The contribution of image minification to discomfort experienced in wearable optics

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Wearable optics have a broad range of uses, for example, in refractive spectacles and augmented/virtual reality devices. Despite the long-standing and widespread use of wearable optics in vision care and technology, user discomfort remains an enduring mystery. Some of this discomfort is thought to derive from optical image minification and magnification. However, there is limited scientific data characterizing the full range of physical and perceptual symptoms caused by minification or magnification during daily life. In this study, we aimed to evaluate sensitivity to changes in retinal image size introduced by wearable optics. Forty participants wore 0%, 2%, and 4% radially symmetric optical minifying lenses binocularly (over both eyes) and monocularly (over just one eye). Physical and perceptual symptoms were measured during tasks that required head movement, visual search, and judgment of world motion. All lens pairs except the controls (0% binocular) were consistently associated with increased discomfort along some dimension. Greater minification tended to be associated with greater discomfort, and monocular minification was often—but not always—associated with greater symptoms than binocular minification. Furthermore, our results suggest that dizziness and visual motion were the most reported physical and perceptual symptoms during naturalistic tasks. This work establishes preliminary guidelines for tolerances to binocular and monocular image size distortion in wearable optics.

Introduction

Wearable optics play an important role in the daily life of millions of people who rely on spectacles to correct their vision. Advances in optical engineering now enable the production of sophisticated optics for augmented and virtual reality (AR/VR) devices (Kress, 2019; Meister & Sheedy, 2008). The discomfort that people experience from short and long-term use of wearable optics, however, remains poorly understood

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(Bist, Kaphle, Marasini, & Kandel, 2021; Kaufeld, Mundt, Forst, & Hecht, 2022). In this article we define discomfort as a combination of perceptual and physical factors that negatively impact people's experience. Clinical surveys quantifying non-tolerance rates to prescription spectacles suggest that people may reject a pair of lenses for a variety of reasons including prescription errors, binocular vision problems, and failure to adapt to optical distortions (Bist et al., 2021; Hrynchak, 2006). But these studies are limited in their ability to illustrate the extent to which optical distortions are responsible for the breadth and magnitude of symptoms experienced by patients. Understanding how and why wearable optics cause discomfort is particularly pressing for AR/VR devices. Unlike spectacles, consumers of these devices may be less motivated to overcome discomfort because the benefits of using AR/VR devices are less obvious than the benefits of wearing corrective spectacles. An investigation of optical distortions and discomfort can help guide the design of spectacle lenses and AR/VR devices, and help identify individual differences in susceptibility to discomfort.

One likely source of discomfort produced by wearable optics is a change in retinal image size produced by distortions like magnification and minification (Chan, Wang, So, & Jia, 2022; Opoku-Baah, Erkelens, Qian, & Sharma, 2022; Tong, Allison, & Wilcox, 2020). Laboratory research has shown that optical magnification and minification can have far reaching perceptual and physical effects. These effects include changes in apparent size of objects (Ogle, 1950), changes in perceived depth (Ames, Ogle, & Gliddon, 1932; Kuhl, Thompson, & Creem-Regehr, 2009; Ogle, 1938; Tong et al., 2020) and changes in perceived world motion (Bruder, Wieland, Bolte, Lappe, & Steinicke, 2013; Sauer et al., 2022). Magnification and minification also alter eye movement demands and may contribute to physical symptoms like dizziness, nausea, and eyestrain often reported when people wear AR/VR devices (Chan et al., 2022; Kaufeld et al., 2022; Saredakis et al., 2020; Stanney, Kennedy, & Drexler, 1997).

An unanswered question for wearable optics is, "How much magnification and minification is tolerable?" Prior published guidelines have proposed tolerance metrics for minification and magnification; however, these metrics are often not based on published empirical data (Farell J. & Booth M., 1975; Hopkins, 1962; Self, 1986). Therefore it is unclear how generalizable these guidelines are. It would be reasonable to posit that larger amounts of distortion might lead to more intense symptoms. However, there is also evidence that the difference in distortion between the two eyes may be a stronger driver of discomfort (Kooi & Toet, 2004). In spectacle tolerance literature, for example, having large differences in prescriptions in each eye, and therefore different retinal images sizes in each eye (aniseikonia), has been noted as a key potential risk factor for dissatisfaction in spectacles (Bist et al., 2021; Cockburn, 1987; Hrynchak, 2006). Interocular differences in retinal image size can also occur in AR/VR devices because of lens manufacturing errors or limitations and scaling errors produced by the display (Deng, Zheng, & Cao, 2015; Draper, Viirre, Furness, & Gawron, 2001). Thus, it is important to understand how realistic levels of distortion magnitude and interocular differences affect a wearer's experience. It should also be noted that past experience with optical distortions may influence comfort (Habtegiorgis, Rifai, & Wahl, 2018; Welch, Bridgeman, Williams, & Semmler, 1998).

Here, we report the results of an experiment investigating the initial perceptual and physical symptoms experienced when wearing minifying lenses over both eyes (binocular) or just one eye (monocular) during natural tasks. Minifiers, rather than other types of optical distortions, were selected because they simulate the retinal image size change associated with myopic spectacle correction (Holden et al., 2016). By including lenses that vary in both minification magnitude and interocular difference, we gain knowledge about underlying sources of discomfort and develop guidelines for lens tolerances. Before presenting the methods and results of our study, we provide a brief summary of the optical, perceptual, and physical factors pertinent to this research question.

Background

Optical minification

Optical minification is a global scaling of the image seen through a lens (Figure 1A) and can be quantified in terms of angular change in image size (M_{angle}):

$$M_{angle} = \frac{\theta'}{\theta}, \quad (1)$$

where θ indicates the original visual angle subtended by the image and θ' indicates the new visual angle (Meister & Sheedy, 2008). For minifiers, M_{angle} is < 1. For a given minification level, the displacement between the points in the original and minified image on the retina increases with increasing eccentricity from the center of the distortion. In this report, we will quantify minification in terms of percentage change in retinal image size.

Effect of minification on perception of space and shape

Minifiers alter the apparent size and vertical/horizontal position of objects (Figure 1A).

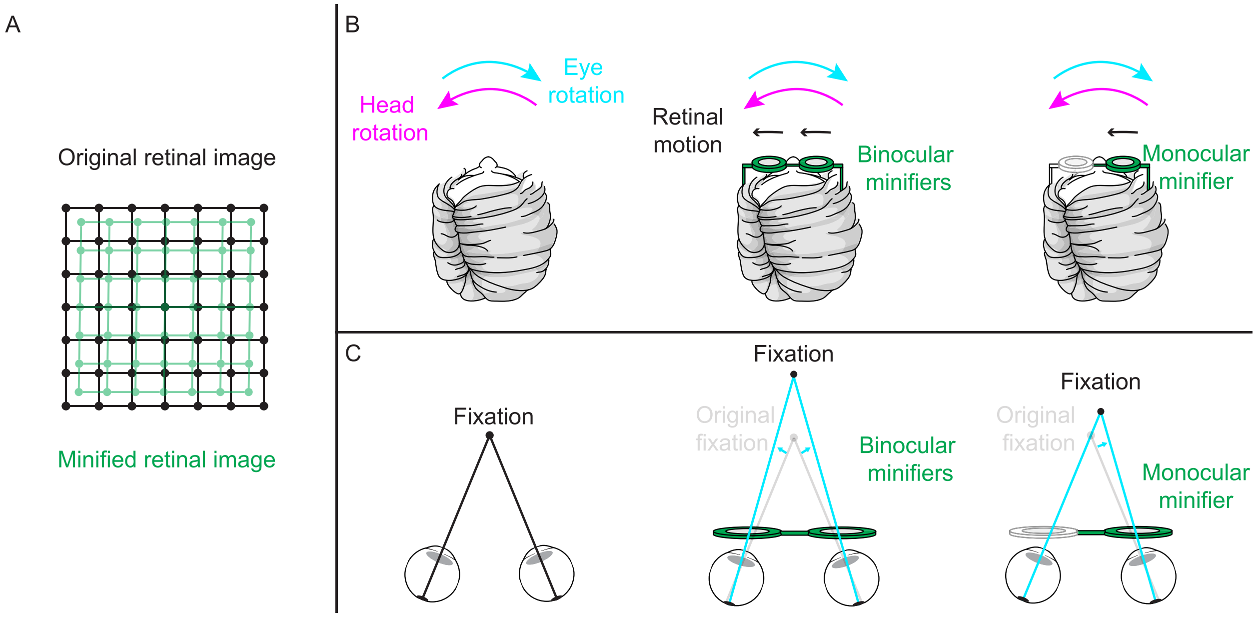

Figure 1. Several effects of minifying lenses. (**A**) Change in retinal image size as a result of minification. The black grid (darker color) is the original retinal image and the green grid (lighter color) illustrates a minified retinal image. (**B**) Top-down illustration of the retinal slip that can occur when VOR is disrupted by binocular and monocular minifiers. Black arrows represent the direction of retinal motion produced by retinal slip. Blue (lighter color) represents the eye rotation and pink (darker color) represents the head rotation. In all three examples, the VOR gain is 1 (eye and head velocity are equal and opposite). However, when minifiers are worn (middle and right panel), there is retinal motion. (**C**) Top-down examples of vergence demands during normal near fixation (left), binocular minification (middle), and monocular minification (right). Minification displaces points toward the optical center of the lens, resulting in a divergent vergence demand for one or both eyes. Illustrations of the glasses wearer are provided by Emily Cooper of Cooperhawk Illustrations, who is unrelated to the paper author.

Monocular minifiers can also modify perceived shape or slant of objects due to alterations to binocular disparities, the differences in the right and left eye's retinal images that provide cues to three-dimensional shape (Ames et al., 1932; Banks & Backus, 1998; Ogle, 1950). Together, these disruptions in perceived space and shape can cause errors or uncertainty when performing tasks like reaching for objects or walking on uneven terrain (Schot, Brenner, Sousa, & Smeets, 2012).

Effect of minification on perception of world and object motion

Because minifiers change the position of points in the visual field, they can also alter perceived self, world, and object motion. For example, during locomotion, the vestibulo-ocular reflex (VOR) keeps the retinal images stable by moving the eyes at the same velocity but in the opposite direction of the head motion sensed by the vestibular system. In other words, the VOR gain (the ratio of eye velocity to head velocity) is ideally 1. When minification is present, the amount the eyes need to rotate to stabilize a target differs from the normal rotation executed by the VOR (Figure 1B). Mismatched eye rotation can result in retinal slip and oscillopsia–the perception that the world is moving even when it is stable (Demer, Honrubia, & Baloh, 1994; Demer, Porter, Goldberg, Jenkins, & Schmidt, 1988). Differences between retinal motion and motion sensed by the vestibular system are also associated with physical symptoms such as motion sickness (Kaufeld et al., 2022; Saredakis et al., 2020; Stanney et al., 1997). Although the VOR gain can adapt quickly, it is possible that oscillopsia is present for a short duration each time wearable optics are put on or removed (Cannon, Leigh, Zee, & Abel, 1985; Demer, Porter, Goldberg, Jenkins, & Schmidt, 1989; Gauthier & Robinson, 1975; Schubert & Migliaccio, 2019). Other sources of changes in perceived motion are considered in the discussion. In this article, we will use the term "swim" to refer to a general perceived distortion in self, object, or world motion. Oscillopsia will specifically refer to the perception of world motion during periodic movement such as head rotation or walking.

Effect of minification on oculomotor demands

Binocular and monocular minifiers also create new demands for how the eyes need to move when looking around the environment (Leigh & Zee, 2015; Remole, 1984, 1989; Schor, Maxwell, McCandless, & Graf, 2002). Figure 1C shows a top-down view of two eyes fixating at a nearby object (black circle). When binocular minifiers are worn (middle panel), points in the image are virtually shifted closer to the optical center of each lens so the eyes must diverge to continue fixating the same point. As depicted in Figure 1A, the minifier produces an increase in displacement as a function of eccentricity. Because the vergence demand depends on the displacement of points, the change in demand increases with viewing eccentricity, creating slightly different vergence demands for each gaze direction. Monocular minification (right panel) produces an additional disruption, because it also alters vertical vergence demands, which are associated with physical discomfort (Remole, 1984). Because these effects increase with eccentricity, they are likely most uncomfortable during eccentric gaze positions.

