Distortions in Wearable Optics: Comfort, Perception, and Adaptation

by

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Abstract

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Many people have had the experience of viewing the world through optics, such as when wearing corrective spectacles or using augmented and virtual reality devices (AR/VR). The purpose of the optical lenses present in spectacles and devices is to bring images into focus, but they also produce unwanted distortions such as magnification and minification that change the retinal image size or shape of an object. Surprisingly, small changes in retinal image size or shape can have substantial perceptual and physical consequences. While spectacles have been around for centuries, there remains a large gap in the literature on how optical distortions affect the viewer. This dissertation contains experimental investigations related to how optical distortions affect perception and comfort, and how these effects change over time. Chapter 1 establishes a fundamental understanding of the onset of perceptual and physical symptoms produced by optical minification. Chapter 2 investigates how people adapt over time to a specific type of monocular distortion that alters depth and shape perception. Chapter 3 investigates how the visual system interprets the geometry of objects when faced with perceptual disruptions caused by optical distortions. Together this research provides a much-needed foundational understanding of optical distortions from multiple domains.

Acknowledgements

I would like to thank my mentor, Emily Cooper, who has been an incredible teacher and partner through my scientific journey. It was an honor to learn from such a dedicated, empathetic, and enthusiastic scientist. I would also like to thank the members of my lab and the vision science community for bringing fellowship and joy to my life these past five years. Finally, I would like to thank my family and my partner for their encouragement and support throughout my PhD.

Contents

INTRODUCTION

Wearable optics have existed for centuries, with the purpose of bringing the world into focus for people with refractive errors.[1] Given the long-standing and widespread use of wearable optics, there is surprisingly little research on how and to what extent optical distortions affect perception and comfort. Distortions are inherently present in many wearable optics and can be defined as any change in retinal image size or shape for the wearer.[2] In this dissertation, I show that small changes in retinal image size can produce substantial changes in perception and comfort which likely affects people's daily lives. Further, this dissertation presents foundational research necessary for evidence-based recommendations for clinicians and optical engineers proscribing and developing wearable optics.

Importantly, optical distortions can be the same or different between the eyes. A difference in retinal image size between the eyes has been given special attention in the literature as it is known to have potentially sizable perceptual and physical consequences.[3–7] Differences in optical distortions between the eyes typically result from variation in each eye's prescription or from manufacturing errors. Much of the focus on differences in retinal image size originates from research on anisometropia, a condition in which individuals have large differences in refractive errors between the eyes.[3,4,8,9] Clinicians have observed that these individuals are less tolerant of their glasses prescription.[5–7] However, the severity of the symptoms and the breadth of perceptual effects are not well understood. For this reason, my dissertation takes particular interest in the perceptual and physical effects when optical distortions differ between the two eyes, but also considers cases in which both eyes receive matched distortions.

The topics of my dissertation span multiple areas of investigation including comfort, perception, and adaptation because all three of these areas are necessary to fully understand the impact of optical distortions. As I will discuss in the following chapters, simply changing retinal image size or shape can have far reaching perceptual and physical consequences. For example, optical distortions can produce a change in depth perception, motion perception, vergence of the eyes, and physical symptoms.[3,10,11] Further, because the visual system is plastic and can undergo perceptual and motor adaptation, it is important to understand how the effects of optical distortions change over time.[12–14] The experiments reported in this dissertation, which investigate the various domains affected by optical distortions, will provide a more holistic and realistic representation of the impact of optical distortions on the observer.

In Chapter 1, I quantify the magnitude and constellation of physical and perceptual symptoms created by monocular and binocular minification during short-term wear of spectacles. As expected, I found that greater magnitudes of minification produced greater symptoms. Additionally, monocular minifiers, in which only one eye's image is distorted, produce greater overall discomfort compared to their binocular counterparts. Interestingly, though, monocular and binocular minification produced different types of symptoms. Namely, monocular magnifiers produced greater eye strain and difficulty interacting with objects while the binocular minifiers elicited greater perceived swim (the perception that the world is moving even when it is stable). These data provide preliminary tolerance recommendations that can give guidance to clinicians and AR/VR engineers.

In Chapter 2, I investigate intermittent versus continuous adaptation to a specific difference in distortion between the eyes. In particular, participants wore a monocular horizontal magnifier which makes one eye's image wider and, when initially worn, produces a change in the perceived slant and shape of surfaces.[3] While previous literature investigated how the change in perceived slant adapts away across 7 days of continuous wear, this is not representative of everyday experiences in wearable optics.[12] For example, individuals may wear their spectacles intermittently throughout the day as they engage in different activities such as reading or jogging. Intermittent exposure could disrupt adaptation, or drive adaptation.[13,15] Further, intermittent exposure could lead to alternate mechanisms of adaptation such as cue reweighting.[16,17] I used psychophysical methods to investigate whether continuous or intermittent wear of these lenses produced a greater magnitude of adaptation to the perceived change in slant and shape. I found that there was no difference in the magnitude of adaptation when the lenses were worn continuously or intermittently for 5 hours. However, there may be differences in the mechanism of adaptation depending on how often and how long the lenses are worn.

In Chapter 3, I take a deeper look at the visual slant and shape illusions created by a monocular horizontal magnifier as shown in Chapter 2. While the cause of the slant illusion has been well established, the cause of the shape illusion has been hypothesized but not tested. I find that the slant illusion predicts the shape illusion when participants experience monocular horizontal, vertical, and uniform magnification. Further, I find that in a natural environment, the shape illusion is so robust that it can make highly familiar objects, like one's own phone, appear to be a trapezoid. These results reveal the underpinnings of the shape illusion and show that these illusions may be more common in everyday prescription spectacles than previously thought.

All three chapters of this dissertation are first author published manuscripts of which I was the primary contributor.[11,18,19]

1 CHAPTER 1

The contribution of image minification to discomfort experienced in wearable optics

1.1 Abstract

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.

1.2 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;[2,20] people experience from short and long-term use of wearable optics, however, remains poorly understood.[5,21] 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.[5,7] 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.[22–24] 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,[3] changes in perceived depth[4,24–26] and changes in perceived world motion[27,28]. 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.[21,22,29,30]

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.[31–33] 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.[34] 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.[5–7] 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.[35,36] 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.[37,38]

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.[39] 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.

1.3 Background

1.3.1 Optical minification

Optical minification is a global scaling of the image seen through a lens (Figure 1.1A) and can be quantified in terms of angular change in image size (M_{angle}):

$$M_{angle} = \frac{\theta'}{\theta},$$

where θ indicates the original visual angle subtended by the image and θ^1 indicates the new visual angle.[2] 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.

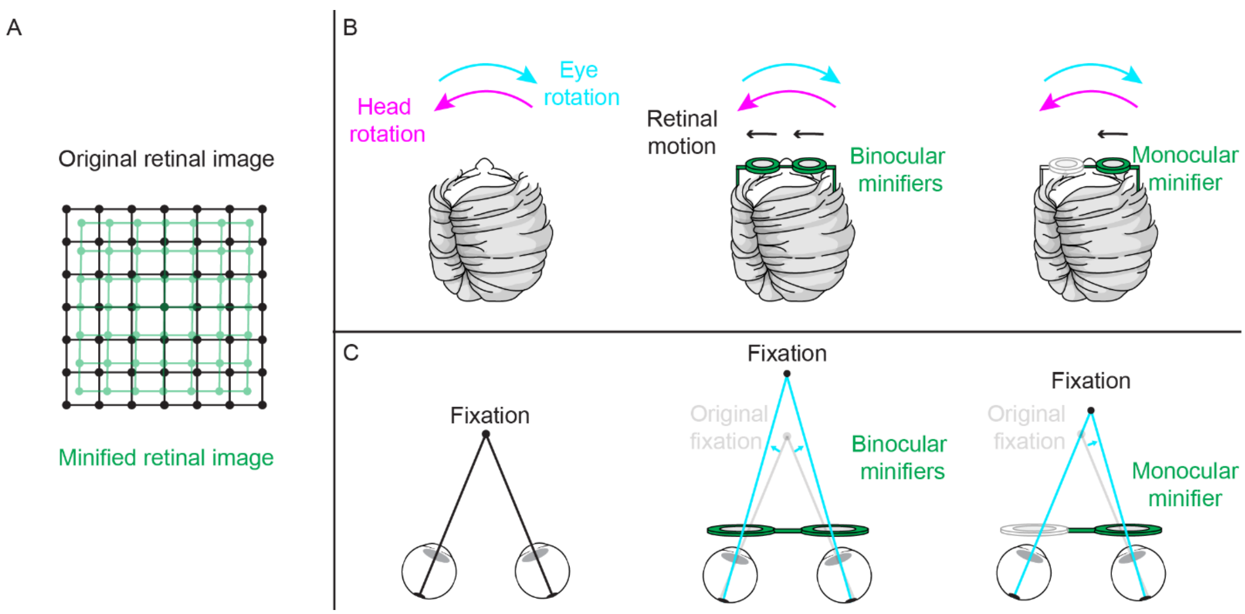

Figure 1.1. Several effects of minifying lenses. (A) Straight-on view of a grid to show the change in retinal image size as a result of minification. The black grid (darker color) is the original retinal image and the green grid (lighter color) illustrates a minified retinal image. (B) Top-down illustration 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.

1.3.2 Effect of minification on perception of space and shape

Minifiers alter the apparent size and vertical/horizontal position of objects (Figure 1.1A). 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.[3,4,40] 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.[41]

1.3.3 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 in the retina differs from the normal rotation executed by the VOR (Figure 1.1B). Mismatched eye rotation can result in retinal slip and oscillopsia–the perception that the world is moving even when it is stable.[42,43] Differences between retinal motion and motion sensed by the vestibular system are also associated with physical symptoms such as motion sickness.[21,29,30] 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.[14,43–45] 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.

1.3.4 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.[46–49] Figure 1.1C 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 1.1A, 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.[47] Because these effects increase with eccentricity, they are likely most uncomfortable during eccentric gaze positions.

1.4 Methods

The experimental methods, hypotheses, and planned statistical tests were pre-registered at Open Science Framework (https://osf.io/dmzy2). Exploratory analyses were also conducted to follow up on the planned tests.

1.4.1 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.

1.4.2 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.[3,4] Lenses were placed in different configurations to create five experimental conditions. The lens configurations for each condition are shown in Figure 1.2A. 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 1.2B). 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 1.S1). Lenses were worn in adjustable trial frames for a controlled and personalized fit and for easy insertion and removal of the lenses (Figure 1.2C). 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 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 ± 0.65 mm) and the pantoscopic tilt (tilt backward or forward of the lenses) was minimized (M = 0.38° ± 0.93°). The trial frames had no wrap. Fitting was always performed with binocular 2% minifiers.

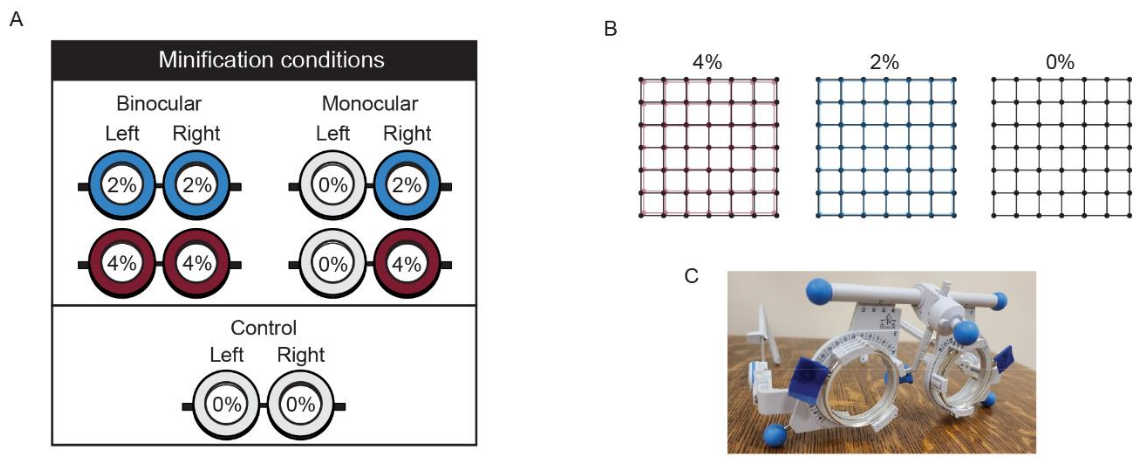

Figure 1.2. (A) Illustration of the within subject minification conditions. Each circle represents a lens. (B) A depiction of the change in image size produced by 4%, 2% and 0% minification. The black grid is the original image and the red or blue grids (lighter color) illustrate the minified images. (C) The trial frames (OCULUS Universal-Messbrille UB4) with 0% lenses inserted.

1.4.3 Experimental procedure

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

1.4.4 Information session

In this session, participants completed a demographics questionnaire, a motion sickness susceptibility questionnaire,[50] 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.[51] Fusional ranges reflect the span of distances over which the vergence system can function and are thought to relate to eyestrain.

1.4.5 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

1.3, and Table 1.1 summarizes the purpose and measurements associated with each session.

