocals, for evaluating the utility and current state of focus-tunable lens technology for correcting presbyopia. Even with this early prototype, the Autofocals are often comparable to and sometimes even exceeds traditional forms of correction. This also has important ramifications for real-world tasks; one user even remarked, "I haven't seen my hand this clearly in decades!" Despite never having worn the Autofocals previously, people preferred them to their own daily correction. This is a promising result for continued pursuit of focus-tunable presbyopia corrections.

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