Methods

The experimental methods, hypotheses, and planned statistical tests were pre-registered at Open Science Framework (https://doi.org/10.17605/OSF.IO/DMZY2). Exploratory analyses were also conducted to follow up on the planned tests.

Participants

Forty adult participants (mean age 21 ± 3.2 years; 10 male, 29 female, 1 nonbinary) completed the experiment. We performed a power analysis based on pilot data to determine the initial target sample size, which was set to 35. After running two participants, we increased the sample size to 40, realizing that there may be smaller differences between the conditions than expected. Participants were recruited who did not wear prescription spectacles or contact lenses more than once a month to capture the experience of people unaccustomed to optical distortions in corrective optics. Thirty-eight of the participants never wore glasses or contact lenses (i.e., self-reported emmetropes), one participant wore glasses less than once a month, and one participant wore ortho-k lenses while sleeping. Participants were screened for visual acuity at a viewing distance of 10 feet (monocular 20/25 equivalent or better and binocular 20/20 equivalent or better) and stereoacuity (at least 50 arc seconds using a Randot test). A total of 46 participants completed some of the experimental sessions. Of these, five participants chose not to continue and one participant was disqualified because they were unable to follow instructions. One participant did not perceive motion in the lenses and therefore could not rank the lenses in terms of motion; however, the rest of their data were still included in the analysis. Informed consent was obtained from all participants, and the experiment procedure was approved by the University of California, Berkeley Institutional Review Board. Participants were compensated at the end of each experimental session.

Minifying lenses

The lenses used in this study were designed to have zero optical power (i.e., not to change the convergence of transmitted light rays like prescription lenses do). These "size lenses" have historically been used in optometric research to isolate the effects of minification or magnification (Ames et al., 1932; Ogle, 1950).

Lenses were placed in different configurations to create five experimental conditions. The lens configurations for each condition are shown in Figure 2A. In the binocular minification conditions, 2% or 4% minifiers were worn in front of both eyes. In the monocular minification conditions, 2% or 4% minifiers were worn in front of the right eye with a 0% lens over the left eye. In the control condition, 0% lenses were worn over both eyes. These levels of minification simulate common distortion magnitudes experienced by spectacle wearers (Figure 2B). For example, with a 10 mm distance from the eye to the lens (vertex distance), 2% and 4% minification approximates the minification in −2 D and −4 D prescriptions. Details about quantification of the experiential lenses can be found in the Supplementary material (Figure S1).

Lenses were worn in adjustable trial frames for a controlled and personalized fit and for easy insertion and removal of the lenses (Figure 2C). The edge thicknesses of the lenses were not the same (0% = 6 mm, 2% = 6 mm, and 4% = 10 mm), resulting in slight differences in weight (0% = 10 g, 2% = 10 g, and 4% = 15 g). The trial frames used for this study had a circular eye shape. The lenses were edged to fit in these frames, resulting in an aperture of 36 mm diameter. Assuming a lens to corneal distance of 10 mm, the radially symmetric monocular field of view through the 0% minifiers was approximately 70°. These lenses were made of a common plastic material (CR-39) and were custom designed and manufactured for this study. Two lenses of each minification level were used

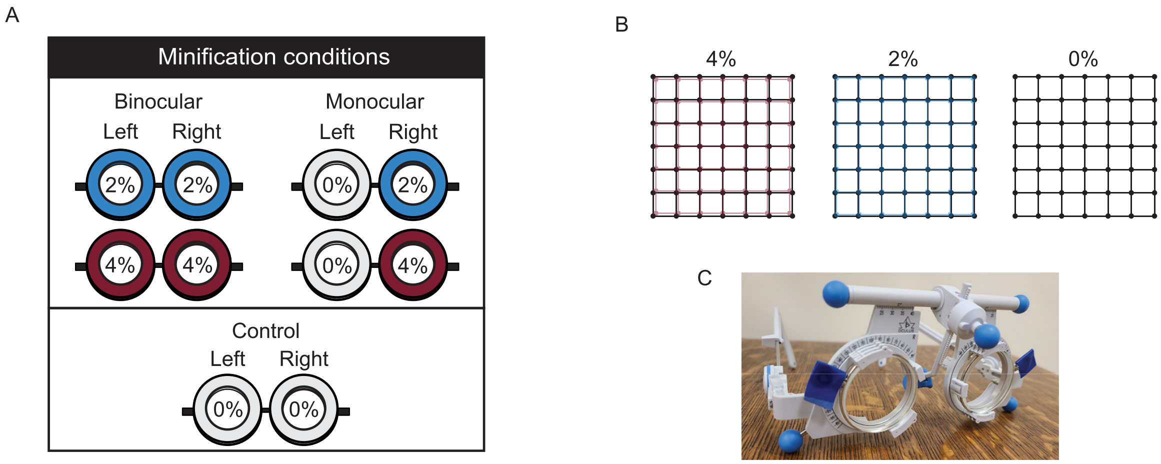

Figure 2. (**A**) Illustration of the within subject minification conditions. Each circle represents a lens. (**B**) A depiction of the change in image size produced by 4%, 2% and 0% minification. The black grid is the original image and the red or blue grids (lighter color) illustrate the minified images. (**C**) The trial frames (OCULUS Universal-Messbrille UB4) with 0% lenses inserted.

to make all minification configurations worn by all participants.

For each participant, the trial frames were carefully fit every session because differences in the position of the eye relative to the lens could change the magnitude of distortion experienced. When fitting, we aligned the pupil as closely as possible to the optical center through horizontal and vertical adjustments made possible by the trial frame. The lens to corneal distance was adjusted to be as close as possible to 10 mm ($M = 10.05 \pm 0.65$ mm) and the pantoscopic tilt (tilt backward or forward of the lenses) was minimized ($M = 0.38° \pm 0.93°$). The trial frames had no wrap. Fitting was always performed with binocular 2% minifiers.

Experimental procedure

The experiment comprised an information session followed by three experimental sessions that were randomized in order and performed on different days.

Information session

In this session, participants completed a demographics questionnaire, a motion sickness susceptibility questionnaire (Golding, 2006), and several measures of visual function (visual acuity, stereoacuity, and eye dominance). Vertical and horizontal fusional ranges were measured at 40 cm and 6 m using prism bars (Antona, Barrio, Barra, Gonzalez, & Sanchez, 2008). Fusional ranges reflect the span of distances over which the vergence system can function and are thought to relate to eyestrain.

Experimental sessions

In each experimental session (one to two hours), participants performed a different activity in every minification condition in a random order. These activities are illustrated in Figure 3, and Table 1 summarizes the purpose and measurements associated with each session.

Naturalistic task and phoria session

The objective of this session was to evaluate whether wearing the lenses during everyday tasks produced physical and perceptual symptoms. The naturalistic task included visual search, interactions with objects, and reading text (Figure 3A). Participants picked up 12 objects one by one from a basket on the floor and placed them on a designated letter marker. Participants identified the appropriate letter marker by reading a posted chart that listed the items to be placed on each marker (e.g., water bottle on marker A). Markers were placed across several tables within a 2.6×2.8 m room. When all objects had been placed on a marker, participants returned the objects to the basket one by one. The locations of the markers were shuffled between conditions. The duration of the task was not standardized or recorded.

When the task was completed for a given condition, participants reported their degree of physical symptoms in terms of headache, dizziness, and nausea on a 1–5

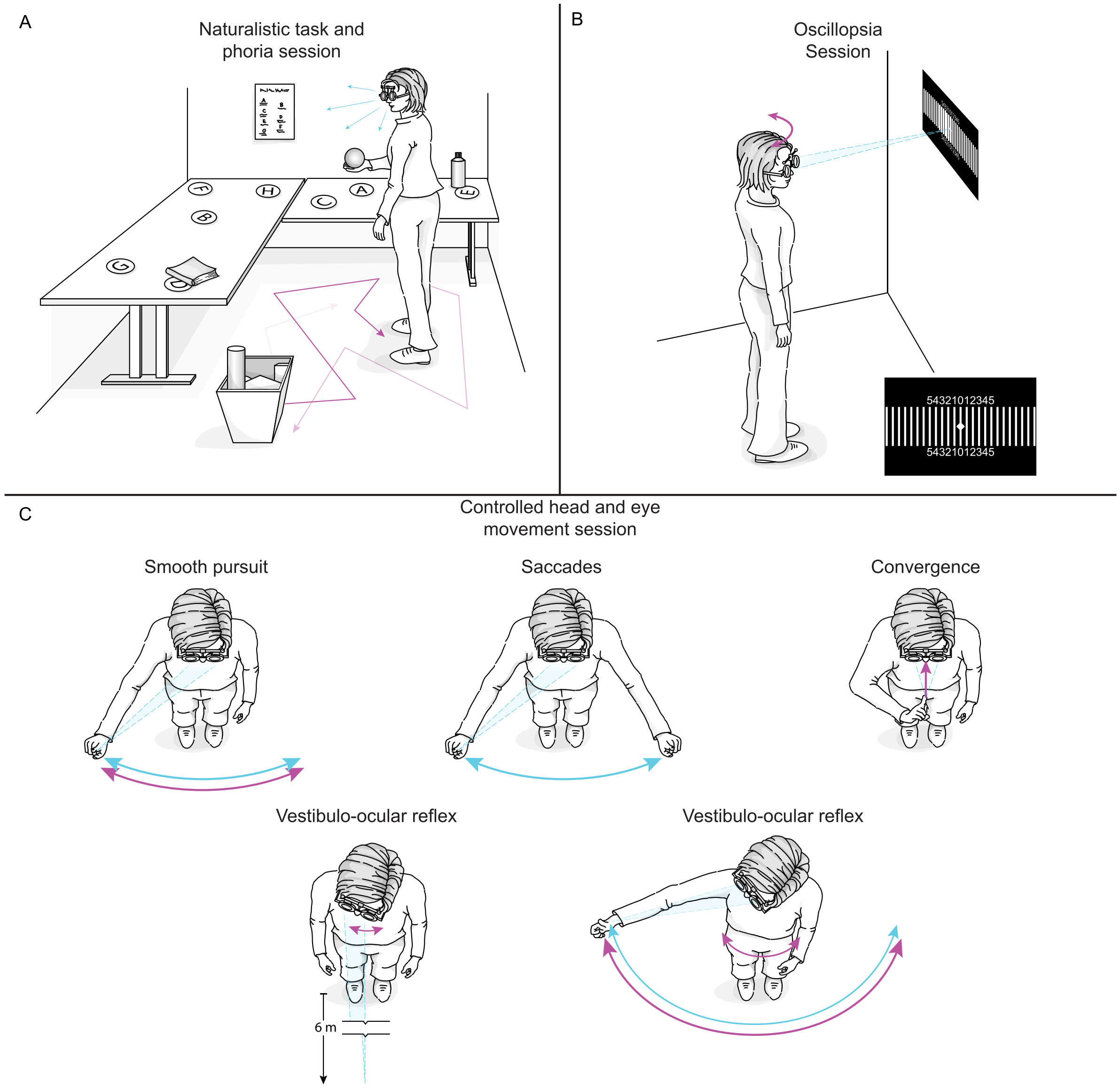

Figure 3. Illustrations of the three experimental sessions. (**A**) Object placement task performed during the naturalistic and phoria session. Participants picked up objects one-by-one from a basket and placed them on a letter marker, using a chart posted on the wall. Blue (lighter arrows) depict eye movements and pink (darker arrows) depict body movement. (**B**) The stimulus and task performed during the oscillopsia session. Participants rotated their head horizontally and reported the perceived movement of an afterimage. (**C**) The five ordered eye and head movements performed during the controlled head and eye movement session. Each movement was performed a few times in a row. Illustrations by Emily Cooper of Cooperhawk Illustrations, who is unrelated to the paper author.

Likert scale (1 = not at all, 2 = mild, 3 = moderate, 4 = bad, 5 = severe). Perceptual effects were evaluated by asking participants to respond to the following questions on the same Likert scale:

- ○ Did you find it difficult or uncomfortable to pick up or interact with objects?
- ○ Did objects look distorted in shape or size?
- ○ Did the objects appear in a different location?
- ○ Did the world appear to move or swim when your body, head or eyes moved?
- ○ Did you experience blurry vision?
- ○ Did you experience double vision?
- ○ (control question) Did you experience shoulder or neck pain?