Experimental session	Purpose	Measurements taken (units)
Naturalistic task and phoria	Identify symptoms during everyday tasks	- Phoria (prism diopters; Δ) - Physical symptoms: headache, dizziness, and nausea (Likert 1-5) - Perceptual symptoms: objects distorted, blurry vision etc. (Likert 1-5) - Eye strain (Likert 1-5) - 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 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 (without ties) - "Would you wear the lenses on a regular basis?" (Yes/No)

Table 1.1. A short description of the purpose of each of the experimental sessions and the measurements taken during the session.

1.4.5.1 Naturalistic task and phoria sessions

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 1.3A). 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 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 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).[46] If an individual's phoria deviates greatly from the current vergence demand, it is thought to put strain on the oculomotor system.[52,53] 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.[9,46,52,54–56] 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.[57] 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.

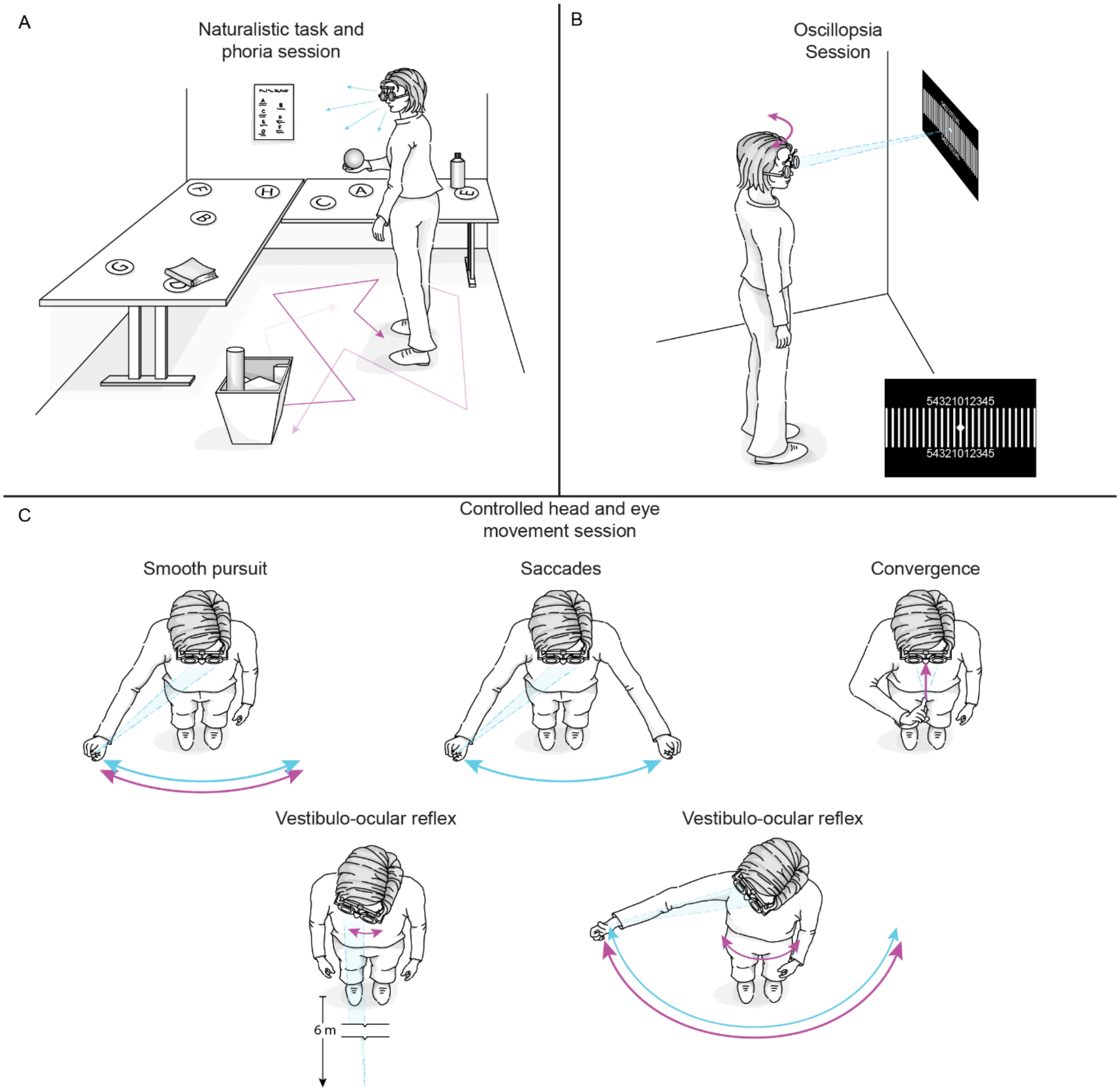

Figure 1.3. Illustrations of the three experimental sessions. (A) Object placement task performed during the naturalistic and phoria session. Participants picked up objects one-by-one from a basket and placed them on a letter marker, using a chart posted on the wall. Blue (lighter arrows) depict eye 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.

1.4.5.2 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.[22,23] To measure the magnitude of oscillopsia during horizontal head rotations, participants reported the perceived movement of an afterimage.[58]

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 1.3B). 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.[59] 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 1.3B). 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.

1.4.5.3 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.[60] Before and after each of the five VOMS movements (Figure 1.3C), 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.

1.4.5.4 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).

1.5 Analysis

1.5.1 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.

1.5.2 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.[61] 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.[62] 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.

1.6 Results and interpretation

1.6.1 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 1.4A) and the overall discomfort ranking of the lenses (Figure 1.4B).

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 1.2A). 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 1.2B). 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.

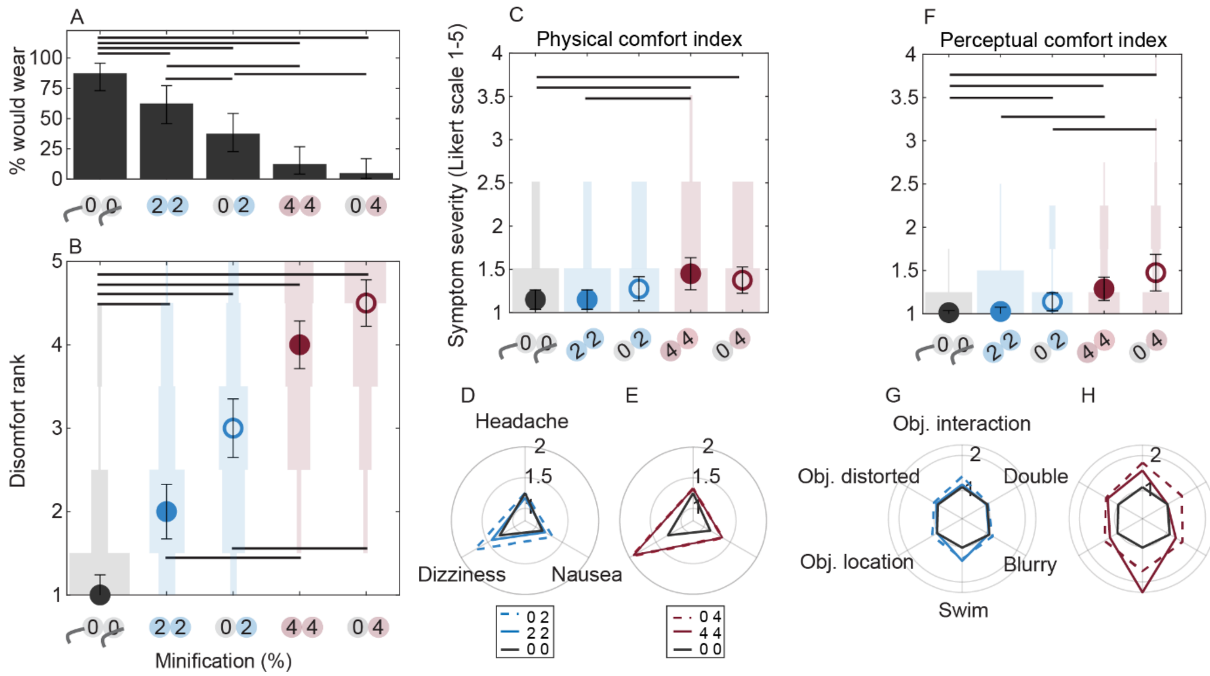

Figure 1.4. Results from the naturalistic task. Black horizontal lines in all plots represent statistically significant differences. (A) The percent of participants who indicated that they would wear the lenses on a regular basis. The error bars are the 95% binomial confidence intervals. (B) Overall 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 1.2 and Supplementary Table 1.S1.

A.

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**

B.

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

C.

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

D.

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 1.2. Pairwise comparisons from the naturalistic task. Statistically significant *p* values are bolded and supplementary values are provided in Table 1.S1. (A) 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. (B) 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. (C) Analysis performed on the physical comfort index in the same way as Table 1.2B. (D) Analysis performed on the perceptual symptom index in the same way as in Table 1.2B.

1.6.2 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 (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 1.4C–E, Table 1.2C). For perceptual discomfort, all but the 2% binocular minifiers were associated with greater symptoms relative to the control (Figures 1.4F–H, Table 1.2D). As expected, there were no significant differences between the lenses for 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 1.4D, 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 1.3A). 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 1.3B). 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.

A.

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**

B.

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

Table 1.3. Post-hoc analysis of individual perceptual symptoms experienced during the naturalistic task. Statistically significant p values are bolded. (A) Results of Wilcoxon sign-rank tests with *V*, corrected *p* values, and *r* as a measure of effect size. 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. (B) 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.

1.6.3 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 yes to this question varied between lenses ($X^2(4) = 60.69$, $p < 0.001$) (Figure 1.5A, Table 1.4A). 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 1.5B, Table 1.4B), the responses again differed across minification conditions ($X^2(4) = 62.95$, $p < 0.001$). The greater minification (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 $6.18° \pm 2.79°$. Furthermore, the motion experienced in the minification conditions was close to the geometric expectations depicted in Figure 1.5C, but due to response variability some of these differences were not statistically significant (Table 1.4C). The motion score results (Figure 1.5D, Table 1.4D) 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.

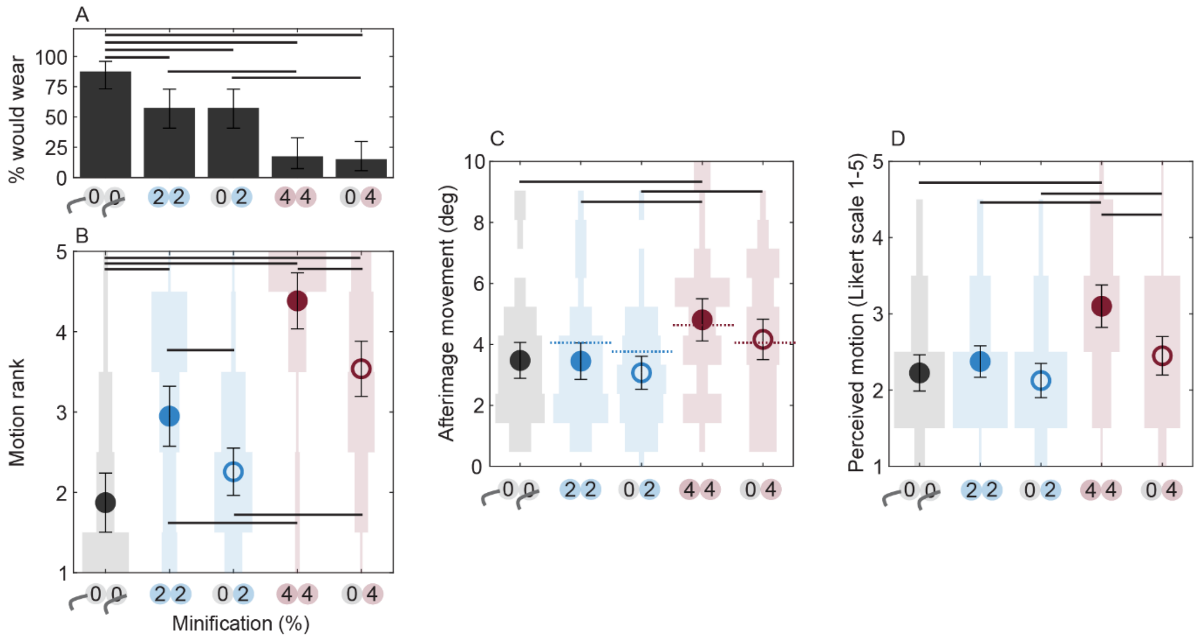

Figure 1.5. Results from the oscillopsia session. Black horizontal lines in all plots represent statistically significant differences. (A) The percent of participants who indicated that they would wear the lenses on a regular basis. The error bars are the 95% binomial confidence intervals. (B) The overall 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 1.4 and Supplementary Table 1.S2.

A.

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**

B.

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**

C.

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**

D.

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 1.4. Pairwise comparisons from the oscillopsia session. Statistically significant p values are bolded and Supplementary values provided in Supplementary Table 1.S2. (A) 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. (B) Results of Wilcoxon sign-rank tests performed on the motion rankings with V, corrected p values, and r as a measure of effect size. (C) Range of afterimage motion. Results of a t-test, corrected p values, and Cohan's d as a measure of effect size. Analysis performed on the afterimage motion score performed in the same

manner as in Table 1.4B. Statistically significant *p* values are bolded. (D) Analysis performed on the afterimage motion score performed in the same manner as in Table 1.4B.

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 1.6A and 1.6B, Tables 1.5A and 1.5B).

Overall, the physical discomfort experienced by participants in this session was mild (Figures 1.6C–1.6G, Tables 1.5C–1.5G). 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 ($X^2(4) = 13.84$, $p = 0.007$).