We also included a question about eyestrain (Did you experience eyestrain or eye tiredness?), which is often characterized as a mixture of physical and perceptual symptoms, so we analyzed this question separately.

Phoria was measured before and after performing the naturalistic task to assess adaptation to the vergence

Experimental session	Purpose	Measurements taken (units)
Naturalistic task and phoria	Identify symptoms during everyday tasks	Physical symptoms: headache, dizziness, and nausea (Likert 1–5) Perceptual symptoms: objects distorted, blurry vision, etc. (Likert 1–5) Eye strain (Likert 1–5) Phoria (prism diopters; Δ) Discomfort ranking "Would you wear the lenses on a regular basis?" (Yes/No)
Oscillopsia	Investigate perceived motion associated with head movement	Afterimage motion range (degrees) Perceived motion (Likert scale 1–5) Motion ranking "Would you wear the lenses on a regular basis?" (Yes/No)
Controlled head and eye movement	Identify which head and eye movements are responsible for physical discomfort in naturalistic task	Physical symptoms: headache, dizziness, and nausea (Likert 1–5) Discomfort ranking "Would you wear the lenses on a regular basis?" (Yes/No)

Table 1. A short description of the purpose of each of the experimental sessions and the measurements taken during the session. All rankings were made without ties.

demands of the lenses. Phoria is the eye's deviation from alignment under monocular viewing (i.e., when the disparity driven fusional system is not activated) (Leigh & Zee, 2015). If an individual's phoria deviates greatly from the current vergence demand, it is thought to put strain on the oculomotor system (Brodsky, 2020; Carter, 1965). To reduce this strain, phorias quickly adapt in a matter of seconds to minutes and can even adapt to non-concomitant vergence demands similar to those produced by monocular minification (Brodsky, 2020; Erkelens, Thompson, & Bobier, 2016; Henson & Dharamshi, 1982; Leigh & Zee, 2015; Toole & Fogt, 2007; Ying & Zee, 2006). A modified Thorington chart and a Maddox rod were used to measure vertical and horizontal phoria. Baseline phoria was measured without lenses on at the start of the experimental session after participants spent five minutes in a dark room. Phoria was evaluated while participants looked straight ahead at near (40 cm), intermediate (1 m), and far (6 m) distances. Furthermore, at 1 m, phoria was measured with their head turned 10° to the right, left, up, and down. Additional measurements of phoria were made with the lenses on before and after the naturalistic task. These measures were taken at 1 m with straight and eccentric gaze positions identical to the 1 m baseline measures. We expected greater phoria at eccentric gaze positions where there are larger displacements between the original and minified retinal images. Between each minification condition, participants spent at least five minutes in a dark room to allow for the dissipation of symptoms and phoria induced by the lenses (North, Dharamshi, & Henson, 1986). If symptoms persisted, participants were encouraged to spend another five minutes in the dark room.

It should be noted that in the initial preregistered study design, we included an additional measure of baseline physical comfort between the initial phoria measurements and the start of the task. However, because no baseline was taken for the perceptual symptoms, we omit this measurement for ease of comparison.

Oscillopsia

The purpose of this session was to investigate the perceived swim (specifically oscillopsia) produced by the lenses, as this was expected to be a key perceptual symptom during the naturalistic task (Chan et al., 2022; Opoku-Baah et al., 2022). To measure the magnitude of oscillopsia during horizontal head rotations, participants reported the perceived movement of an afterimage (Wist, Brandt, & Krafczyk, 1983).

Participants fixated on a white dot 1.8 m away from them in a dimly lit room and rotated their head to the beat of a 2 Hz metronome at an amplitude of ±15°, which was demarcated by tape on the wall (Figure 3B). Participants practiced this movement with feedback from the experimenter to achieve the appropriate amplitude and speed. A 2 Hz frequency horizontal head rotation was chosen because it activates the VOR in a similar way to everyday movement (Rinaudo, Schubert, Figtree, Todd, & Migliaccio, 2019). Before each minification condition, the same head rotation was performed without lenses for one minute to return to a baseline VOR state. Then, participants were given a binocular centrally located vertical afterimage (11° in height) delivered by a quick onset flash device. The afterimage was reported to lay over the fixation point during head stationary fixation. However, during head rotation with the minifiers, we expected the afterimage to move right to left as an indicator of incorrect gaze stabilization. Within 10 seconds of receiving the afterimage, participants reported its horizontal movement by referencing the numbered white lines that were surrounding the fixation dot (Figure 3B). For example, if the afterimage moved from the left number 2 line to the right number 3 line, participants reported, "2 left and 3 right." The dimensions of the white lines were selected for visibility during pilot testing (1.6° tall and 1.0° apart). Before the measurement, participants practiced the afterimage task extensively to ensure that they were reporting motion due to retinal slip and not voluntary eye movements. Although practice improved consistency in performance, it was accepted that the nature of these methods would lead to some variability. Oscillopsia was quantified as the absolute range of perceived motion in degrees. If the reported afterimage range was not inclusive of zero or the participant did not report the range within about 10 seconds, the task was repeated.

As an additional measure of perceived visual motion, participants reported how much motion they perceived on a 1–5 Likert scale after completing the task (1 = not at all, 2 = mild, 3 = moderate, 4 = bad, 5 = severe). It is possible that participants may have perceived motion in depth in the monocular minifiers because of modified binocular disparity, but this was not investigated.

Controlled head and eye movement session

The purpose of this session was to investigate which head and eye movements were most likely responsible for the physical discomfort experienced in the naturalistic session. In each minification condition, participants performed a modified vestibular ocular motor screening (VOMS) assessment to recreate typical movements executed during natural tasks (Mucha et al., 2014). Before and after each of the five VOMS movements (Figure 3C), participants reported their headache, dizziness, and nausea on the 1–5 Likert scale (1 = not at all, 2 = mild, 3 = moderate, 4 = bad, 5 = severe). The task was standardized using a metronome to indicate the frequency of the movement. The amplitude of the movement was indicated by tape on the wall (adjusted for height) which was used as a reference when participants performed head and eye movements. The experimenter provided feedback if the movement was not the desired frequency or magnitude. The order of movements was as follows:

Smooth pursuits: Participants kept their head still and fixated their pointer finger while moving it side to side or up and down ±30° at 0.5 Hz. This was completed four times each for horizontal and vertical pursuits.
Saccades: Participants kept their head still and looked as quickly as possible between their outstretched fingers placed at ±30° 10 times. This was performed for horizontal and vertical saccades.
Convergence: Participants fixated their outstretched pointer finger while they slowly brought it toward their nose. When participants saw double or their finger touched their nose, they repeated the action and performed it a total of three times.
VOR: Participants fixated letter targets (0.4°) at 6 m while rotating their head ±10° to the beat of the metronome (3 Hz) for 10 seconds. This task was performed with horizontal and vertical head rotations.
Full body rotation: Participants rotated their head and upper body with their arm outstretched ±80° to the right and left at 1 Hz while fixating their raised thumb. This was performed five times.

Smooth pursuits, saccades, and convergence movements were performed in front of a uniform black wall 0.7 m away, VOR was performed while looking down a hallway, and full body rotation was done in the middle of a mostly uniform black room. The visual content of the hallway during the VOR task was varied, including a bookshelf, doorway, and a table. A five-minute break was taken between each minification condition, and, if symptoms persisted, participants were encouraged to take another five-minute break. For consistency with the standard VOMS procedure, the movements were always completed in the same order.

Summary rankings

At the end of each of the experimental sessions, participants put on each pair of lenses again to rank them relative to each other. In the naturalistic task and phoria session and the controlled head and eye movements session, participants ranked lenses on the basis of comfort, whereas in the oscillopsia session, viewers ranked the lenses based on perceived motion. Finally, they indicated whether they would wear the lenses on a regular basis, which was described as about five hours a day (yes or no).

Analysis

Summary indexes

Summary indexes were used to quantify the overall effects of the lenses by aggregating some of the Likert ratings. A *physical comfort index* was determined by simply taking the median across the three physical symptoms (headache, dizziness, and nausea) measured for each participant and minification condition. Although these symptoms are distinct, taking the median provides an overall measure of physical discomfort. Later we will discuss the individual symptoms participants experienced. Because these symptoms were measured in both the naturalistic and phoria session and the controlled head and eye movement session, we calculated a separate index for each session. For the controlled head and eye movement session, baseline symptoms were used to normalize the index relative to the symptoms reported before starting the movements, which is consistent with traditional VOMS scoring. A *perceptual comfort index* was calculated for each participant and minification condition by taking the median response for all the perceptual questions, excluding the control and eyestrain question. This index was calculated only for the naturalistic task and phoria session because that is the only session in which the perceptual questions were asked.

Statistical tests

To examine statistically significant differences between all minification conditions, we applied Friedman tests to the Likert responses and the ranking responses. We used Wilcoxon signed-rank tests for follow-up pairwise comparisons and calculated r values for effect size (Fritz, Morris, & Richler, 2011). An analysis of variance (ANOVA) was used to evaluate differences between the continuous outcome measures: afterimage motion and phoria adaptation. Paired t-tests were used for pairwise comparisons, and Cohen's d was calculated as a measure of effect size. We should note that in some instances, the afterimage motion and phoria data contained violations of the assumptions of a standard ANOVA. We thus also ran permutation-based ANOVAs (using the aovp function in the lmPerm package from R) to determine whether these violations affected our interpretation. In all cases, the significance of the main effects and interactions was unchanged. As such, we report the statistics from the original ANOVAs. To evaluate responses to the question "Would you wear the lenses on a regular basis?" (yes/no) we ran a Cochran Q test and performed pairwise comparisons using a McNemar test for significance (Siegel, 1956). We used an odds ratio to assess the effect size, calculated by dividing the "yes" count from the lens with more yeses by the "yes" count of the lens with fewer yeses. For all pairwise comparisons, we corrected for multiple comparisons using a false discovery rate of 5%. To further reduce the possibility of false discoveries, our analysis excluded pairwise comparisons that were not relevant to our working hypotheses, such as monocular 2% versus binocular 4% and binocular 2% versus monocular 4%. Although we used nonparametric statistics for all ordinal responses, for visualization purposes, we show mean, 95% confidence interval, and histograms of all dependent variables. Tables reporting the means, medians, and 95% confidence intervals are included in the Supplementary material. In the results text, we highlight key pairwise statistical comparisons of interest. The figures indicate all statistically significant pairs, and we include the full set of comparison results in the associated tables.

Results and interpretation

During the naturalistic task, overall discomfort increased with the magnitude of minification and with the magnitude of interocular minification difference

The naturalistic task aimed to capture the overall comfort in the lenses during everyday activities. In this section, we examine the yes/no responses to "Would you wear the lenses on a regular basis?" (Figure 4A) and the overall discomfort ranking of the lenses (Figure 4B).

We found significant differences between the probability that participants would wear a given set of lenses on a regular basis ($X^2(4) = 71.62$, $p \leq 0.001$, Table 2A). Participants were less likely to want to wear all minifying lens pairs as compared to the control lenses. Participants were also less likely to want to wear the higher level of minification (4%) compared to the lower level of minification (2%) regardless of whether the minification was monocular or binocular. As expected, participants were less likely to want to wear the 2% monocular lenses than the 2% binocular lenses. However, this difference was not statistically significant for the 4% lenses.

For the discomfort rankings, there were also significant differences between the lenses ($X^2(4) = 87.42$, $p < 0.001$, Table 2B). Consistent with the results above, participants ranked the control lenses as significantly more comfortable than all other lenses. Furthermore, the lowest level of minification (2%) was ranked as more comfortable than the highest minification (4%). Within minification levels, there was a trend toward the binocular minifiers being more comfortable, but this difference was not significant.