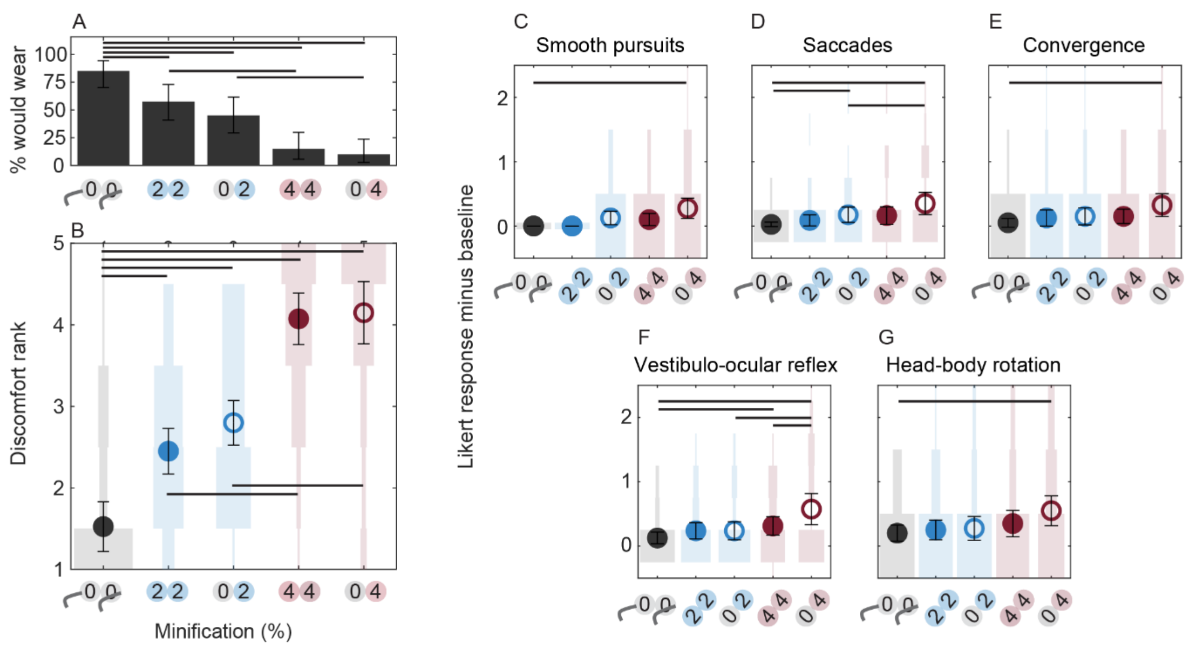

Figure 1.6. Results from the controlled head and eye movement session. Black horizontal lines in all plots represent statistically significant differences. (A) The percent of participants who indicated that they would wear the lenses on a regular basis. The error bars are the 95% binomial confidence 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 1.5 and Supplementary Table 1.S3.

A.

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**

B.

Comparison	*V*	*p*	*r*
00 and 22	**189.0**	**0.003**	**0.48**
00 and 02	**104.0**	**< 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**

C.

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

D.

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**

E.

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

F.

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**

G.

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 1.5. Pairwise comparisons from the controlled head and eye movement session. Statistically significant *p* values are bolded and supplementary values provided in Supplementary Table 1.S3 (A) Results of McNemar tests of significance (X^2), corrected *p* values, and the odds ratio as a measure of effect size. (B) Results of Wilcoxon sign-rank tests on the discomfort rankings with *V*, corrected *p* values, and *r* as a measure of effect size. (C) Analysis of the smooth pursuit physical comfort index reported in the same manner as in Table 1.5B. "N/A" indicates that both minification conditions compared were identical and, consequently, a Wilcoxon could not be run. (D) Analysis of the saccades physical comfort index reported in the same manner as in Table 1.5B. (E) Analysis of the convergence physical comfort index reported in the same manner as in Table 1.5B. (F) Analysis of the vestibulo-ocular reflex physical comfort index reported in the same manner as in Table 1.5B. (G) Analysis of the full body rotation physical comfort index reported in the same manner as in Table 1.5B.

1.6.4 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 1.4D, 1.4E), 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 1.6). 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 1.7. Consequently, these results suggest that dizziness increased with fast head movements compared to body fixed eye movements.

Post-hoc analysis of dizziness from controlled head and eye movement session

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 1.6. 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.

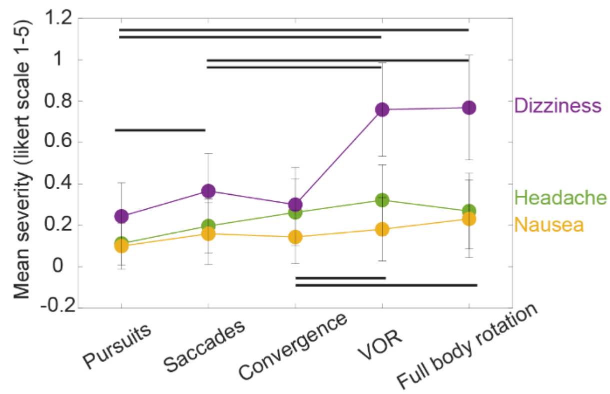

Figure 1.7. Post-hoc analysis of dizziness from controlled head and eye movement session. Markers represent mean headache, dizziness, and nausea across lenses (excluding 0% lenses). Black lines indicate significant differences in dizziness between the movements reported in Table 1.6. The error bars represent the 95% confidence intervals. The head and eye movements are listed in the order that they were performed.

1.6.5 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 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 1.8A, Table 1.7A). 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 1.4B).

We next investigated phoria as evidence of fusional demand produced by the minification. Initial phoria was quantified as the difference between phoria 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 1.7B). All gaze positions (straight, right, left, up, down) were measured for both horizontal and vertical phoria, but Figure 1.8 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 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 1.7C). Overall, there was little evidence of phoria adaptation in any 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.

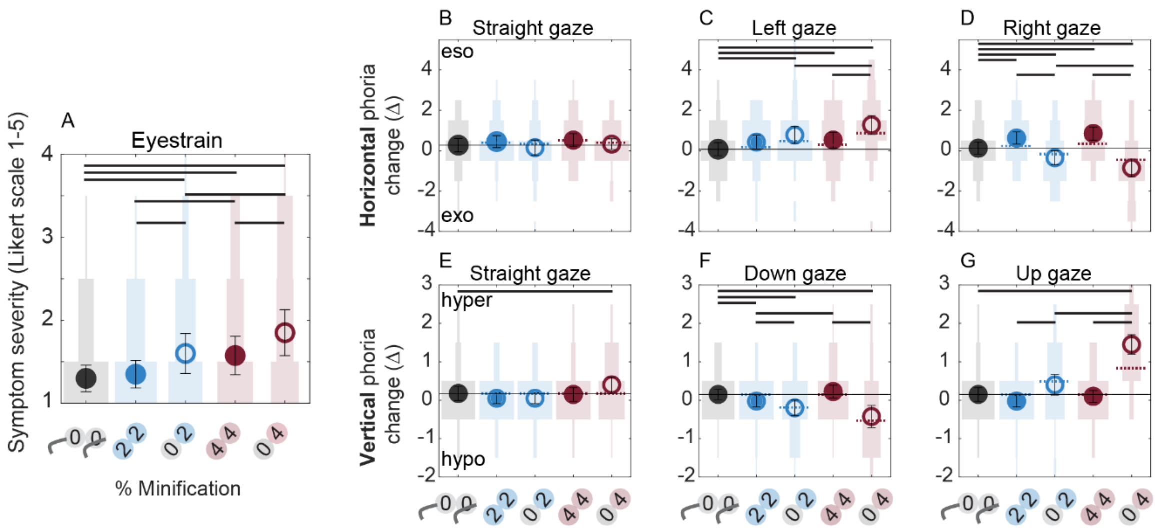

Figure 1.8. Eyestrain and phoria. Black horizontal lines in all plots represent statistically significant differences. (**A**) Eyestrain measured after the naturalistic task. Circles and error bars indicate means and 95% confidence intervals. The open circles are the monocular minifiers and the closed 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 1.7A and Supplementary Table 1.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 1.7 and Supplementary Table 1.S5.

A.

Comparison	*V*	*p*	*r*
00 and 22	18.00	0.608	0.081
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**

B.

	Horizontal		*Vertical*	
	F(4,4)	*p*	*F(4,4)*	*p*
Main effect of lenses	**8.16**	**<0.001**	**17.28**	**<0.001**
Main effect of gaze	**7.89**	**<0.001**	**18.59**	**<0.001**
Interaction	**6.35**	**<0.001**	**11.71**	**<0.001**

C.

	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 1.7. Eye strain and phoria results. (A) Wilcoxon sign-rank tests with V, corrected p values, and r as a measure of effect size. Supplementary values provided in Table 1.S5. (B) Two-way ANOVA of the initial horizontal and vertical phoria with the F value and p reported. (C) Two-way ANOVA of the adaptation to horizontal and vertical phoria reported in the same way as B. Supplementary values provided in Table 1.S6. (D) Eye strain and phoria results. Two-way ANOVA on the adaptation to horizontal and vertical phoria reported in the same way as in Table 1.7B.

1.7 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.

1.7.1 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 1.5). 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.[21,29,30] 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.

1.7.2 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 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.

1.7.3 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.[31–34] 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 1.9 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 (pm) and binocular image size distortion (pb) as a function of retinal image size distortion (M) are as follows:

$$P_b = \begin{cases} 17.50M + 87.50, if\ M < 0 \\ -17.50M + 87.50, if\ M > 0 \end{cases} \qquad \text{Equation 1.2}$$

$$P_b = \begin{cases} 21.50M + 87.50, if\ M < 0 \\ -21.50M + 87.50, if\ M > 0 \end{cases} \qquad \text{Equation 1.3}$$

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.

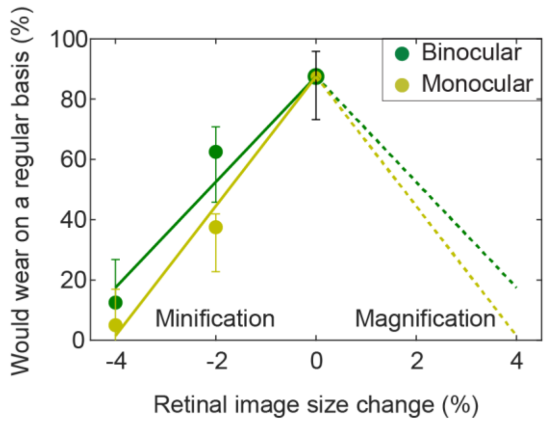

Figure 1.9. Estimated distortion tolerance based on responses to "would you wear the lenses on a regular basis" (which is about 5 hours a day) from the naturalistic session. The lines are regression lines for binocular (dark green) and monocular (light green) minification. Error bars and circles depict the percentages across all participants and the associated 95% binomial confidence intervals. Dashed lines indicate extrapolated tolerance levels for magnification.

1.7.4 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.[63] Regardless, investigating predictors of individual differences stands out as a potentially impactful direction for future investigation

1.7.5 Short-term and long-term comfort

Initial comfort may determine future use of a given optical device 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.[29,64,65] 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.[12] 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 also differ depending on whether the device is worn continuously or across intermittent periods.[15,18,66] Understanding the adaptation of phenomena that underlie dominant symptoms like eyestrain, swim, and dizziness could be a fruitful way to investigate the long-term effects of optical distortions.

1.7.6 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.[2] 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.[10,67] While 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.

1.7.7 Conclusions

Wearable optics are an essential part of providing visual clarity and supporting immersive entertainment and training in AR/VR devices. This study provides a valuable foundation for the design and manufacturing of optical components for AR/VR devices and may help improve outcomes for spectacle wearers. Future investigations should consider exploring how individual differences may influence comfort and the longer-term effects of minification.

1.8 Acknowledgements

Thank you to Dylan Fox for his help scheduling and recruiting participants and to Emily Cooper of Cooperhawk Illustrations for her contributions to the graphics in this paper.

1.9 Supplementary material

1.9.1 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 1.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:

$$r_d = r + kr^3 \quad \text{Equation 1.S1}$$

The best fit k value tended to be quite small (for example, 3.21×10^9 for one of the 2% lenses and 7.4×10^9 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.[24,25,68] 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.

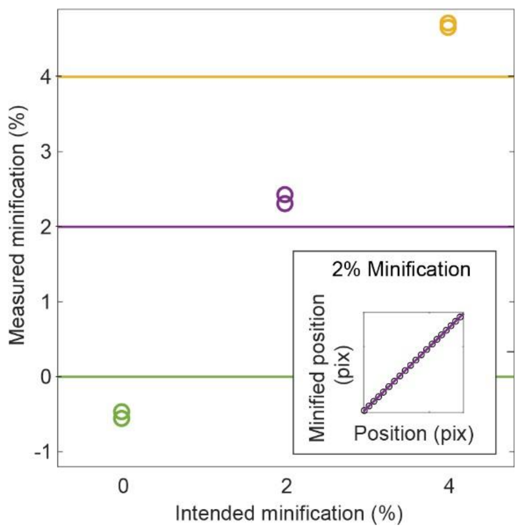

Figure 1.S1. Measured minification from six lenses. The inset figure depicts an example of the process of quantifying minification in one lens. The x and y axis range from 0 to 2000 pixels. The black circles are the horizontal position of the original and minified grid points in the photographs (the 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.