In the naturalistic task, perceived swim and dizziness were the greatest symptoms reported

The majority of both physical and perceptual symptoms were reported to be mild, however, the minification conditions were consistently associated with different responses on both the physical ($X^2(4) = 18.98$, $p < 0.001$) and perceptual comfort indices

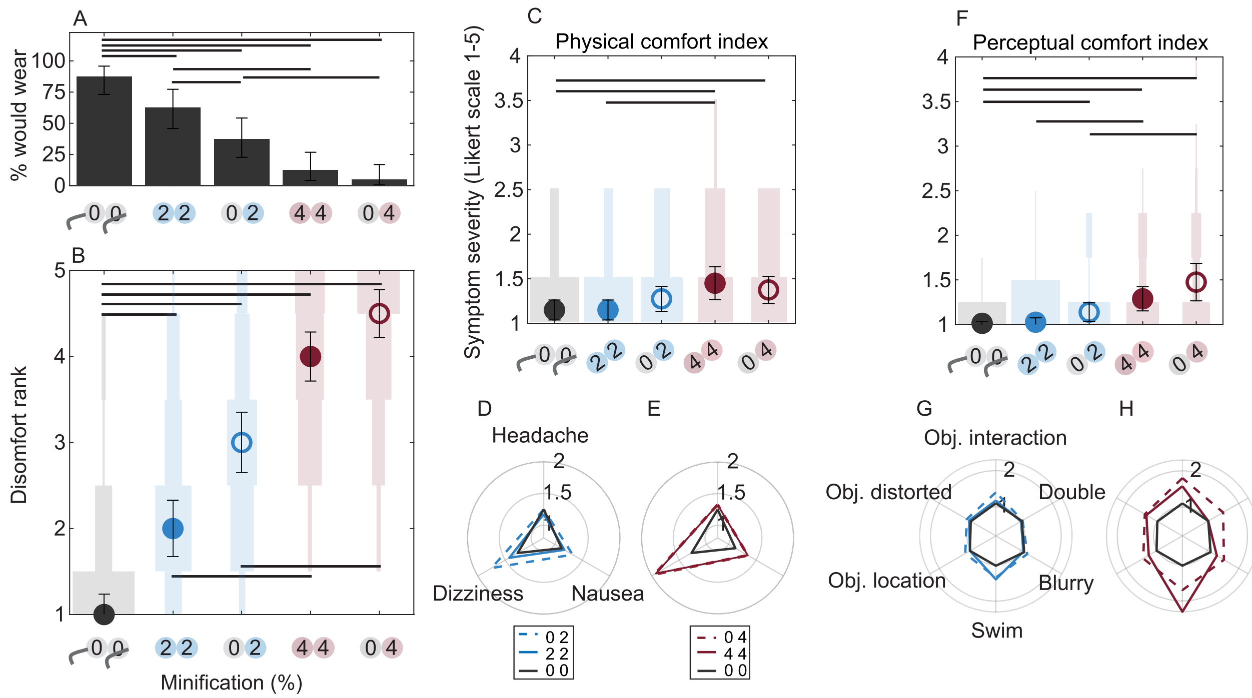

Figure 4. Results from the naturalistic task. Black horizontal lines in all plots represent statistically significant differences. (**A**) The percent of participants who indicated that they would wear the lenses on a regular basis. The error bars are the 95% binomial confidence intervals. (**B**) Overall discomfort ranks (without ties). Circles and error bars indicate means and 95% confidence intervals. The open circles are the monocular minifiers and the closed circles are the binocular minifiers. Blue denotes the 2% minifiers and red denotes the 4% minifiers. The width of the violin histograms under the data points represents the number of responses of a certain value. (**C**) Physical comfort index, plotted in the same manner as B. (**D**, **E**) Individual physical symptom responses that constitute the physical comfort index for the 2% (left) and 4% (right) lenses. The dashed lines are the responses for the monocular minifiers and the solid lines are for the binocular minifiers. In E, the dashed line is obscured by the solid line. The radial distance indicates the mean symptom severity. (**F**) Perceptual comfort index, plotted in the same manner as C. (**G**, **H**) Individual perceptual symptom responses that constitute the perceptual comfort index, plotted in the same manner as D and E. Supplementary values are provided in Table 2 and Supplementary Table S1.

Comparison	X^2	*p*	*Odds ratio*
00 and 22	**5.06**	**0.033**	**1.40**
00 and 02	**16.41**	**<0.001**	**2.33**
00 and 44	**26.28**	**<0.001**	**7.00**
00 and 04	**31.03**	**<0.001**	**17.50**
22 and 02	**4.05**	**0.050**	**1.66**
44 and 04	0.57	0.450	2.50
22 and 44	**16.41**	**<0.001**	**5.00**
02 and 04	**9.60**	**0.003**	**7.50**

Table 2A. Pairwise comparisons from the naturalistic task: Percent of people who would wear the lenses on a regular basis. Results of McNemar tests of significance (X^2), corrected *p* values, and the odds ratio as a measure of effect size. Statistically significant *p* values are bolded. Supplementary values are provided in Supplementary Table S1.

Comparison	*V*	*p*	*r*
00 and 22	**163.00**	**<0.001**	**0.54**
00 and 02	**58.00**	**<0.001**	**0.76**
00 and 44	**12.50**	**<0.001**	**0.85**
00 and 04	**6.00**	**<0.001**	**0.87**
22 and 02	277.50	0.081	0.29
44 and 04	341.00	0.340	0.15
22 and 44	**43.50**	**<0.001**	**0.79**
02 and 04	**104.50**	**<0.001**	**0.66**

Table 2B. Pairwise comparisons from the naturalistic task: Results of Wilcoxon sign-rank tests on the discomfort ranking of the lenses with *V*, corrected *p* values, and *r* as a measure of effect size. Statistically significant p values are bolded. Supplementary values are provided in Supplementary Table S1.

($X^2(4) = 41.97$, $p < 0.001$). For physical discomfort, both the monocular and binocular 4% minifiers were associated with significantly greater symptoms than the control lenses (Figures 4C–E, Table 2C). For perceptual discomfort, all but the 2% binocular minifiers were associated with greater symptoms relative to the control (Figures 4F–H, Table 2D). As expected, there were no significant differences between the lenses for

Comparison	*V*	*p*	*r*
00 and 22	27.50	1.000	0.00
00 and 02	18.00	0.232	0.23
00 and 44	**0.00**	**0.012**	**0.50**
00 and 04	**14.00**	**0.037**	**0.39**
22 and 02	18.00	0.232	0.23
44 and 04	30.00	0.401	0.15
22 and 44	**6.50**	**0.012**	**0.47**
02 and 04	9.00	0.242	0.21

Table 2C. Pairwise comparisons from the naturalistic task: Analysis performed on the physical comfort index in the same way as Table 2B. Statistically significant *p* values are bolded. Supplementary values are provided in Supplementary Table S1.

Comparison	*V*	*p*	*r*
00 and 22	1.00	1.000	0.00
00 and 02	**0.00**	**0.049**	**0.34**
00 and 44	**0.00**	**0.002**	**0.53**
00 and 04	**4.00**	**0.002**	**0.58**
22 and 02	4.50	0.119	0.26
44 and 04	45.00	0.101	0.28
22 and 44	**0.00**	**0.002**	**0.53**
02 and 04	**32.50**	**0.007**	**0.46**

Table 2D. Pairwise comparisons from the naturalistic task: Analysis performed on the perceptual symptom index in the same way as in Table 2B. Statistically significant *p* values are bolded. Supplementary values are provided in Supplementary Table S1.

Movement	*V*	*p*	*r*
Swim vs. Obj. interact	**1621.00**	**0.001**	**0.26**
Swim vs. Obj. distorted	**2580.00**	**<0.001**	**0.48**
Swim vs. Obj. location	**2636.00**	**<0.001**	**0.48**
Swim vs. blurry	**2347.50**	**<0.001**	**0.43**
Swim vs. double	**2520.50**	**<0.001**	**0.53**

Table 3A. Post-hoc analysis of individual perceptual symptoms experienced during the naturalistic task: Results of Wilcoxon sign-rank tests with *V*, corrected *p* values, and *r* as a measure of effect size. Statistically significant *p* values are bolded. The tests were performed on perceptual symptoms pooled across the lenses (except 0% lens). Comparisons were only run between swim and the other perceptual reports to assess if swim was the greatest perceptual factor measured.

Movement	*V*	*p*	*r*
Dizziness vs. headache	**2875.00**	**<0.001**	**0.50**
Dizziness vs. nausea	**2874.00**	**<0.001**	**0.45**

Table 3B. Post-hoc analysis of individual physical symptoms experienced during the naturalistic task: Results of Wilcoxon sign-rank tests with *V*, corrected *p* values, and *r* as a measure of effect size. Statistically significant *p* values are bolded. The tests were performed on the physical symptoms that were pooled across the lenses (except 0% lens). Comparisons were only run between dizziness and the other symptoms recorded to determine if dizziness was the greatest physical symptom measured.

the question about shoulder/neck pain (even though the omnibus test reached significance, no pairwise follow up tests were significant: $X^2(4) = 10.58$, $p = 0.03$). Although these results show that participants experienced relatively mild physical and perceptual symptoms, as discussed in the previous section, many participants still reported that they would not wear the lenses on a regular basis. The absence of significant symptom severity differences between some of the lenses could be due to variability in task speed and strategy. These results highlight the importance of understanding both symptom experience and individual preferences when studying how people respond to wearable optics.

To better understand the specific physical and perceptual symptoms that participants experienced, we conducted a post-hoc analysis of the individual questions that constituted the physical and perceptual comfort indexes (Figures 4D, E, G, H). Specifically, we wanted to know if the apparent dominance of swim and dizziness was statistically significant. A Friedman test showed that across all lenses (excluding the control), perceived swim was the greatest perceptual symptom reported ($X^2(5) = 123.91$, $p < 0.001$) (Table 3A). Qualitatively, the binocular minifiers produced the greatest average swim. Conversely, the monocular lenses produced a more varied set of perceptual symptoms. A Friedman test on the physical symptoms showed that dizziness was the greatest physical symptom reported compared to headache and nausea ($X^2(2) = 69.68$, $p < 0.001$) (Table 3B). In the next sections, we examine the results of the oscillopsia session and the controlled head and eye movement session to clarify these motion-related physical and perception phenomena (perceived swim and dizziness) and understand how they differ between the binocular and monocular minifiers.

Binocular minification produced greater oscillopsia, likely making the world appear to swim to a greater extent during natural tasks

At the end of the oscillopsia session, in which participants focused on perceived motion, participants reported whether they would wear the lenses on a regular basis. The percent of participants who said

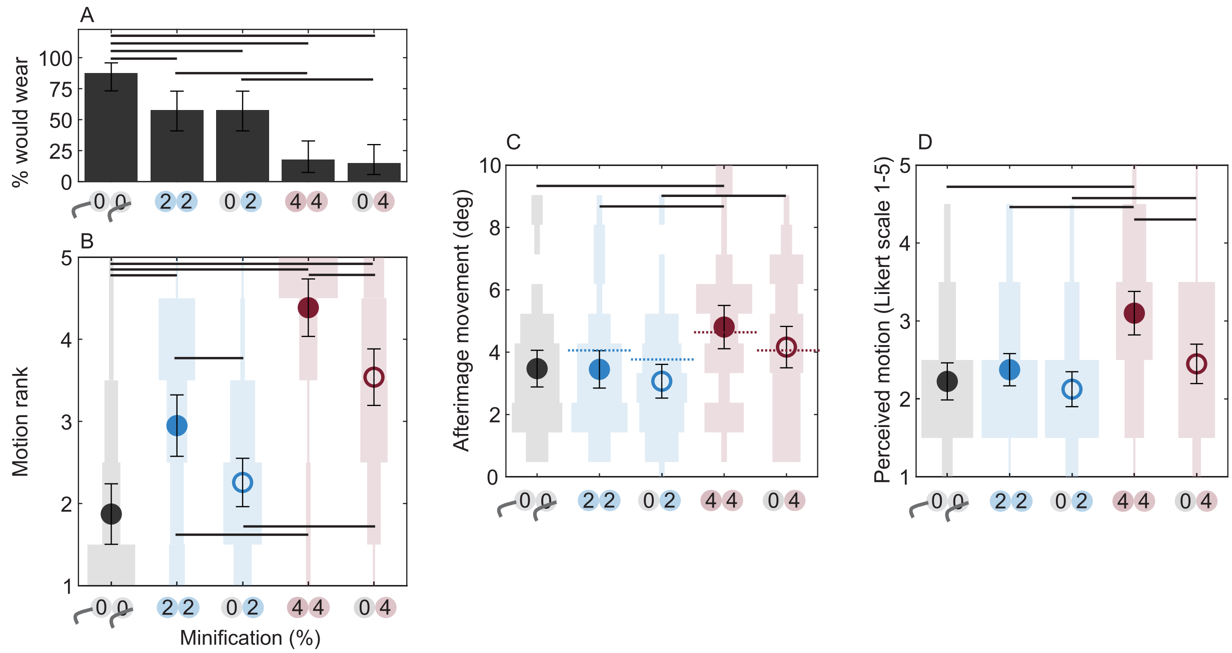

Figure 5. Results from the oscillopsia session. Black horizontal lines in all plots represent statistically significant differences. (**A**) The percent of participants who indicated that they would wear the lenses on a regular basis. The error bars are the 95% binomial confidence intervals. (**B**) The overall motion rankings (without ties). Circles and error bars indicate means and 95% confidence intervals. The open circles are the monocular minifiers and the closed circles are the binocular minifiers. Blue denotes the 2% minifiers and red denotes the 4% minifiers. The width of the violin histograms under the data points represents the number of responses of a certain value. (**C**) The mean perceived movement of the afterimage is plotted in the same manner as B. The dotted lines represent the geometrically expected horizontal retinal slip assuming the participant's VOR gain is 1 and the minification is constant across the visual field. (**D**) The mean perceived motion rated on a Likert scale (1–5) and plotted in the same manner as B. Supplementary values provided in Table 4 and Supplementary Table S2.

Comparison	X^2	*p*	*Odds ratio*
00 and 22	**6.72**	**0.013**	**1.52**
00 and 02	**8.64**	**0.005**	**1.52**
00 and 44	**26.03**	**<0.001**	**5.00**
00 and 04	**23.76**	**<0.001**	**5.83**
22 and 02	0.00	1.000	1.00
44 and 04	0.00	1.000	1.17
22 and 44	**11.25**	**0.002**	**3.29**
02 and 04	**13.47**	**<0.001**	**3.83**

Table 4A. Pairwise comparisons from the oscillopsia session: Percent of people who would wear the lenses on a regular basis. Results of McNemar tests of significance (X^2), corrected *p* values, and the odds ratio as a measure of effect size. Statistically significant *p* values are bolded. Supplementary values provided in Supplementary Table S2.

Comparison	*V*	*p*	*r*
00 and 22	**168.00**	**0.003**	**0.50**
00 and 02	274.00	0.089	0.27
00 and 44	**48.50**	**<0.001**	**0.77**
00 and 04	**98.00**	**<0.001**	**0.66**
22 and 02	**543.00**	**0.034**	**0.35**
44 and 04	**603.00**	**0.003**	**0.48**
22 and 44	**113.00**	**<0.001**	**0.63**
02 and 04	**119.00**	**<0.001**	**0.61**

Table 4B. Pairwise comparisons from the oscillopsia session: Results of Wilcoxon sign-rank tests performed on the motion rankings with *V*, corrected *p* values, and *r* as a measure of effect size. Statistically significant *p* values are bolded. Supplementary values provided in Supplementary Table S2.

yes to this question varied between lenses ($X^2(4) = 60.69$, $p < 0.001$) (Figure 5A, Table 4A). Participants were again significantly less likely to want to wear all minifying lenses as compared to the control condition. The differences between the responses for the monocular and binocular minifiers of the same magnitude, however, were negligible in this session. When participants ranked the lenses based on the motion they experienced (Figure 5B, Table 4B), the responses again differed across minification conditions ($X^2(4) = 62.95$, $p < 0.001$). The greater minification

Comparison	*t*	*p*	*d*
00 and 22	0.09	0.931	−0.01
00 and 02	1.50	0.190	−0.23
00 and 44	**−3.67**	**0.002**	**0.65**
00 and 04	−2.20	0.068	0.35
22 and 02	1.06	0.337	0.21
44 and 04	1.66	0.167	0.30
22 and 44	**−3.73**	**0.002**	**0.66**
02 and 04	**−3.60**	**0.002**	**0.57**

Table 4C. Pairwise comparisons from the oscillopsia session: Range of afterimage motion. Results of a *t*-test, corrected *p* values, and Cohan's *d* as a measure of effect size. Statistically significant *p* values are bolded. Supplementary values provided in Supplementary Table S2.

Comparison	*V*	*p*	*r*
00 and 22	105.00	0.280	0.17
00 and 02	71.50	0.520	0.10
00 and 44	**70.50**	**<0.001**	**0.61**
00 and 04	70.50	0.143	0.27
22 and 02	159.00	0.152	0.25
44 and 04	**432.00**	**0.002**	**0.53**
22 and 44	**100.00**	**0.002**	**0.53**
02 and 04	**65.50**	**0.035**	**0.38**

Table 4D. Pairwise comparisons from the oscillopsia session: Analysis performed on the afterimage motion score performed in the same manner as in Table 4B. Statistically significant *p* values are bolded. Supplementary values provided in Supplementary
Table S2.

(4%) received a higher motion rank compared to the lower level of minification (2%). Within minification levels, the binocular lenses were given a higher motion rank than the monocular lenses. These rankings are consistent with our expectations for the amount of retinal motion elicited by the different lens pairs.

The afterimage motion range—which provided a measurement of the magnitude of motion perceived in visual degrees—also differed between the lenses as expected based on a one-way ANOVA ($F(4) = 8.69$, $p < 0.001$). The afterimage motion in the 0% lenses was a little less than the afterimage motion reported in Wist et al. (1983) of 6.18° ± 2.79°. Furthermore, the motion experienced in the minification conditions was close to the geometric expectations depicted in Figure 5C, but due to response variability some of these differences were not statistically significant (Table 4C). The motion score results (Figure 5D, Table 4D) also differed between lenses (X^2 (4) = 39.60, $p < 0.001$) and followed the same trend as the afterimage motion range, validating the afterimage motion results.

In the controlled head and eye movement session, viewer discomfort increased with the magnitude of the minification

In the controlled head and eye movement session, participants executed movements and reported their physical discomfort. At the end of this session, the differences between the lenses for the question "would you wear the lenses on a regular basis?" ($X^2(4) = 58.67$, $p < 0.001$) were similar to the naturalistic session, as were the differences in the mean discomfort ranking between lenses ($X^2(4) = 79.94$, $p < 0.001$) (Figures 6A and 6B, Tables 5A and 5B).

Overall, the physical discomfort experienced by participants in this session was mild (Figures 6C–6G, Tables 5C–5G). Nonetheless, there were several significant differences in the physical comfort index between the lenses associated with all of the different movements: smooth pursuits ($X^2(4) = 22.93$, $p < 0.001$), saccades ($X^2(4) = 21.31$, $p < 0.001$), convergence ($X^2(4) = 13.06$, $p = 0.011$), VOR ($X^2(4) = 25.14$, $p < 0.001$), and full body rotation ($X^2(4) = 13.84$, $p = 0.007$).

Large head and body movements likely contributed to the dizziness experienced during the naturalistic task

Dizziness was the greatest physical symptom reported in the naturalistic session (Figure 4D, 4E), so we performed a post hoc analysis on the controlled head and eye movement data to determine which head and eye movements produced the most dizziness. Dizziness significantly differed between movements ($X^2(4) = 184.88$, $p < 0.001$) with the full body rotation and the VOR associated with the greatest dizziness compared to the other movements (Table 6). As these were the final two tasks in the VOMS series, some of the increase in symptom severity may be an ordering effect. However, the increase across the ordered movements was qualitatively more pronounced for dizziness than for nausea and headache, plotted for comparison in Figure 7. Consequently, these results suggest that dizziness increased with fast head movements compared to body fixed eye movements.

Eye strain and phoria were greater for the monocular minifiers within minification levels

As a final analysis, we turn to the assessments of eyestrain and phoria during the naturalistic session. This analysis helps us understand the oculomotor discomfort experienced by participants, independent of head motion. After completing the naturalistic task, participants reported significant differences in eyestrain

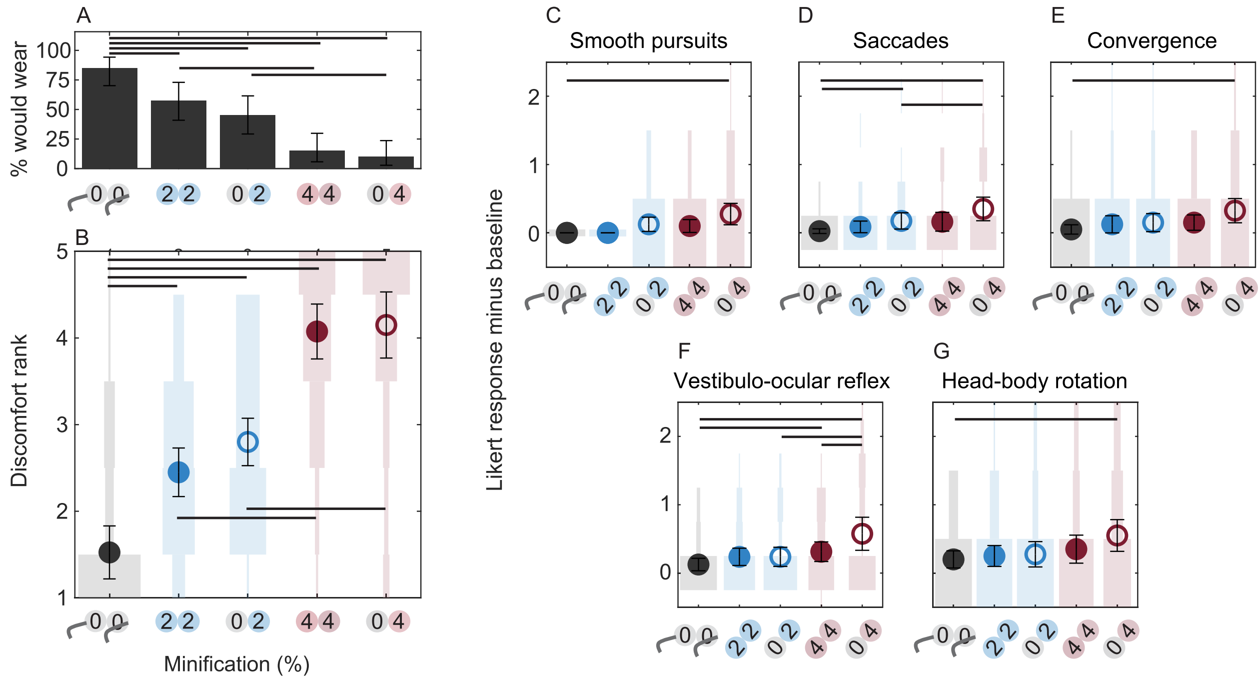

Figure 6. Results from the controlled head and eye movement session. Black horizontal lines in all plots represent statistically significant differences. (**A**) The percent of participants who indicated that they would wear the lenses on a regular basis. The error bars are the 95% binomial confidence intervals. (**B**) The overall discomfort rankings (without ties). Circles and error bars indicate means and 95% confidence intervals. The open circles are the monocular minifiers and the closed circles are the binocular minifiers. Blue denotes the 2% minifiers and red denotes the 4% minifiers. The width of the violin histograms under the data points represents the number of responses of a certain value. (**C**–**G**) The physical comfort index for smooth pursuits, saccades, convergence, the VOR, and head-body rotation plotted in the same manner to B. Supplementary values in Table 5 and Supplementary Table S3.

Comparison	X^2	*p*	*Odds Ratio*
00 and 22	**5.26**	**0.029**	**1.48**
00 and 02	**11.25**	**0.001**	**1.89**
00 and 44	**24.30**	**<0.001**	**5.67**
00 and 04	**26.28**	**<0.001**	**8.50**
22 and 02	0.84	0.410	1.28
44 and 04	0.10	0.752	1.50
22 and 44	**12.19**	**0.001**	**3.83**
02 and 04	**12.07**	**0.001**	**4.50**

Table 5A. Pairwise comparisons from the controlled head and eye movement session: Results of McNemar tests of significance (X^2), corrected *p* values, and the odds ratio as a measure of effect size. Statistically significant *p* values are bolded. Supplementary values provided in Supplementary Table S3.