1.9.2 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 1.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 1.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 1.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 1.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								
	Straight gaze			*Leftward gaze*			*Rightward gaze*		
Min	*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
22	0.45	0.00	0.30	0.43	0.50	0.34	0.63	1.00	0.30
02	0.15	0.00	0.38	0.78	1.00	0.42	-0.35	-0.50	0.35
44	0.53	0.00	0.31	0.53	1.00	0.38	0.85	1.00	0.33
04	0.33	0.00	0.27	1.28	1.00	0.47	-0.85	-1.00	0.44

	Vertical Phoria								
	Strait gaze			*Downward gaze*			*Upward gaze*		
Min	*M*	*Mdn*	*CI*	*M*	*Mdn*	*CI*	*M*	*Mdn*	*CI*
00	0.18	0.00	0.18	0.15	0.00	0.13	0.15	0.00	0.18
22	0.05	0.00	0.14	-0.03	0.00	0.15	-0.03	0.00	0.15
02	0.05	0.00	0.14	-0.20	0.00	0.20	0.40	0.00	0.27
44	0.15	0.00	0.18	0.23	0.00	0.16	0.10	0.00	0.15
04	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								
	Straight gaze			*Leftward gaze*			*Rightward gaze*		
Compare	*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**
00 & 02	0.70	0.635	-0.11	**-3.75**	**0.002**	**0.59**	**2.28**	**0.033**	**-0.45**
00 & 44	-0.50	0.380	0.24	**-2.52**	**0.026**	**0.40**	**-5.41**	**<0.001**	**0.73**
00 & 04	-0.31	0.762	0.05	**-6.43**	**<0.001**	**0.94**	**4.39**	**<0.001**	**-0.81**
22 & 02	1.74	0.380	0.28	-1.71	0.108	-0.29	**5.10**	**<0.001**	**0.93**
44 & 04	1.54	0.380	0.22	**-3.91**	**0.001**	**-0.55**	**7.06**	**<0.001**	**1.38**
22 & 44	-0.60	0.635	0.08	-0.63	0.534	0.09	-1.60	0.118	0.22
02 & 04	-1.07	0.466	0.17	**-2.79**	**0.016**	**0.35**	**2.30**	**0.033**	**-0.39**

	Vertical Phoria								
	Strait gaze			*Downward gaze*			*Upward gaze*		
Compare	*t*	*p*	*d*	*t*	*p*	*d*	*t*	*p*	*d*
00 & 22	1.96	0.119	-0.24	**2.21**	**0.044**	**-0.39**	1.86	0.093	-0.33
00 & 02	1.71	0.154	-0.24	**3.58**	**0.002**	**-0.65**	-1.96	0.092	0.34
00 & 44	0.30	0.877	-0.04	-1.00	0.323	0.16	0.50	0.623	-0.09
00 & 04	-1.94	0.119	0.37	**4.16**	**0.001**	**-0.80**	**-9.63**	**<0.001**	**1.86**
22 & 02	0.00	1.000	N/A	**2.21**	**0.044**	**0.31**	**-3.98**	**0.001**	**-0.61**
44 & 04	-2.51	0.066	-0.42	**4.60**	**<0.001**	**0.87**	**-9.00**	**<0.001**	**-2.03**
22 & 44	-1.16	0.337	0.20	**-3.61**	**0.002**	**0.50**	-1.40	0.192	0.26
02 & 04	**-3.82**	**0.004**	**0.65**	1.78	0.095	-0.28	**-6.26**	**<0.001**	**1.26**

Table 1.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.

2 CHAPTER 2

Perceptual adaptation to continuous versus intermittent exposure to spatial distortions

2.1 Abstract

Purpose: To examine perceptual adaptation when people wear spectacles that produce unequal retinal image magnification.

Methods: Two groups of 15 participants (10 male; mean age 25.6 ± 4.9 years) wore spectacles with a 3.8% horizontal magnifier over one eye. The continuous-wear group wore the spectacles for 5 hours straight. The intermittent-wear group wore them for five 1-hour intervals. To measure slant and shape distortions produced by the spectacles, participants adjusted visual stimuli until they appeared frontoparallel or equiangular, respectively. Adaptation was quantified as the difference in responses at the beginning and end of wearing the spectacles. Aftereffects were quantified as the difference before and after removing the spectacles. We hypothesized that intermittent wear may lead to visual cue reweighting, so we fit a cue combination model to the data and examined changes in weights given to perspective and binocular disparity slant cues.

Results: Both groups experienced significant shape adaptation and aftereffects. The continuous-wear group underwent significant slant adaptation and the intermittent group did not, but there was no significant difference between groups, suggesting that the difference in adaptation was negligible. There was no evidence for cue reweighting in the intermittent wear group, but unexpectedly, the weight given to binocular disparity cues for slant increased significantly in the continuous-wear group.

Conclusions: We did not find strong evidence that adaptation to spatial distortions differed between the two groups. However, there may be differences in the cue weighting strategies employed when spectacles are worn intermittently or continuously.

2.2 Introduction

Prescription spectacles make vision clearer, but they can also produce spatial distortions that change the apparent shape, depth, and speed of objects in the world.[3,4,12,26,41,43,44,47,69–71] While spectacle wearers might initially experience discomfort from these distortions, they often report becoming used to them over time and can even switch seamlessly between having their spectacles on and off.[5,7,72,73]

Previous research has examined how the visual system adapts to continuous exposure to spatial distortions.[12,37,69,74–76] However, there has been much less investigation of adaptation when spectacles are taken off and on throughout the day.[13] On one hand, intermittent exposure might disrupt continuous processes required to maintain adaptation. However, research suggests that it may also drive some types of adaptation.[13,15] For example, intermittent exposure to altered colors has been associated with strong color adaptation across days,[15] and intermittent visuomotor disruptions are well known to drive motor adaptation (i.e., savings or context-specific adaptation).[77–80] Intermittent exposure may result in nontraditional forms of adaptation such as cue reweighting, with multiple exposures leading the visual system to reinterpret the trustworthiness or reliability of cues.[16,17,81–85] Indeed, intermittent and continuous adaptation pose different challenges to the visual system that may necessitate different mechanisms of adaptation.

We investigated continuous and intermittent adaptation to a monocular horizontal magnifying lens that simulates spatial distortions present in some prescription spectacles. The difference in retinal image size between the eyes creates a slant distortion called the "geometric effect," which has been well studied (Figure. 2.1A).[3,4,12,70,86] It also produces a change in perceived shape, but this is not as well understood (Figure 2.1B).[3,26,70,86] Figure 2.1C provides a free-fusible stereo pair to demonstrate these perceptual effects.

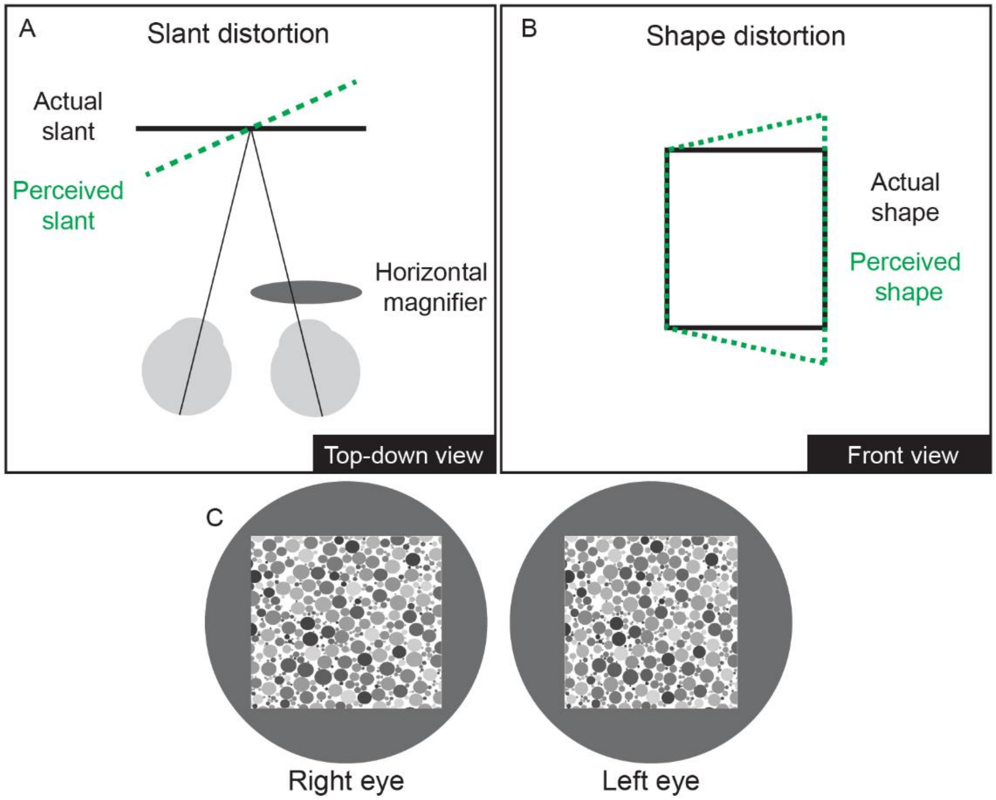

Figure 2.1. Spectacles that produce monocular horizontal magnification cause two perceptual distortions. (A) Surfaces appear to be slanted away from the magnified eye. (B) Surfaces appear taller on the side closer to the magnified eye. It should be noted that it may also be possible to perceive the left side as shorter relative to the original shape. (C) Free-fusible stereo pair with one image horizontally magnified by 10%. If this stimulus is cross-fused, it should result the in percept illustrated in panels A and B. If it is divergently fused, the percept will be reversed.

2.3 Methods

2.3.1 Participants

A power analysis was performed based on pilot data and prior literature. We aimed for a statistical power of ~0.8 for comparing the means to two independent samples with an effect size of 1 (n = 17). Given challenges for recruitment during the COVID-19 pandemic, we reduced the target sample size for each group to 15 prior to starting data collection. Criteria for participation included being at least 18 years old, binocular 20/20 vision (contact lenses okay), and stereoacuity of at least 50 arc seconds (Randot test). Participants who met these criteria were screened in a practice session in which they performed the slant adjustment task (procedure below) and were excluded if their responses had a standard deviation greater than 7° after practice completion (n = 13). A total of 33 participants completed the main experiment, of whom three were excluded after debriefing questions revealed that they performed the experimental tasks or procedure incorrectly. The final sample size constituted 30 participants (15 per group; continuous-wear group, mean age = 25.8 ± 6.5 years, 5 male; intermittent- wear group, mean age = 25.5 ± 2.5 years, 5 male). Upon completing the main experiment, we added a control group that only underwent a short period of adaptation (1 hour, n = 15, mean age = 25.1 ± 4.2 years, 3 male). The participants met the same criteria described above. The study was approved by the

University of California, Berkeley Institutional Review Board. Informed consent was obtained, and participants were compensated for their time.

2.3.2 Spectacles

Participants wore spectacles with a horizontal magnifier (also known as a meridional size lens) over the right eye and a plano lens over the left eye (Figure 2.2).[12] These spectacles have no power and make the right eye's retinal image 3.8% wider than the left eye's image, approximately the amount of magnification produced by a lens correcting 4 D of 0 axis astigmatism at a 10-mm vertex distance.[2] This monocular horizontal magnification changes the binocular disparity gradient and produces a perceived slant away from the magnified eye even though perspective cues for slant are unchanged (Figure 2.1A).[3,4,12,70] We can describe how the magnification corresponds to slant as follows:[3,12,26]

$$S_d = tan^{-1}\left(\frac{M-1}{M+1} * \frac{2z}{a}\right). \qquad \text{Equation 2.1}$$

Here, S_d is the slant indicated by binocular disparity, $z$is the distance to the stimulus, M is the magnification, and a is the interpupillary distance (IPD). For this experiment, S_d is 9.8° with M equal to 1.038, z equal to 29.3 cm (the approximate viewing distance to the visual stimuli), and a equal to 6.3 cm. This means that a frontoparallel plane viewed through the spectacles will produce a disparity gradient consistent with a plane that is slanted 9.8° away from the magnified eye. To remove this disparity gradient, the plane would need to be slanted 9.8° in the opposite direction. Here, we use the sign convention of positive slants away from the right eye (in this case, the magnified eye) and negative slants toward.

Monocular horizontal magnification also makes rectangles appear as trapezoids (Figure 2.1B).[3,26,70,86] This shape distortion is not well understood but likely results from how the visual system combines retinal shape and binocular disparity cues to infer object shape and slant in the world. For example, when viewing a frontoparallel rectangular object, binocular disparity will indicate that the surface is slanted (Figure 2.1A), while the image of the object on the retina remains a rectangle. Consequently, the visual system infers that the object is a trapezoid, which can produce a rectangular image when slanted. The slant and shape distortions are sometimes perceived together and sometimes alone.

The fit of the spectacles, such as the vertex distance and the IPD of the participant, will change the magnification of the spectacles and, therefore, the slant distortion. We had two spectacle frame sizes, but beyond that, we did not customize fit. We assumed that the effects of fit were small relative to the overall distortions.

Figure 2.2 Experimental spectacles with a horizontal magnifier over the right eye.