Comparison	*V*	*p*	*r*
00 and 22	**189.00**	**0.003**	**0.48**
00 and 02	**104.00**	**<0.001**	**0.66**
00 and 44	**13.50**	**<0.001**	**0.85**
00 and 04	**52.50**	**<0.001**	**0.77**
22 and 02	303.50	0.155	0.24
44 and 04	380.50	0.690	0.06
22 and 44	**56.50**	**<0.001**	**0.76**
02 and 04	**112.00**	**<0.001**	**0.64**

Table 5B. Pairwise comparisons from the controlled head and eye movement session: Results of Wilcoxon sign-rank tests on the discomfort rankings with *V*, corrected *p* values, and *r* as a measure of effect size. Statistically significant *p* values are bolded. Supplementary values provided in Supplementary Table S3.

between the lenses ($X^2(4) = 25.16$, $p < 0.001$). All lenses except of the 2% binocular lenses were associated with greater eyestrain than the controls. Greater minification was associated with greater eyestrain, and the monocular minifiers produced significantly more eyestrain than the binocular minifiers (Figure 8A, Table 7A). This result may explain why the monocular lenses were ranked as slightly more uncomfortable than their binocular counterparts in the naturalistic task, despite their tendency to create less perceived swim (Figure 4B).

We next investigated phoria as evidence of fusional demand produced by the minification. Initial phoria was quantified as the difference between phoria

Comparison	*V*	*p*	*r*
00 and 22	N/A	N/A	N/A
00 and 02	0.00	0.073	0.33
00 and 44	0.00	0.083	0.28
00 and 04	**0.00**	**0.019**	**0.47**
22 and 02	0.00	0.073	0.33
44 and 04	4.00	0.073	0.32
22 and 44	0.00	0.084	0.28
02 and 04	9.00	0.095	0.26

Table 5C. Pairwise comparisons from the controlled head and eye movement session: Analysis of the smooth pursuit physical comfort index reported in the same manner as in Table 5B. “N/A” indicates that both minification conditions compared were identical and, consequently, a Wilcoxon could not be run. Statistically significant *p* values are bolded. Supplementary values provided in Supplementary Table S3.

Comparison	*V*	*p*	*r*
00 and 22	2.50	0.232	0.20
00 and 02	**5.00**	**0.036**	**0.41**
00 and 44	6.00	0.084	0.31
00 and 04	**0.00**	**0.010**	**0.51**
22 and 02	11.00	0.232	0.21
44 and 04	**11.00**	**0.057**	**0.35**
22 and 44	14.00	0.335	0.15
02 and 04	**6.00**	**0.043**	**0.38**

Table 5D. Pairwise comparisons from the controlled head and eye movement session: Analysis of the saccades physical comfort index reported in the same manner as in Table 5B. Statistically significant *p* values are bolded. Supplementary values provided in Supplementary Table S3.

measured before the naturalistic task with and without the lenses on. As expected, a two-way ANOVA of the initial phoria measured at 1 m revealed a significant main effect of lens and head position and a significant interaction (Table 7B). All head positions (straight, right, left, up, down) were measured for both horizontal and vertical phoria, but Figure 8 only shows significant pairwise comparisons of interest. The magnitude of horizontal and vertical phoria was greater for eccentric gaze directions compared to forward viewing, as expected from the viewing geometry. We found that within minification levels, the monocular minifiers produced a greater magnitude of phoria compared to the binocular minifiers; however, this difference was only sometimes statistically significant.

Phoria adaptation was investigated because it may indicate oculomotor compensation to the fusional demands of the lenses. Phoria adaptation was quantified by taking the difference between the phoria measurements taken with the lenses on before and

Comparison	*V*	*p*	*r*
00 and 22	6.00	0.500	0.14
00 and 02	3.50	0.207	0.24
00 and 44	0.00	0.155	0.28
00 and 04	**6.00**	**0.041**	**0.44**
22 and 02	12.50	0.860	0.03
44 and 04	18.00	0.155	0.28
22 and 44	9.00	0.860	0.04
02 and 04	10.00	0.155	0.30

Table 5E. Pairwise comparisons from the controlled head and eye movement session: Analysis of the convergence physical comfort index reported in the same manner as in Table 5B. Statistically significant *p* values are bolded. Supplementary values provided in Supplementary Table S3.

Comparison	*V*	*p*	*r*
00 and 22	14.00	0.137	0.27
00 and 02	9.50	0.175	0.24
00 and 44	**24.00**	**0.040**	**0.37**
00 and 04	**6.50**	**0.011**	**0.50**
22 and 02	39.00	1.000	0.00
44 and 04	**33.50**	**0.032**	**0.40**
22 and 44	40.50	0.299	0.18
02 and 04	**11.50**	**0.013**	**0.46**

Table 5F. Pairwise comparisons from the controlled head and eye movement session: Analysis of the vestibulo-ocular reflex physical comfort index reported in the same manner as in Table 5B. Statistically significant *p* values are bolded. Supplementary values provided in Supplementary Table S3.

Comparison	*V*	*p*	*r*
00 and 22	27.50	0.717	0.08
00 and 02	20.00	0.583	0.12
00 and 44	18.00	0.355	0.21
00 and 04	**6.50**	**0.016**	**0.49**
22 and 02	25.00	0.824	0.04
44 and 04	14.50	0.251	0.26
22 and 44	13.50	0.441	0.17
02 and 04	18.00	0.095	0.36

Table 5G. Pairwise comparisons from the controlled head and eye movement session: Analysis of the full body rotation physical comfort index reported in the same manner as in Table 5B. Statistically significant *p* values are bolded. Supplementary values provided in Supplementary Table S3.

after the naturalistic task. There were no significant differences in horizontal or vertical phoria adaptation between the lenses despite the ANOVA revealing a main effect of minification condition (Table 7C). Overall, there was little evidence of phoria adaptation in any

Movement	*V*	*p*	*r*
Pursuit vs. saccades	**327.00**	**<0.001**	0.28
Pursuit vs. converge	208.50	0.171	0.11
Pursuit vs. VOR	**131.00**	**<0.001**	**0.63**
Pursuit vs, full body	**231.50**	**<0.001**	**0.56**
Saccades vs. converge	925.50	0.127	0.13
Saccades vs. VOR	**202.00**	**<0.001**	**0.58**
Saccades vs. full body	**384.00**	**<0.001**	**0.54**
Converge vs. VOR	**201.00**	**<0.001**	**0.60**
Converge vs. full body	**160.00**	**<0.001**	**0.57**
VOR vs. full body	1276.00	0.829	0.02

Table 6. Results from post-hoc analysis of dizziness from controlled head and eye movement sessions. Dizziness for each movement was calculated by pooling across the minification conditions (excluding 0% lenses). Wilcoxon sign-rank tests with *V*, corrected p values, and *r* as a measure of effect size. Statistically significant *p* values are bolded.

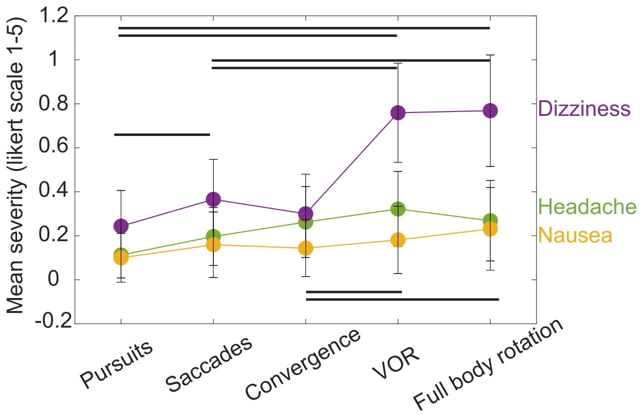

Figure 7. Post-hoc analysis of dizziness from controlled head and eye movement session. Markers represent mean headache, dizziness, and nausea across lenses (excluding 0% lenses). Black lines indicate significant differences in dizziness between the movements reported in Table 6. The error bars represent the 95% confidence intervals. The head and eye movements are listed in the order that they were performed.

condition. Together, these results support the idea that the slightly greater discomfort associated with the monocular minifiers during the naturalistic task may result from eyestrain caused by unnatural eye movements like vertical vergence.

Discussion

By investigating the multifaceted effects of optical minification in a single experiment, this study provides new insights into discomfort from distortions in wearable optics. The results emphasize the importance of considering retinal image size changes when evaluating the comfort and utility of spectacles and AR/VR devices. Even though our study only included mild to moderate levels of minification, each lens pair was consistently associated with increased discomfort along some dimension.

Understanding the underlying causes of perceived swim and dizziness

Disruption of world motion was salient to participants when performing the naturalistic task in this experiment. In fact, perceived swim and dizziness were the greatest perceptual and physical symptoms reported. The oscillopsia session verified that some of the perceived swim likely resulted from a mismatch between the current VOR gain and the gain needed to stabilize the retinal image when minification was present. This theory is supported by the fact that the magnitude of afterimage motion seen during the oscillopsia session was close to the retinal slip expected if a participant's VOR gain remained 1 during head rotation with a minifier (Figure 5). Even though VOR is known to rapidly adapt, we infer that VOR disruption can account for some of the swim experienced during the naturalistic task.

We also expected swim to be associated with dizziness because head movements stimulate the vestibular system and visual-vestibular conflicts may be a primary contributor to dizziness. The connection between dizziness and large head movements was supported by the controlled head and eye movement session, where we found that movements involving large and fast head turns produced greater dizziness. Interestingly, previous literature investigating comfort in AR/VR devices similarly found disorientation, rather than nausea or oculomotor discomfort, to be the dominant symptom reported (Kaufeld et al., 2022; Saredakis et al., 2020; Stanney et al., 1997). These results suggest that perceived swim and dizziness may be particularly salient symptoms and play an important role in comfort with wearable optics. Furthermore, large and fast head movements may intensify these symptoms.

Reframing differences between monocular and binocular distortions

When it came to the hypothesis that monocular minification would be more troublesome than binocular minification, the results were mixed. Although monocular minifiers tended to be rated worse than binocular minifiers during a naturalistic task, this difference was relatively small and not always statistically significant. Indeed, when participants were asked to focus on visual motion, the binocular minifiers were rated as producing more motion than the

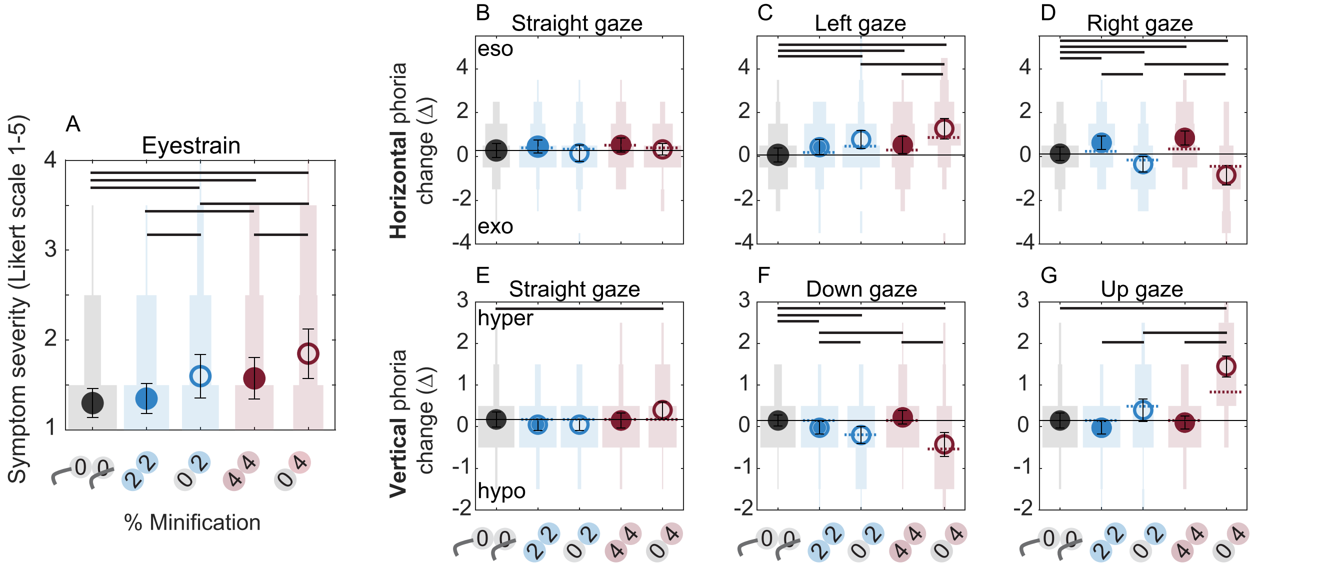

Figure 8. Eyestrain and phoria. Black horizontal lines in all plots represent statistically significant differences. (**A**) Eyestrain measured after the naturalistic task. Circles and error bars indicate means and 95% confidence intervals. The open circles are the monocular minifiers and the closed circles are the binocular minifiers. Blue denotes the 2% minifiers and red denotes the 4% minifiers. The width of the violin histograms under the data points represents the number of responses of a certain value. Supplementary values in Table 7A and Supplementary Table S4. (**B**–**D**) Initial horizontal phoria change measured at 1 m in prism diopters plotted in the same manner as A. Dotted red and blue lines represent the geometrically expected phoria change when viewers were 1m from the target assuming a constant minification across the lenses. Positive values indicate that participants were displaying esophoria (eso) while negative values indicate exophoria (exo). (**E**–**G**) Initial vertical phoria change plotted in the same manner as B–D. Positive values indicate that participants were displaying hyperphoria (hyper) and negative values indicate hypophoria (hypo). Supplementary values in Table 7 and Supplementary Table S5.