2.3.3 Apparatus

Visual stimuli were presented on a VIEWPixx 3D (LCD panel with LED backlight) with a screen resolution of 1920 × 1080 pixels, a refresh rate of 120 Hz, a pixel pitch of 0.27 mm (subtending 0.053 visual angle), and a maximum luminance of approximately 100 cd/m2 (VPixx Technologies, Montreal, Canada). Stereoscopic images were presented with a 3DPixx shutter glasses system (Nvidia, Santa Clara, CA, USA). During the experiment, the participant sat in a dark room in a chinrest approximately 29.3 cm from the display with their eyes aligned with the center. Irregularly shaped pieces of black paper were placed along the edges of the display so that participants could not use the edges of the display as a reference. All stimuli were presented using Psychtoolbox (version 3.0.15) and OpenGL in MATLAB (MATLAB R2019b; The MathWorks, Natick, MA, USA).36,37

2.3.4 Slant task

This task identified the initial slant distortion, adaptation, and aftereffects. The stimuli isolated different cues for slant (binocular disparity and perspective) to determine which cues were responsible for changes in the perceived slant. The task was also used to quantify changes in the weight given to each cue.

2.3.4.1 Task

Participants fixated a red dot (0.4° diameter) while using the arrow keys to adjust the slant of the stimulus around a vertical axis until it appeared frontoparallel. Each stimulus was composed of white dots (100% maximum luminance) against a dark gray background (2% maximum luminance to reduce crosstalk). Thirty trials of each of the three stimulus types were interleaved. On each trial, the initial slant of the stimulus was randomized and the maximum and minimum slants were jittered so that the center of the adjustable range was not frontoparallel.

2.3.4.2 Disparity-only stimulus

Binocular disparity cues for slant were isolated by generating a binocular dynamic random dot cloud of a planar surface with a maximum diameter of 16° (Figure 2.3A). To remove perspective cues for slant, the shape and dot density did not change with slant, using the method described in Hillis et al.[16] Dot diameter was set such that each dot subtended 0.05° within the range of typical stimulus slant adjustments (although small differences in angular dot size could occur if participants adjusted a stimulus to an extreme angle). To further decrease the likelihood that participants would rely on perspective cues for slant, the dot density tapered off toward the edges of the stimulus, with 0.25 dots/deg^2 in the central 8° diameter and 0.04 dots/deg^2 elsewhere.

2.3.4.3 Perspective-only stimulus

Perspective cues for slant (perspective convergence, texture density, and foreshortening) were isolated by generating a monocular dot grid (13 by 13 dots subtending 16° × 16° when frontoparallel with a dot density of 0.66 dots/deg^2; Figure 2.3B). The x and y positions of the dots were jittered slightly to reduce the reliability of the perspective cues, as in natural situations in which objects do not have perfectly regular textures. Dots were rendered at the same size as the disparity-only condition, such that cues from changes in dot size were unavailable and matched across conditions. The stimulus was presented only to the left eye (the eye without the magnifier) to remove cues for binocular disparity. To minimize cues from motion, the stimulus disappeared each time the participant pressed the keys.

2.3.4.4 Dual-cue stimulus

The same dot grid described above was presented binocularly so that perspective and binocular disparity cues for slant were present (Figure 2.3C). The jittered dot grid reduced the reliability of the perspective cues ensuring that both binocular disparity and perspective contributed to the dual-cue percept.

2.3.5 Shape Task

This task was used to quantify the initial shape distortion, adaptation, and aftereffects (Figure 2.1B). A binocular frontoparallel black quadrilateral (0.9% luminance) on a gray background (2% maximum luminance) was presented (16° by 16° when adjusted into a square; Figure 2.3D). This stimulus had minimal disparity cues across the surface of the shape, but disparity cues were present at the edges. Participants used key presses to independently adjust the y coordinates of the top right and bottom right corners until it appeared square. The task was repeated for 10 trials. The initial positions of the corners and adjustment range varied on each trial as described for the slant task.

2.3.6 Procedure

As depicted in Figure 2.4, the slant task and the shape task were performed in sequence and constituted one measurement. All groups performed two measurements (pretest, start of adaptation), wore the experimental spectacles during their daily activities, and then performed another two measurements (end of adaptation, posttest). Participants were encouraged to diversify their visual experiences while wearing the spectacles. A debriefing questionnaire was given at the end of the study to verify that participants performed the experimental tasks and procedure correctly.

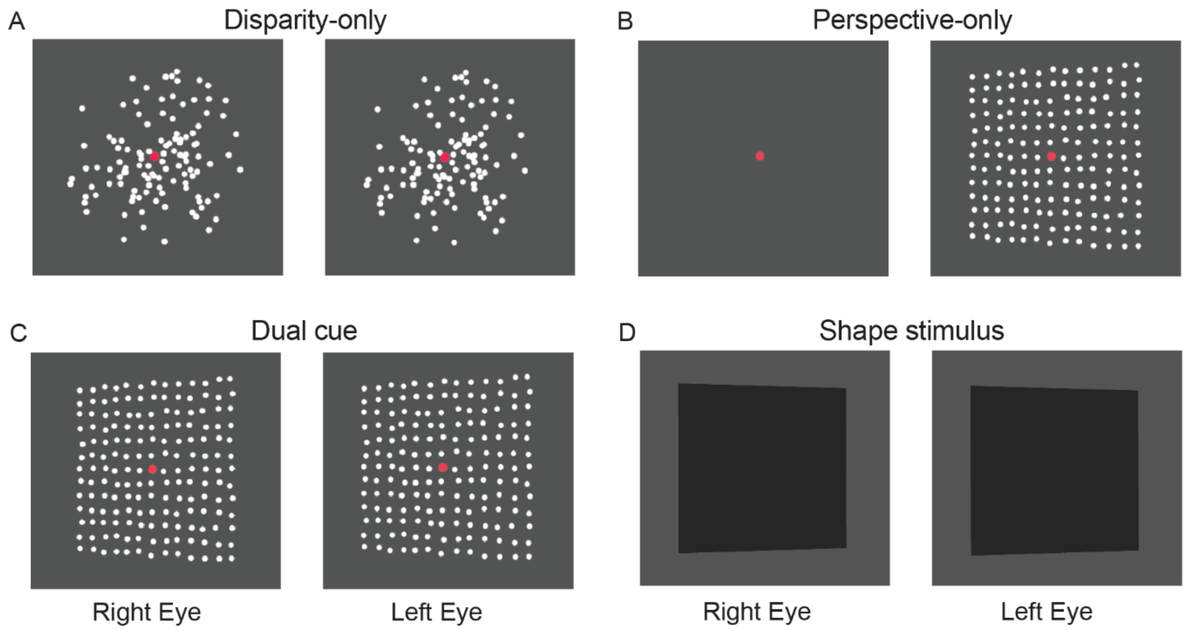

Figure 2.3. Schematics of stimuli presented during the slant task (A–C) and the shape task (D). Dot size, dot density, and luminance values are adjusted for visibility.

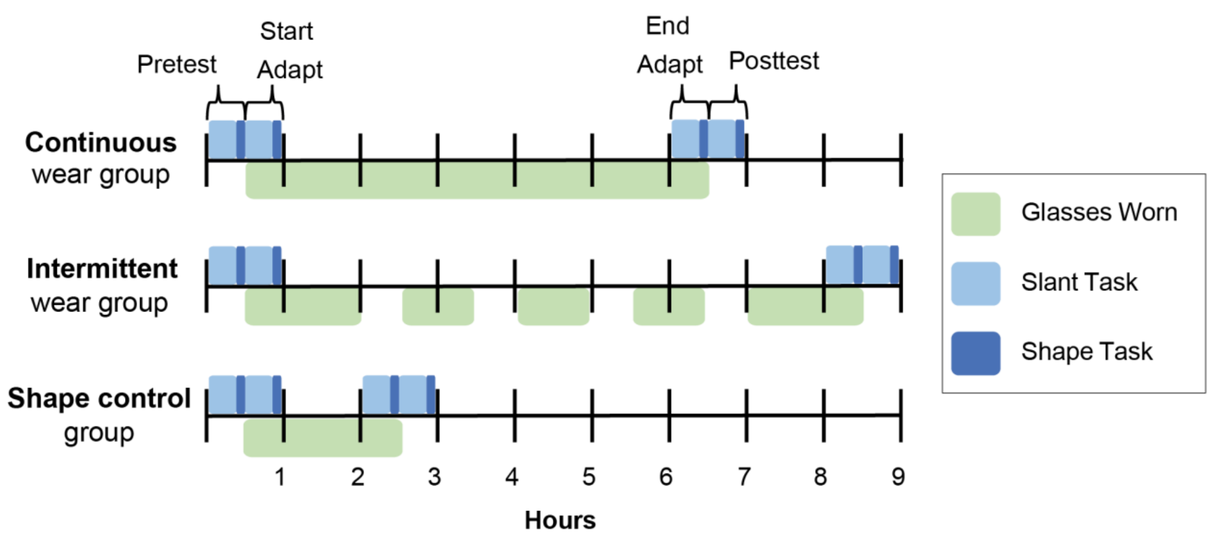

Figure 2.4. Procedure for the continuous, intermittent, and shape control groups. Four measurements (pretest, start and end of adaptation, and posttest) were taken for all groups. Participants went about their daily activities while wearing the spectacles.

2.3.7 Groups

2.3.7.1 Continuous-wear group

Participants were instructed to wear the spectacles continuously for 5 hours during their daily activities. They were encouraged to keep the spectacles on, but if necessary, they were allowed to remove the spectacles twice for no more than a total of 30 minutes. The spectacles could not be removed 2 hours prior to the "end of adaptation" measurement.

2.3.7.2 Intermittent-wear group

Participants were instructed to wear the experimental spectacles for a total of 5 hours with 20- to 30-minute breaks in between each hour. The schedule for taking the spectacles off and on was drawn on a calendar template that the participant used as a reference throughout the day.

2.3.7.3 Shape control group

After seeing that both the continuous- and intermittent-wear groups experienced significant shape adaptation in the main experiment, we were curious whether this effect could be explained by rapid shape adaptation in the last hour of spectacle wear. We thus recruited a control group who wore the spectacles for only 1 hour continuously during their daily activities and performed the same tasks as the other groups. The hour of wearing the spectacles was always directly followed by the end of adaptation and posttest measurements. The pretest and start of adaptation measurements were sometimes performed a few hours before the adaptation period.

2.3.8 Analysis

For every measurement in each condition, outliers that were more than three scaled maximum absolute deviations from the median were removed from the data. For all statistical analyses, we then used one-sample t-tests to ask whether each dependent variable differed significantly from zero. We conducted independent samples t-tests to examine differences between groups. In addition to t-statistics, degrees of freedom, and P-values, we report the mean (M), standard deviation, and effect sizes (quantified using Cohen's d) for each comparison.

2.3.8.1 Difference scores

Changes in slant and shape perception were quantified for each participant using difference scores (Figure 2.5). The difference between the pretest and the start of adaptation quantified the initial slant distortion when the glasses were put on. The difference between start and end of adaptation captured the magnitude of perceptual adaptation while wearing the glasses. The difference between the pretest and posttest quantified the after-effect caused by the spectacles. Shape judgments were quantified as the ratio of the height of the right side of the quadrilateral to the left side. Ratio differences greater than 0 indicate that the height of the right side decreased between measurements, and differences less than 0 indicate that the height of the right side increased between measurements.

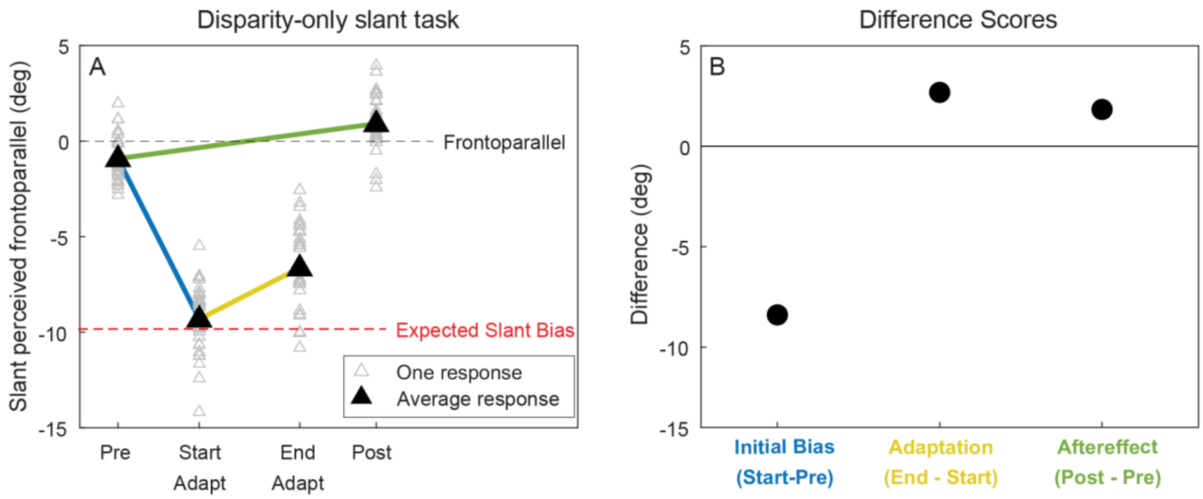

Figure 2.5. Example of how slant judgments are converted into difference scores for one participant. (A) Each slant judgment trial (gray triangle) and the average (filled black triangle) for the four measurements are shown for this participant. Lines connect pairs of averages that are subtracted to create each difference score. (B) The three resulting difference scores: initial distortion (blue), adaptation (yellow), and aftereffect (green).