Comparison	*V*	*p*	*r*
00 and 22	18.00	0.608	0.08
00 and 02	**11.00**	**0.035**	**0.40**
00 and 44	**12.00**	**0.035**	**0.39**
00 and 04	**15.00**	**0.004**	**0.55**
22 and 02	**47.50**	**0.047**	**0.33**
44 and 04	**36.00**	**0.035**	**0.38**
22 and 44	**18.00**	**0.049**	**0.32**
02 and 04	**34.00**	**0.043**	**0.35**

Table 7A. Pairwise comparisons from eye strain and phoria measures: Eyestrain on a Likert scale 1–5. Pairwise eyestrain comparisons using Wilcoxon sign-rank tests with a test statistic of *V*, corrected *p* values, and *r* as a measure of effect size. Statistically significant *p* values are bolded. Supplementary values provided in Supplementary Table S4.

	Horizontal		*Vertical*	
	F(4,4)	*p*	*F(4,4)*	*p*
Main effect of lenses	**8.16**	**<.001**	**17.28**	**<.001**
Main effect of gaze	**7.89**	**<.001**	**18.59**	**<.001**
Interaction	**6.35**	**<.001**	**11.71**	**<.001**

Table 7B. Pairwise comparisons from eye strain and phoria measures: Two-way ANOVA on the initial horizontal and vertical phoria change with the *F* value and *p* reported. Statistically significant *p* values are bolded. Degrees of freedom indicated in parentheses. Supplementary values provided in Supplementary Table S5.

	Horizontal		*Vertical*	
	F(4,4)	*p*	*F(4,4)*	*p*
Main effect of lenses	**3.13**	**0.014**	**5.28**	**<0.001**
Main effect of gaze	0.38	0.822	0.58	0.679
Interaction	0.69	0.809	1.21	0.250

Table 7C. Eye strain and phoria results. Two-way ANOVA on the adaptation to horizontal and vertical phoria reported in the same way as in Table 7B. Statistically significant *p* values are bolded.

monocular minifiers. On the other hand, when asked about eyestrain during the naturalistic task, participant responses indicated that the monocular minifiers were worse. Thus, we suggest that comfort differences between monocular and binocular minifiers should be reframed. Rather than thinking of monocular minifiers as unilaterally worse, it may be more prudent to consider how physical and perceptual symptoms differ between lens types.

Estimates of image size distortion tolerance in wearable optics

An estimate of people's tolerances for optical minification and magnification can be valuable for optical engineers and optometrists to maximize comfort and increase the likelihood of a patient or a user adopting a pair of spectacles or a wearable device (Farell & Booth, 1975; Hopkins, 1962; Kooi & Toet, 2004; Self, 1986). We estimated minification tolerance by fitting a regression line to the responses to the question "would you wear the lenses on a regular basis?" which was recorded after completing the naturalistic task. We fit the data separately for the monocular and binocular minifiers and extrapolated the prediction to the magnification range, as this is simply an increase in retinal image size instead of a decrease. All lines were forced to have a value of 87.50% when no distortion was present. Figure 9 shows the data and resulting fits. Here, we denote the percentage of image size distortion as negative for minification and positive for magnification. The resulting equations for predicting the percentage of yeses for monocular image size distortion (p_m) and binocular image size distortion (p_b) as a function of retinal image size distortion (M) are as follows:

$$p_b = \begin{cases} 17.50M + 87.50, & \text{if } M < 0 \\ -17.50M + 87.50, & \text{if } M > 0 \end{cases} \quad (2)$$

$$p_m = \begin{cases} 21.50M + 87.50, & \text{if } M < 0 \\ -21.50M + 87.50, & \text{if } M > 0 \end{cases} \quad (3)$$

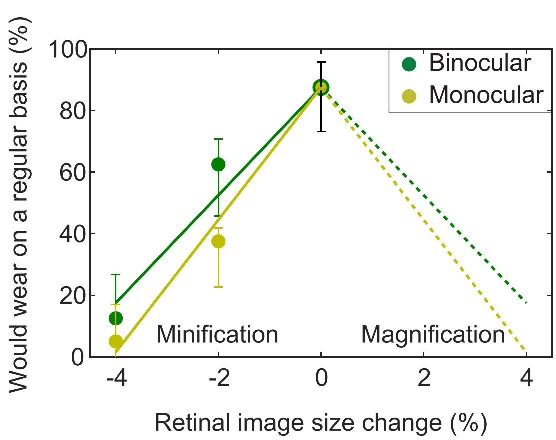

Figure 9. Estimated distortion tolerance based on responses to "would you wear the lenses on a regular basis" (which is about 5 hours a day) from the naturalistic session. The lines are regression lines for binocular (dark green) and monocular (light green) minification. Error bars and circles depict the percentages across all participants and the associated 95% binomial confidence intervals. Dashed lines indicate extrapolated tolerance levels for magnification.

It should be noted that these tolerances are based on responses taken after performing a short task and therefore may not be representative of longer-term wear (e.g., after wearing the lenses for a whole day). Our data indicate that 50% of people would tolerate wearing a 1.7% difference in minification or magnification between the two eyes, or a 2.1% binocular minification or magnification. As both interocular difference and absolute minification affect comfort, it is likely that these two effects will compound. For example, having 2% distortion in one eye and 4% in the other produces the same interocular difference as the 2% monocular condition, however, there is more overall distortion and the viewer would likely experience more discomfort. These tolerance estimates are necessarily preliminary, because they are based on a relatively small number of minification levels. Also, the desire to wear a device may shift tolerance levels. That is, people may be more likely to overcome discomfort if they experience a great improvement in the clarity of their vision or if they benefit substantially from using an AR/VR device.

Predictors of individual differences in comfort

People likely differ consistently in how they respond and adapt to wearable optics. For example, some participants' judgements of comfort corresponded closely to their symptoms, whereas others did not. This highlights the importance of not just understanding symptom experience, but also individual personality, preferences, and adaptability. Individualized comfort predictions could benefit both optical producers and consumers. Lens manufacturers, for example, could invest in specialized designs for individuals with distortion sensitivity, while producing more generalized designs for resilient wearers. In this experiment, we hypothesized that scores from the motion sickness susceptibility questionnaire, fusional reserve, eye dominance, and baseline phoria might predict individual differences in physical comfort and eyestrain. However, after performing spearman correlations with false discovery rate correction, we did not find any significant correlations. It is possible that the discomfort symptoms experienced in the present study were so mild that consistent individual differences were present but difficult to detect. On the other hand, individual characteristics such as sensitivity to cue conflicts or attention to the task demands, may be stronger predictors of discomfort (Fulvio, Ji, & Rokers, 2021). Regardless, investigating predictors of individual differences stands out as a potentially impactful direction for future investigation.

Short-term and long-term comfort

Initial comfort may determine future use of a given device with wearable optics and could also be predictive of the initial symptoms experienced each time that they are worn. However, it is also vital to understand long-term comfort as it likely differs systematically from short-term symptoms and may explain some of the differences between our results and previously proposed tolerance levels. Studies that investigate simulator sickness have not reached a consensus on whether symptoms increase or decrease over time (Dużmańska, Strojny, & Strojny, 2018; Park et al., 2008; Saredakis et al., 2020). This may be a result of the fact that some symptoms may compound while others may decrease with adaptation overtime (individual differences may also be relevant in this domain). Another complexity of anticipating long-term comfort in optical distortions is that adaptation to the many effects of distortions will likely occur asynchronously. Distortions cause disruptions across different domains—perceptual, visual-motor, and oculomotor—which are known to adapt at different rates. For example, adaptation of the VOR can take just minutes, while adaptation to perceptual depth distortions can take days (Adams, Banks, & van Ee, 2001). The extent of adaptation to all these effects at any given time will likely contribute to different symptom arrays. Further, the type of adaptation may differ depending on whether the device is worn continuously or across intermittent periods (Li, Tregillus, & Engel, 2022; Li, Tregillus, Luo, & Engel, 2020; McLean, Manning, & Cooper, 2022). Understanding the adaptation of phenomena that underlie dominant symptoms like visual swim and dizziness could be a fruitful way to investigate the long-term effects of optical distortions.

Possible sources of perceived swim other than VOR disruption

During the naturalistic task, there were likely other sources of perceived motion, in addition to VOR disruption, that could have contributed to the perceived swim. For example, it should be noted that we only investigated horizontal motion and not motion in depth which could be expected to occur in the monocular minifiers because of changes to binocular disparities. As discussed previously, distortions can change perceived self, world, and object motion. For example, when minifiers are worn, the retinal image of an object will move slower across the retina than without minification, possibly resulting in the object appearing to move more slowly. The speed that objects move across the retina (i.e., optic flow) can also alter perception of self-motion and perceived depth via changes to motion parallax. If objects appear to move more slowly, observers may perceive themselves to be moving more slowly as well. Further, alterations in the relative motion of objects during self-motion may cause the observer to perceive objects as closer or farther than they are. Lenses are also rarely flawless and often exhibit changes in distortion across the lens, sometimes in the form of radial distortions or higher order aberrations (Meister & Sheedy, 2008). Perceived swim can be caused when objects pass through these different levels of distortions producing a rippling effect through the image often termed pupil swim (Durgin & Li, 2010; Geng et al., 2018). Although this experiment did not isolate these additional forms of motion, the motion ranking and perceptual swim question likely capture the combined percept of multiple motion distortions. Importantly, our results support the notion that symptoms related to visual motion make up a key component of discomfort in optical eyewear. Thus a detailed understanding of visual motion during natural tasks and how this motion may be distorted either locally or globally by wearable optics may yield fruitful guidelines for lens design.

Conclusions

Wearable optics are an essential part of providing visual clarity and supporting immersive experiences in AR/VR devices. This study suggests that perceived swim and dizziness may be important indicators of comfort during short-term use of wearable optics. By providing a comprehensive empirical investigation of the short-term effects of minification, we hope that this study provides a valuable foundation for the design and manufacturing of optical components for AR/VR devices. At the same time, these findings may help improve outcomes for spectacle wearers because they can guide future research on how to minimize or eliminate the specific symptoms that people experience when they get new prescription glasses. Future investigations should consider exploring how individual differences may influence comfort and the effects of minification during more prolonged wear.