2.3.8.2 Perspective-only slant correction

The monocular frontoparallel judgments in the perspective-only condition were corrected before analysis. Consistent with prior work, participants viewing a monocular stimulus systematically reported the apparent frontoparallel plane to be slanted toward the viewing eye. This indicates that participants used their viewing eye, instead of the cyclopean eye, as a reference for frontoparallel. To correct for this, we redefined frontoparallel (zero slant) for this condition as the surface orientation orthogonal to the visual axis of the participants' left eye, as described in previous literature.[16]

2.3.8.3 Weight calculation

We used the slant task data to calculate the relative weight that each participant gave to the disparity and perspective cues at each measurement time, based on a cue combination model.[12,16,87] The details of our model and weight calculations are described in the Appendix. Weights were only calculated for the start and end of adaptation measurements. This is because the weight calculation requires perspective and disparity cues to conflict, which only occurs when the spectacles are being worn. Participants whose data did not fit the model were excluded from this analysis (four from the continuous group and two from the intermittent group).

2.4 Results

2.4.1 Initial slant distortion caused by spectacles

As expected, the spectacles did not produce an initial change in the perceived slant of the perspective-only stimulus for either group (Figure 2.6A; $M_{cont} = -0.65° \pm 2.03°$, $t(14) = -1.24$, $p = 0.237$, $d = -0.32$; $M_{inter} = -0.79° \pm 1.58°$, $t(14) = -1.93$, $p = 0.074$, $d = -0.50$). This confirms that the horizontal magnifier does not change monocular cues for slant. Consistent with previous literature, both groups experienced a significant change in perceived slant of the disparity-only stimulus (Figure 2.6B; $M_{cont} = -8.35° \pm 1.90°$, $t(14) = -17.02$, $p < 0.001$, $d = -4.39$; $M_{inter} = -8.87° \pm 1.80°$, $t(14) = -19.08$, $p < 0.001$, $d = -4.92$). It is notable that in both groups, the slant required for the stimulus to appear frontoparallel was smaller in magnitude than the geometric disparity distortion (9.8°; red arrow). This difference was significant for the continuous group ($t(14) = 3.01$, $p = 0.009$) but not the intermittent group ($t(14) = 2.07$, $p = 0.058$). Both groups also experienced a significant change in perceived slant when viewing the dual-cue stimulus (Figure 2.6C; $M_{cont} = -3.68° \pm 3.80°$, $t(14) = -3.76$, $p = 0.002$, $d = -0.97$; $M_{inter} = -4.94° \pm 2.27°$, $t(14) = -8.43$, $p < 0.001$, $d = -2.18$). This is likely a result of participants partially relying on binocular disparity to make slant judgments when both cues were present. There were no significant differences between groups in any condition, which is expected since the two conditions were identical at this point (perspective only: $t(28) = 0.21$, $p = 0.833$, $d = 0.079$; disparity only: $t(28) = 0.76$, $p = 0.451$, $d = 0.28$; dual cue: $t(28) = 1.10$, $p = 0.279$, $d = 0.40$).

2.4.2 Slant adaptation from perspective

As expected, there was also no significant slant adaptation or aftereffect in either group for the perspective-only stimulus because the spectacles do not change perspective cues (Figure 2.6D, 6G; adaptation: $M_{cont} = 0.62° \pm 2.45°$, $t(14) = 0.97$, $p = 0.347$, $d = 0.25$; $M_{inter} = -0.47° \pm 2.32°$, $t(14) = -0.79$, $p = 0.444$, $d = -0.20$; between groups: $t(28) = 1.25$, $p = 0.222$, $d = 0.45$; aftereffects: $M_{cont} = -0.76° \pm 1.65°$, $t(14) = -1.78$, $p = 0.096$, $d = -0.46$; $M_{inter} = -0.62° \pm 1.87°$, $t(14) = -1.28$, $p = 0.221$, $d = 0.14$; between groups: $t(28) = -0.22$, $p = 0.825$, $d = -0.083$).

2.4.3 Slant adaptation from binocular disparity

We expected that the continuous-wear group would undergo some disparity adaptation. While the continuous group did adapt significantly (Figure 2.6E; $M_{cont} = 1.01° \pm 1.63°$, $t(14) = 2.39$, $p = 0.032$, $d = 0.62$) and the intermittent-wear group did not ($M_{inter} = 0.67° \pm 2.07°$, $t(14) = 1.25$, $p = 0.231$, $d = 0.32$), there was ultimately no significant difference between groups, and the effect size between groups was small ($t(28) = 0.50$, $p = 0.622$, $d = 0.18$). No comparisons were significant for the aftereffect measure (Figure 2.6H; $M_{cont} = 0.48° \pm 1.40°$, $t(14) = 1.34$, $p = 0.200$, $d = 0.35$; $M_{inter} = 0.21° \pm 1.51°$, $t(14) = 0.55$, $p = 0.593$, $d = 0.14$; between groups: $t(28) = 0.51$, $p = 0.613$, $d = 0.19$). In the dual cue condition, we did not observe any significant adaptation or aftereffects (Figure 2.6F, 2.6I; adaptation: $M_{cont} = -0.93° \pm 1.85°$, $t(14) = -1.94$, $p = 0.07$, $d = -0.50$; $M_{inter} = -0.72° \pm 3.20°$, $t(14) = -0.87$, $p = 0.397$, $d = -0.23$; between groups: $t(28) = -0.21$, $p = 0.834$, $d = -0.08$; aftereffects: $M_{cont} = 0.41° \pm 1.50°$, $t(14) = 1.07$, $p = 0.303$, $d = 0.28$; $M_{inter} = 0.19° \pm 1.61°$, $t(14) = 0.46$, $p = 0.651$, $d = 0.12$; between groups: $t(28) = 0.39$, $p = 0.700$, $d = 0.14$).

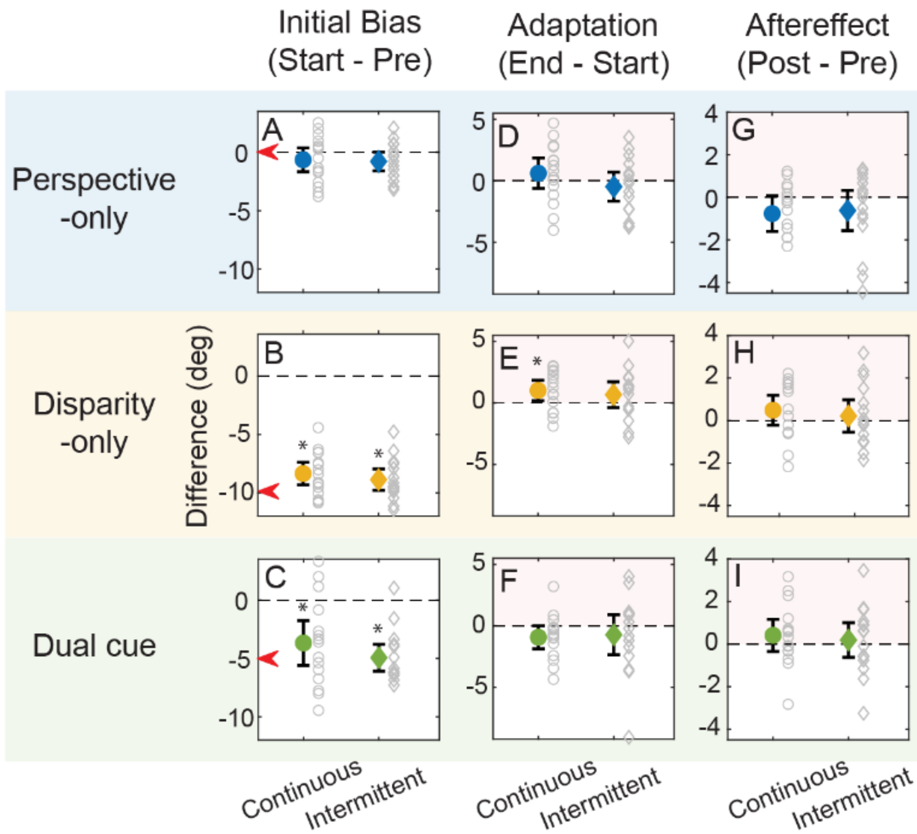

Figure 2.6. Results for the slant task. Initial slant distortion (A–C), adaptation (D–F), and aftereffects (G–I) for the continuous (Cont.) and intermittent (Inter.) groups are plotted as circles and diamonds, respectively. Each stimulus is plotted in a separate column. For the initial distortion plots, the red arrows indicate the expected initial slant distortion. For the dual-cue condition, this estimate is based on the assumption that the perspective and disparity weights are roughly equal. Filled markers indicate the average across participants (error bars are 95% confidence intervals) and individual participant data are plotted as open markers. Asterisks indicate statistically significant single sample t-tests. Red shaded regions indicate that adaptation and aftereffects would be reflected by positive values.

2.4.4 Reweighting of perspective and disparity cues for slant

We hypothesized that the intermittent-wear group might adapt to the slant distortion by downweighing disparity cues for slant (because they change as the spectacles are taken on and off) and upweighing perspective cues.[17,81,85,88] As depicted in Figure 2.7, we instead observed a significant change in weighting for the continuous-wear group, in which this group actually upweighted disparity ($M_{cont} = 0.23 \pm 0.23$, $t(10) = 3.36$, $p = 0.007$, $d = 1.01$). There was no significant change in weight for the intermittent group ($M_{inter} = 0.055 \pm 0.22$, $t(12) = 0.92$, $p = 0.378$, $d = 0.25$). The difference between the groups was marginally significant and the effect size was medium to large ($t(22) = -1.94$, $p = 0.065$, $d = 0.75$). These data suggest that even though the continuous-wear group was continuously experiencing a slant distortion from binocular disparity, they upweighted disparity after their time in the spectacles. We will consider potential explanations for this result in the Discussion.

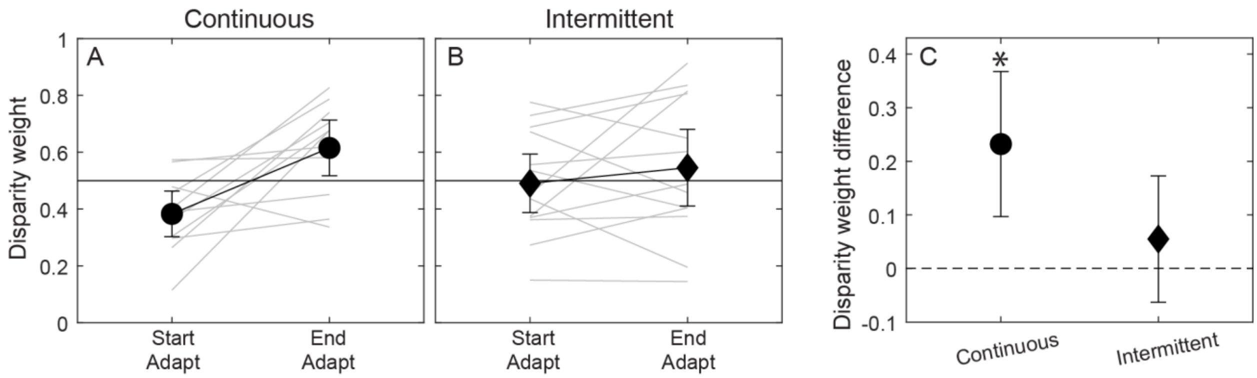

Figure 2.7. The average weight for binocular disparity in the start and end of adaptation measurements for the (A) continuous group (circles) and (B) intermittent group (diamonds). (C) For the continuous group, there was a significant change in disparity weight (end adapt – start adapt). Filled markers indicate the average across participants (error bars are 95% confidence intervals) and individual participant data are plotted as gray lines. Asterisks indicate statistically significant single sample t-tests.

2.4.5 Evidence for shape distortion in spectacles

As expected, both groups experienced a significant shape distortion upon putting on the spectacles (Figure 2.8A; $M_{cont} = -0.018 \pm 0.0084$, $t(14) = -8.30$, $p < 0.001$, $d = -2.14$; $M_{inter} = -0.024 \pm 0.0084$, $t(14) = -11.17$, $p < 0.001$, $d = -2.88$). This confirms that our novel method for measuring the shape distortion is effective at capturing the distortion produced by the spectacles. The average amount of shape distortion in both groups was generally consistent with the expected shape change due to the slant distortion (red arrow), but the magnitude was smaller. Unexpectedly, there was a small but significant difference between groups ($t(28) = 2.1$, $p = 0.047$, $d = 0.72$). It is unclear why the groups differ in initial distortion, since the procedures for the groups were identical for this measurement.

2.4.6 Shape adaptation

Both groups experienced significant shape adaptation (Figure 2.8B; $M_{cont} = 0.0042 \pm 0.0075$, $t(14) = 2.20$, $p = 0.046$, $d = 0.57$; $M_{inter} = 0.0059 \pm 0.0051$, $t(14) = 4.49$, $p < 0.001$, $d = 1.16$), and there was no significant difference between groups ($t(28) = -0.70$, $p = 0.489$, $d = -0.26$). Both groups also had a significant aftereffect (Figure 2.8C; $M_{cont} = 0.0060 \pm 0.0043$, $t(14) = 5.37$, $p < 0.001$, $d = 1.39$; $M_{inter} = 0.0057 \pm 0.0070$, $t(14) = 3.17$, $p = 0.0068$, $d = 0.82$), with no significant difference between groups ($t(28) = 0.11$, $p = 0.912$, $d = 0.041$).

2.4.7 Shape control group

Like the other groups, the control group experienced a significant initial change in perceived shape when the glasses were first put on ($M_{control} = -0.023 \pm 0.011$, $t(14) = -8.29$, $p < 0.001$, $d = -2.14$). Unlike the intermittent-wear group, the control group did not experience significant shape adaptation ($M_{control} = 0.0027 \pm 0.011$, $t(14) = 0.94$, $p = 0.361$, $d = 0.24$), but there was no significant difference between the intermittent and control groups ($t(28) = 0.99$, $p = 0.326$, $d = 0.37$). The control group did experience a significant aftereffect ($M_{control} = 0.0065 \pm 0.010$, $t(14) = 2.52$, $p = 0.025$, $d = 0.65$), which was not significantly different from the intermittent group ($t(28) = -0.25$, $p = 0.802$, $d = -0.094$). To ensure the control group had a similar experience to the continuous- and intermittent-wear groups, the control group also performed the slant tasks.

Across all other tasks performed by this group, we observed no significant adaptation effects, aftereffects, or cue reweighting.

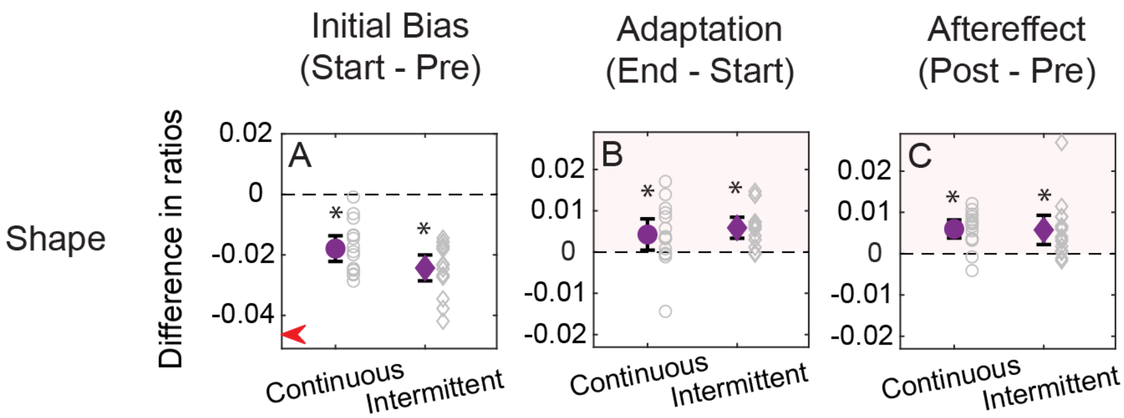

Figure 2.8. The average difference scores for the shape task. Initial distortion (A), adaptation (B), and aftereffects (C) for the continuous (Cont.) and intermittent (Inter.) groups are plotted in the same manner as Figure 2.6. The red arrow in A indicates the expected initial shape distortion, which was calculated based on the assumption that the shape in the world is inferred from the distorted slant indicated by binocular disparity and the shape of the retinal image. Note, however, that the binocular disparity slant cues were weaker in the shape stimulus which may explain why the initial distortion is less than predicted. Shaded regions indicate that adaptation and aftereffects would be reflected by positive values.

2.5 Discussion

These results have practical implications for new spectacle wearers and motivate future work in this domain. Below, we discuss three key insights: potential differences in continuous and intermittent adaptation to distortions, the importance of shape distortions, and individual differences in adaptability.

2.5.1 Differences in continuous and intermittent adaptation to distortions

Our results suggest that the continuous- and intermittent- wear groups differed in the reweighting of perspective and binocular disparity cues for slant. We initially hypothesized that the intermittent group would downweigh disparity cues. However, we found evidence that the continuous- wear group upweighted disparity cues. After 5 hours of continuous exposure to the spectacles, the continuous-wear group began relying on the distorted binocular disparity cues more than they did before the adaptation period. In other words, the continuous-wear group relied less on perspective cues. The change in weight might be explained by the salience of the shape distortion. For many participants, the shape distortion was more noticeable than the slant distortion during common tasks such as viewing a phone and computer screen. This persistent shape distortion could have caused the continuous-wear group to infer that perspective cues like shape are untrustworthy and to downweigh them. While this result may seem paradoxical if the shape distortion is caused by disparity cues, it is in line with previous work suggesting that in some circumstances, the shape distortion has a circular effect on perceived slant.[86] However, as noted in the Appendix, we must take caution with the conclusions we draw about reweighting because changes in calculated weights could reflect other perceptual processes not included in our cue combination model.

Some of our findings conflict with the results of Adams et al.,[12] who investigated 7 days of continuous exposure to a monocular horizontal magnifier and found no evidence for slant cue reweighting. These seemingly conflicting findings may reflect different stages of slant adaptation. For example, reweighting may only be present after shorter periods of continuous adaptation when the shape distortion is salient. Over time, continued reduction of the shape distortion may ultimately result in a restoration of the original cue weighting. Both studies report disparity adaptation, which likely results from a reinterpretation of retinal disparity that may increase monotonically over time.[69,89]

The notion that the frequency of distortion exposure may alter the type of adaptation could inform recommendations for new spectacle wearers (particularly those who experience unwanted distortions due to different lens powers between the two eyes). For example, if adaptation is more robust with continuous wear, new spectacle wearers may be instructed to wear their spectacles all day for the first few days. If intermittent adaptation proves to be advantageous, people could be instructed instead to initially remove their spectacles repeatedly throughout the day. The results of this study cannot yet directly specify new guidelines, but they provide a set of insights and a roadmap for future clinically oriented work. In particular, these results highlight that both adaptation and cue reweighting likely need to be taken into account to understand how people experience spectacle distortions over time.

2.5.2 Shape distortion

To our knowledge, this report is the first systematic investigation of the shape distortion produced by monocular horizontal magnification. As mentioned above, many participants indicated that the shape distortion was more salient than the slant distortion, suggesting that shape distortion may have greater clinical relevance. We hypothesize that the shape distortion is a result of inferences made from binocular disparity cues for slant and the retinal image of the object. In keeping with this hypothesis, the average initial shape distortion was consistent with (but smaller than) the distortion predicted geometrically from disparity-defined surface slant (Figure 2.8A). However, across participants, we did not find a significant correlation between the initial shape distortion and the initial slant distortion from disparity ($r = 0.25$, $p = 0.191$, both groups). Further, we did not observe a correlation between the slant and shape adaptation and after effects (adaptation: $r = 0.09$, $p = 0.644$; aftereffects: $r = -0.15$, $p = 0.422$). Even if the two perceptual phenomena have a common cause, it is not necessary that the perception of slant and shape is mutually consistent or that they adapt in the same way. Indeed, the results of our control group suggest that some amount of shape adaptation may occur quite rapidly. Our results, therefore, motivate a need to better understand how conscious visual percepts, such as the distortions experienced by patients who receive a new pair of spectacles, are affected when perceptual processes underlying adaptation occur at different rates.

2.5.3 Individual differences in adaptability

To some extent, the variability we observed across participants within each group may be due to reliable individual differences in distortion percepts and adaptability. To examine potential individual differences, we conducted a set of post hoc correlational analyses. First, we considered individual differences in the initial distortion caused by the spectacles. We calculated the correlation between the disparity-only and dual-cue conditions and combined across the continuous- and intermittent-wear groups. As predicted, we found a significant positive correlation in the initial distortion in these two conditions ($r = 0.45$, $p = 0.013$), suggesting that variability in initial distortion is to some extent related to stable differences in percepts. We also found that this correlation was significant at both the adaptation and aftereffect measurements (adaptation: $r = 0.51$, $p = 0.004$; aftereffect: $r = 0.69$, $p = < 0.001$). These results are consistent with the notion that the disparity-based slant estimate contributed lawfully to the dual-cue slant estimate, but we caution that cue reweighting (which there is some evidence for) would be expected to disrupt this correlation.

Last, we asked whether the amount of adaptation for each participant was correlated with the amount of aftereffect. Interestingly, we did not find any significant correlation here (disparity-only slant adaptation versus aftereffect: $r = 0.18$, $p = 0.331$; dual-cue slant adaptation versus aftereffect: $r = 0.22$, $p = 0.239$; shape adaptation versus aftereffect: $r = 0.24$, $p = 0.206$). This suggests that individuals who experienced larger amounts of adaptation did not consistently experience a larger aftereffect. We speculate that the removal of the spectacles before the final posttest measurement may have been a contextual cue that altered the aftereffect differently for different people. Indeed, contextual cues are known to play an important role in low-level adaptation and are often used to drive rapid switching between different adaptation states.[77,78,80] Recent research has highlighted additional ways in which contextual information in the natural environment can influence adaptation, but individual differences in this domain have not been thoroughly explored.[15] Specifically, the presence of additional visual cues from the natural environment (e.g., objects of known shape) may be necessary to cue individuals to remain in their adapted state. Without these cues present, individual variability may increase. In future work, these contextual effects could be explored by including images of familiar objects within the test stimulus. If individuals vary in how robustly they rely on contextual cues, we could then ask whether specific instructions to spectacle wearers might facilitate or hinder their ability to leverage contextual information to speed up the adaptation process.

2.5.4 Conclusion

Despite the long history of laboratory research and clinical knowledge about the spatial distortions produced by spectacles, much remains unknown about how the visual system overcomes these distortions. Knowledge of how exposure frequency relates to the time scale and mechanism of adaptation will improve our understanding of adaptation and may also provide guidelines for those who struggle to adapt to spectacles.

2.6 Acknowledgements

The authors thank Marty Banks for helpful discussions.

2.7 Appendix

We measured the physical slant that was perceived as frontoparallel when perspective and disparity cues were isolated and when they were presented together. We aimed to use these data to calculate the relative weight that each participant gave to the disparity and perspective cues at each measurement time. We denote the physical slant in the world as S and the observer's slant estimates as $\hat{S}$. We assume that the slant estimated when both cues are presented together ($\hat{S}_{combo}$) is a linear combination of the slant estimates from the binocular disparity cues ($\hat{S}_d$) and perspective cues ($\hat{S}_p$). We also assume that the weights given to the disparity cues (w_d) and perspective cues (w_p) are both within the range of 0 to 1 (inclusive) and sum to 1:

$$\hat{S}_{combo} = w_d \hat{S}_d + w_p \hat{S}_d \quad \text{2.A1}$$

$$w_d + w_p = 1 \quad \text{2.A2}$$

We also assume slant estimates from each cue are determined by the physical slant of the stimulus and an additive bias (B):

$$\hat{S} = S + B \quad \text{2.A3}$$

Bias terms associated with different visual cues may differ, so we denote the biases from disparity-based estimates and perspective-based estimates as Bd and Bp, respectively. We can now rewrite Equation 2.A1 as

$$\hat{S}_{combo} = w_d(S + B_d) + (1 - w_d)(S + B_p) \quad \text{2.A4}$$

To measure Bd and Bp at the start of adaptation and the end of adaptation, we asked participants to adjust a disparity-only and perspective-only stimulus until $\hat{S} = 0$ (that is, until the surface appeared frontoparallel). The average physical slant that the stimulus was set to across repeated trials is denoted as F, and we use subscripts with the condition names to indicate each measurement. Using Equation 2.A3, we can then solve for the bias associated with each cue at each measurement time as follows:

$$B_d = -F_{disparity-only} \quad \text{2.A5}$$

$$B_p = -F_{perspective-only} \quad \text{2.A6}$$

Note that when the glasses are on, Bd incorporates both any internal biases and the geometric biases induced by the glasses. In the dual-cue condition with the glasses on, participants adjust a stimulus with both disparity and texture cues present until the estimated slant is frontoparallel ($\hat{S}_{combo} = 0$), and we denote the physical slant of the stimulus setting in this condition as F_{combo}. Under the preceding assumptions, we can rewrite Equation 2.A4 as follows, in terms of our measured quantities and a single unknown weight (w_d):

$$0 = w_d\left(F_{combo} - F_{disparity-only}\right) + (1 - w_d)(F_{combo} + F_{perspective-only}) \quad \text{2.A7}$$

This equation simplifies to

$$w_d = \frac{F_{perspective-only} - F_{combo}}{F_{perspective-only} - F_{disparity-only}}. \quad \text{2.A8}$$

In addition to assuming that the dual-cue estimate is a linear combination of the estimates from disparity and perspective alone, this model assumes that the only pertinent biases are additive biases on disparity and perspective estimates. Further, we assume that these biases can be accurately measured with the cue isolation stimuli. Because the slants involved in our experiment are relatively small, we think it is reasonable to assume that the cue-isolating stimuli are a reliable measure of bias in the dual-cue stimulus.[16] However, the fact that the solution to Equation 2.A8 for some participants results in a weight that is less than 0 or greater than 1 (6 of 30 participants) suggests that additional sources of bias that our model does not account for are playing a nonnegligible role, at least for some people. Since other depth cues in the stimulus indicate a frontoparallel slant, these failures may indicate a contribution of a multiplicative bias, or a bias that changes based on the stimulus appearance. For example, the dot cloud used in the disparity-only condition differed in appearance from the dot grid used in the dual-cue stimulus. We thus proceed with the planned analysis using the participants with successful fits but take caution in interpreting the resulting weight changes over time. These changes likely indicate changes in how participants are combining disparity with other information but may incorporate more factors than just a shift between the linear weight terms in Equation 2.A1.