Keywords: optical distortion, augmented reality, binocular vision, eye movements

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Supplementary material

Validation of lens minification and quantification of radial distortions

The minification in the lenses was validated by capturing images (with a Google Pixel smartphone camera) through the optical center of the lenses at a vertex distance of approximately 10 mm. We compared the horizontal displacement of grid points with and without the lens present in a 52° horizontal field of view (Figure S1). All of the lenses had approximately the amount of expected minification. The deviation of the 2% and 4% lenses from their expected values is indicative of the presence of minor radial distortions, which are an increase in minification or magnification with greater eccentricity from the optical center. To determine the amount of radial distortion, we fit the data to a radial distortion model with r and r_d as the radial distance from the optical center to a given point in the normal or distorted image, respectively. k is a constant whose magnitude represents the degree of radial distortion:

$$r_d = r + kr^3. \quad \text{Equation S1}$$

The best fit k value tended to be quite small (for example, 3.21 x 10^{-9} for one of the 2% lenses and 7.4 x 10^{-9} for one of the 4% lenses). Although this measurement was taken in a smaller field of view than that experienced by the participants (~70° monocular field of view), both k values are notably smaller than the perceptually relevant radial distortions investigated in visual research (Kuhl et al., 2009; Tong, Allison, & Wilcox, 2019; Tong et al., 2020). Therefore, our lenses likely have a negligible degree of perceptually relevant radial distortion. It should be noted that the 0% lenses had a small amount of magnification.

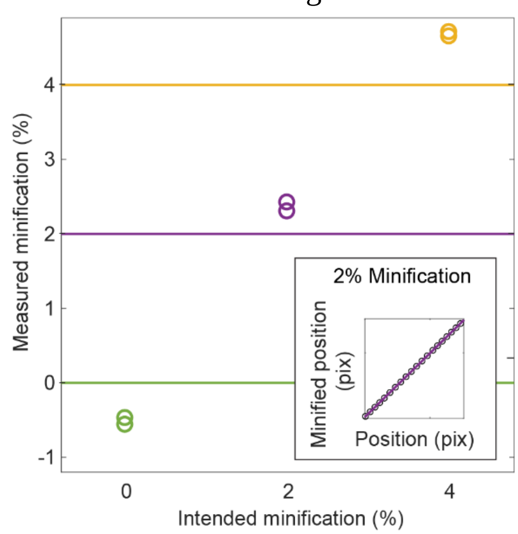

Figure S1. Measured minification from six lenses. The inset figure depicts an example of the process of quantifying minification in one lens. The x and y axis range from 0 to 2000 pixels. The black circles are the horizontal position of the original and minified grid points in the photographs (the number of these points depicted was decreased to improve visibility). The slope of the purple regression line is the measured minification for that lens and is plotted in the larger figure as one of the purple markers. This process was performed for each marker in the larger figure. The horizontal lines represent the expected magnitude of minification.

Additional results from the naturalistic, oscillopsia, and controlled head and eye movement sessions

A. Percent of people who would wear the lenses on a regular basis

Min	*Percent "yes"*	*95% CI*
00	87.50	22.62
22	62.50	31.47
02	37.50	31.47
44	12.50	22.62
04	5.00	16.31

B. Discomfort ranking

Min	*M*	*Mdn*	*95% CI*
00	1.40	1.00	0.24
22	2.38	2.00	0.33
02	3.00	3.00	0.35
44	3.98	4.00	0.28
04	4.25	4.50	0.28

C. Physical symptom index

Min	*M*	*Mdn*	*95% CI*
00	1.15	1.00	0.11
22	1.15	1.00	0.11
02	1.28	1.00	0.14
44	1.45	1.00	0.19
04	1.38	1.00	0.15

D. Perceptual symptom index

Min	*M*	*Mdn*	*95% CI*
00	1.01	1.00	0.02
22	1.03	1.00	0.05
02	1.14	1.00	0.11
44	1.29	1.00	0.14
04	1.48	1.00	0.21

Table S1. The results from the naturalistic task. (A) The percent of people who reported that they would wear the lenses on a regular basis and the 95% binomial confidence intervals. (B-D) Mean, median, and 95% confidence intervals for the discomfort ranking, physical comfort index, and perceptual comfort index. The first column titled "Min" indicates the magnitude of minification in the left and right eye, respectively.

A. Percent of people who would wear the lenses on a regular basis

Min	*Percent "yes"*	*95% CI*
00	87.50	22.62
22	57.50	32.07
02	57.50	32.07
44	17.50	25.44
04	15.00	24.13

B. Motion rank

Min	*M*	*Mdn*	*95% CI*
00	1.87	1.00	0.36
22	2.95	3.00	0.37
02	2.26	2.00	0.29
44	4.38	5.00	0.35
04	3.54	4.00	0.34

C. Range of afterimage motion in degrees

Min	*M*	*Mdn*	*95% CI*
00	3.47	2.85	0.59
22	3.45	2.85	0.60
02	3.07	2.85	0.54
44	4.80	4.76	0.69
04	4.16	3.81	0.66

D. Motion score

Min	*M*	*Mdn*	*95% CI*
00	2.23	2.00	0.24
22	2.38	2.00	0.21
02	2.13	2.00	0.22
44	3.10	3.00	0.28
04	2.45	2.00	0.25

Table S2. Results from the oscillopsia session. (A) The percent of people who reported that they would wear the lenses on a regular basis and the 95% binomial confidence intervals. (B-D) The mean, median, and 95% confidence interval for the motion ranking, range of afterimage motion, and motion scores. The first column titled "Min" indicates the magnitude of minification in the left and right eye, respectively.

A. Percent of people who would wear the lenses on a regular basis

Min	*Percent "yes"*	*95% CI*
00	85.00	24.13
22	57.50	32.07
02	45.00	32.25
44	15.00	24.13
04	10.00	20.87

B. Discomfort rank

Min	*M*	*Mdn*	*95% CI*
00	1.53	1.00	0.31
22	2.45	2.00	0.28
02	2.80	3.00	0.27
44	4.08	4.00	0.32
04	4.15	5.00	0.38

C. Smooth pursuit physical comfort index

Min	*M*	*Mdn*	*95% CI*
00	0.00	0.00	0.00
22	0.00	0.00	0.00
02	0.13	0.00	0.10
44	0.10	0.00	0.09
04	0.28	0.00	0.16

D. Saccades physical comfort index

Min	*M*	*Mdn*	*95% CI*
00	0.03	0.00	0.03
22	0.09	0.00	0.09
02	0.18	0.00	0.12
44	0.16	0.00	0.14
04	0.35	0.00	0.17

E. Convergence physical comfort index

Min	*M*	*Mdn*	*95% CI*
00	0.05	0.00	0.07
22	0.13	0.00	0.13
02	0.15	0.00	0.13
44	0.15	0.00	0.11
04	0.33	0.00	0.18

F. VOR physical comfort index

Min	*M*	*Mdn*	*95% CI*
00	0.13	0.00	0.09
22	0.24	0.00	0.13
02	0.24	0.00	0.14
44	0.31	0.00	0.14
04	0.58	0.00	0.24

G. Full body rotation comfort symptom index

Min	*M*	*Mdn*	*95% CI*
00	0.20	0.00	0.13
22	0.25	0.00	0.15
02	0.28	0.00	0.19
44	0.35	0.00	0.21
04	0.55	0.00	0.23

Table S3. Results from the controlled head and eye movement session. (A) The percent of people who reported that they would wear the lenses on a regular basis and the 95% binomial confidence intervals. (B) The mean, median, and 95% confidence interval for the discomfort ranking. (C-G) Mean, median, and 95% confidence interval for the smooth pursuit, saccades, convergence, VOR, and full body rotation comfort symptom index. The first column titled "Min" indicates the magnitude of minification in the left and right eye, respectively.

Min	*M*	*Mdn*	*95% CI*
00	1.300	1.00	0.16
22	1.35	1.00	0.17
02	1.60	1.00	0.24
44	1.58	1.00	0.23
04	1.85	2.00	0.28

Table S4. Eye strain reported after performing the naturalistic task. Mean, median, and 95% confidence interval of eyestrain across participants. The first column titled "Min" indicates the magnitude of minification in the left and right eye, respectively.

A. Initial phoria

	Horizontal phoria									Vertical Phoria								
	Straight gaze			*Leftward gaze*			*Rightward gaze*			*Strait gaze*			*Downward gaze*			*Upward gaze*		
Min	*M*	*Mdn*	*CI*	*M*	*Mdn*	*CI*	*M*	*Mdn*	*CI*	*M*	*Mdn*	*CI*	*M*	*Mdn*	*CI*	*M*	*Mdn*	*CI*
00	0.28	0.00	0.33	0.08	0.00	0.32	0.13	0.00	0.30	0.18	0.00	0.18	0.15	0.00	0.13	0.15	0.00	0.18
22	0.45	0.00	0.30	0.43	0.50	0.34	0.63	1.00	0.30	0.05	0.00	0.14	-0.03	0.00	0.15	-0.03	0.00	0.15
02	0.15	0.00	0.38	0.78	1.00	0.42	-0.35	-0.50	0.35	0.05	0.00	0.14	-0.20	0.00	0.20	0.40	0.00	0.27
44	0.53	0.00	0.31	0.53	1.00	0.38	0.85	1.00	0.33	0.15	0.00	0.18	0.23	0.00	0.16	0.10	0.00	0.15
04	0.33	0.00	0.27	1.28	1.00	0.47	-0.85	-1.00	0.44	0.40	0.00	0.20	-0.43	-1.00	0.29	1.45	1.00	0.25

B. Initial phoria pairwise comparisons

	Horizontal phoria									Vertical Phoria								
	Straight gaze			*Leftward gaze*			*Rightward gaze*			*Strait gaze*			*Downward gaze*			*Upward gaze*		
Compare	*t*	*p*	*d*	*t*	*p*	*d*	*t*	*p*	*d*	*t*	*p*	*d*	*t*	*p*	*d*	*t*	*p*	*d*
00 & 22	-1.27	0.426	0.18	-1.77	0.108	0.33	**-3.39**	**0.002**	**0.52**	1.96	0.119	-0.24	**2.21**	**0.044**	**-0.39**	1.86	0.093	-0.33
00 & 02	0.70	0.635	-0.11	**-3.75**	**0.002**	**0.59**	**2.28**	**0.033**	**-0.45**	1.71	0.154	-0.24	**3.58**	**0.002**	**-0.65**	-1.96	0.092	0.34
00 & 44	-0.50	0.380	0.24	**-2.52**	**0.026**	**0.40**	**-5.41**	**<0.001**	**0.73**	0.30	0.877	-0.04	-1.00	0.323	0.16	0.50	0.623	-0.09
00 & 04	-0.31	0.762	0.05	**-6.43**	**<0.001**	**0.94**	**4.39**	**<0.001**	**-0.81**	-1.94	0.119	0.37	**4.16**	**0.001**	**-0.80**	**-9.63**	**<0.001**	**1.86**
22 & 02	1.74	0.380	0.28	-1.71	0.108	-0.29	**5.10**	**<0.001**	**0.93**	0.00	1.000	N/A	**2.21**	**0.044**	**0.31**	**-3.98**	**0.001**	**-0.61**
44 & 04	1.54	0.380	0.22	**-3.91**	**0.001**	**-0.55**	**7.06**	**<0.001**	**1.38**	-2.51	0.066	-0.42	**4.60**	**<0.001**	**0.87**	**-9.00**	**<0.001**	**-2.03**
22 & 44	-0.60	0.635	0.08	-0.63	0.534	0.09	-1.60	0.118	0.22	-1.16	0.337	0.20	**-3.61**	**0.002**	**0.50**	-1.40	0.192	0.26
02 & 04	-1.07	0.466	0.17	**-2.79**	**0.016**	**0.35**	**2.30**	**0.033**	**-0.39**	**-3.82**	**0.004**	**0.65**	1.78	0.095	-0.28	**-6.26**	**<0.001**	**1.26**

Table S5. Phoria measured in naturalistic and phoria session in prism diopters. (A) Mean, median, and 95% confidence interval of initial phoria, which was the difference between the phoria with and without the glasses on. The first column titled "Min" indicates the magnitude of minification in the left and right eye, respectively. (B) Results from t tests performed on the initial phoria measurement with Cohan's *d* as a measure of effect size. "N/A" denotes occasions when Cohan's *d* cannot be computed because the pooled standard deviation is zero.