3 CHAPTER 3

How small changes to one eye's retinal image can transform the perceived shape of a very familiar object

3.1 Abstract

Vision can provide useful cues about the geometric properties of an object, like its size, distance, pose, and shape. But how the brain merges these properties into a complete sensory representation of a three-dimensional object is poorly understood. To address this gap, we investigated a visual illusion in which humans misperceive the shape of an object due to a small change in one eye's retinal image. We first show that this illusion affects percepts of a highly familiar object under completely natural viewing conditions. Specifically, people perceived their own rectangular mobile phone to have a trapezoidal shape. We then investigate the perceptual underpinnings of this illusion by asking people to report both the perceived shape and pose of controlled stimuli. Our results suggest that the shape illusion results from distorted cues to object pose. In addition to yielding new insights into object perception, this finding challenges the field to explain the principles that govern how the brain combines information from multiple visual cues in natural settings. The shape illusion can occur when people wear everyday prescription spectacles, thus these findings also provide insight into the cue combination challenges that some spectacle wearers experience on a regular basis.

3.2 Significance statement

We describe and investigate a surprising visual illusion in which humans can misperceive the shape of a highly familiar object: their own mobile phone while they hold it in their hands. Unlike many other illusions that rely on sparse visual information, this shape illusion is robust in a fully natural environment. Our results indicate that this illusion results from a failure of the visual system to discard a single distorted visual cue. This failure challenges our current understanding of sensory cue combination in natural settings. We suggest that the visual system may be unable to disregard visual cues that are given special privileges in cue combination.

3.3 Introduction

Even under the best of circumstances, vision provides ambiguous information about the geometric properties of objects. For example, a change in the retinal image of an object can be caused by a change in that object's shape, pose, or both. As such, an important stage of visual processing is to combine information across multiple cues to determine the best guess about the geometric properties of the world. This cue combination increases the precision of sensory estimates, resolves ambiguities, and facilitates a stable neural representation of objects [81,90,91]. As a result, in daily life our percepts of object shape seem to be stable and relatively veridical. Here, however, we describe and investigate an illusion in which cue combination appears to distort the perceived shape of a real, familiar object. We leverage this illusion to better understand how the visual system merges multiple cues, along with past experiences, to determine the geometry of objects in the world.

The illusion we study arises when one of the eye's images is slightly magnified. This scenario has long been a topic of perceptual investigations because it can occur when people wear prescription spectacles with unequal power between the eyes [3,4,12,18,40,70,86,92–94]. Prescription spectacles that cause perceptual distortions and visual discomfort may lead people to eschew vision correction, so understanding this illusion is of both theoretical and practice importance. Previous research on this topic has focused on using controlled visual stimuli to investigate how monocular image size differences can distort the perceived pose and, specifically, the perceived slant of surfaces. This change in perceived slant can be mathematically explained by the resulting pattern of binocular disparities (i.e., the differences between the left and right eye's retinal images) [94].

During our own research on this topic, however, we observed informally that under natural viewing conditions many observers were unaware of any slant distortion. Instead, they were more disturbed by a salient but poorly understood illusion of object shape [3,18,70,86,92,93,95]. Specifically, when looking at rectangular objects, participants reported that one side appeared taller than the other. Here, we first report an investigation that aimed to capture the consistency and magnitude of this shape illusion with real objects. Our investigation further confirmed that percepts of distorted object slant were weaker and less consistent than the shape illusion. Next, we report a controlled perceptual study showing that this shape illusion is linked to distorted binocular disparity cues for object slant, even if the distorted slant does not reach awareness during natural viewing. The inability of the visual system to disregard distorted visual cues in the presence of multifaceted sensory information and prior knowledge suggests a new constraint on how the visual system represents the shapes of objects.

3.4 Results

3.4.1 Monocular retinal image magnification produces a strong shape illusion under natural viewing conditions

We first aimed to quantify the shape illusion under natural viewing conditions of real objects, with rich sensory cues and prior knowledge. Thus, we asked participants to hold their own mobile phone in their hand and look at it through either a pair of control spectacles (plano lenses in front of both eyes) or experimental spectacles (a plano lens over the left eye and a 3.8% horizontal magnifier over the right eye). Then, participants removed the spectacles and drew the shape that they perceived the phone to have. Illustrations of the average resulting shapes are shown in Figure 3.1A (control spectacles) and B (experimental spectacles). As expected, the experimental spectacles elicited a strong and consistent illusion of a trapezoidal shape.

We quantified the magnitude of the illusion as a shape ratio: the ratio between the length of the right side and the left side in each drawing. When participants wore the experimental spectacles, they systematically drew the right side of their phones taller than the left side, but they did not do so for the control spectacles (Figure 3.1C, left bars). We wondered if this illusion might be even stronger for an unfamiliar object, so participants also performed the same task with a small, textured plastic square (that is, a flat rectangular prism with a square-shaped face). We found that the shape illusion was similar for this unfamiliar object (Figure 3.1C, right bars).

A two-way repeated measures ANOVA revealed a significant main effect of spectacles ($F(19) = 121.58$, $p < 0.001$), but no main effect of object type ($F(19) = 0.55$, $p = 0.466$) or interaction ($F(19) = 0.97$, $p = 0.337$). The effect sizes associated with wearing the experimental spectacles were large for both the phone ($d = 2.40$) and the square ($d = 2.53$).

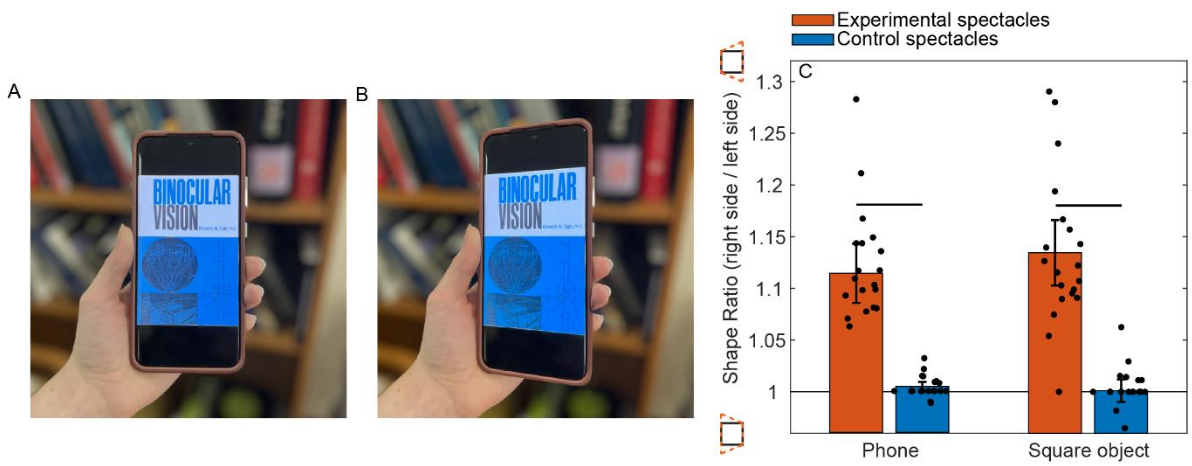

Figure 3.1. Spectacles with a monocular horizontal magnifier cause real objects to appear distorted under natural viewing conditions. (A) An image of a mobile phone held fronto-parallel to the camera was warped to match the average shape ratio that participant's drew when wearing the control spectacles (plano lenses). (B) The same image was warped to match the average shape ratio that participants drew when wearing the experimental spectacles with a monocular horizontal magnifier. The increase in length on the right side is equally split between the bottom and top right corners, however, participant's varied in whether they saw equal or unequal stretching of top right and bottom right corners of their phones. (C) The shape ratio: the average ratio of the length of the right side of participant's drawings to the left side of the drawings. This includes drawings of their own phone (left) and an unfamiliar square object (right). The black dots in the figure represent each participant's shape ratio. Numbers greater than 1 indicate that the right side was drawn taller than the left side, and ratios below 1 indicate that the left side was drawn taller than the right side. Error bars represent the 95% confidence intervals and horizontal lines represent significant differences. If we assume that perceived shape is determined based on the binocular disparities created by the spectacles, and assume a typical viewing distance of 35cm, we expect participants to see a shape ratio of 1.05 with the experimental spectacles on.

3.4.2 Hypothesized explanation for the shape illusion

Previous literature has posited that percepts of shape and slant are linked, which may provide an explanation for this shape illusion [86,93,96–99]. By way of example, a square object in the world that is frontoparallel to the line of sight will project to retinal images that are roughly square-shaped, whereas a square with a pose that is slanted away from an observer on one side will produce trapezoidal retinal images (Figure 3.2A, B). In addition, the retinal images in the two eyes are not perfectly identical, they have binocular disparities that also reflect the geometric properties of objects. If the square is slanted to face the right eye, for example, the retinal image in the right eye will be slightly wider than in the left. This creates a gradient of horizontal binocular disparities. As such, the human visual system uses information from perspective, binocular disparity, and other cues to infer the most likely three-dimensional pose and shape of an object given a pair of retinal images [100].

While the horizontal monocular image magnification produced by our experimental spectacles only slightly alters one eye's image, this systematically changes patterns of binocular disparities. Specifically, this alteration produces binocular disparity cues consistent with an object slanted to face the magnified eye [3], while leaving both retinal images still approximately square (one is a square, one is a rectangle) (Figure 3.2C). Importantly, for a flat surface in the world to create a square retinal image when it is slanted, the object must be trapezoidal in the world. Thus, the proposed explanation for the observed shape illusion is that the visual system is utilizing the altered binocular disparity cues along with the shape of the retinal images to incorrectly infer the object's shape (Figure 3.2D). However, empirical studies have been inconclusive about the strength and mechanism of the relationship between perceived object slant and perceived object shape [54,96,99,101–103]. Thus, we wondered if the participants in our study who reported the shape illusion may also be experiencing an illusory slant of the objects.

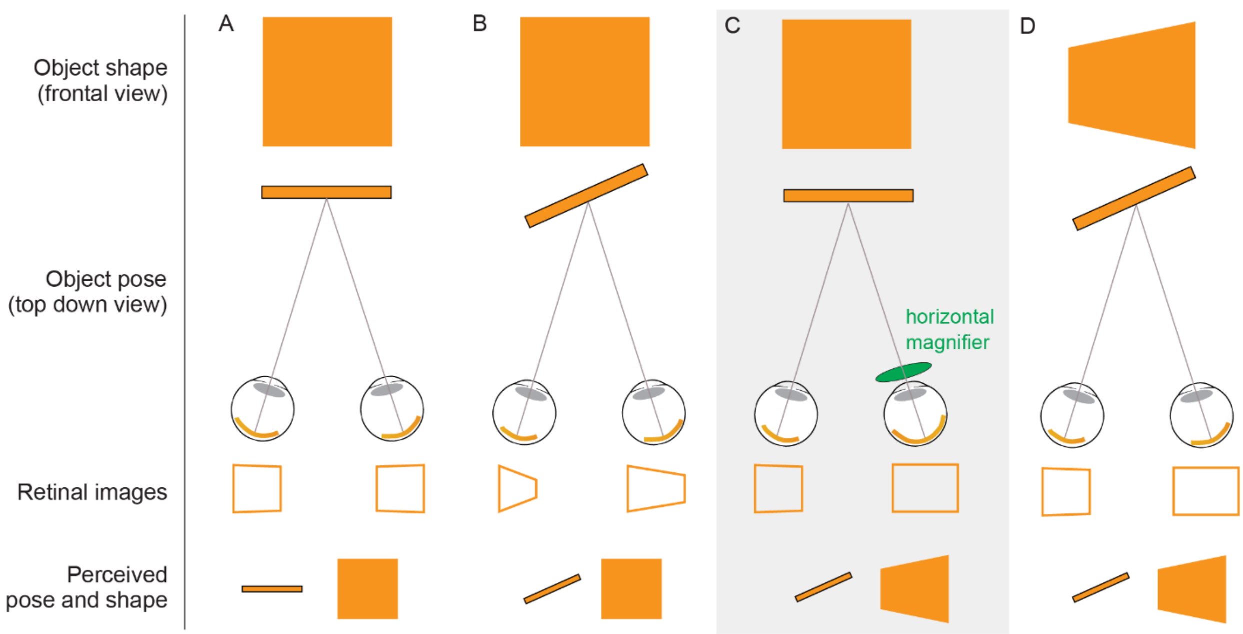

Figure 3.2. How shape and slant may combine to create a perception of a three-dimensional object. (A) A frontoparallel square (i.e., not slanted in depth) casts roughly square-shaped retinal images, and its geometric properties (pose and shape) are likely to be perceived accurately. Small deviations from rectilinearity in the retinal images arise from each eye's view of the square coming from a slightly different angle. (B) A square that is slanted to face the right eye casts trapezoidal retinal images due to perspective projection. The trapezoidal retinal image in the right eye is also wider than the retinal image in the left eye, resulting in horizontal retinal disparities that provide useful cues to slant angle. (C) If an observer views a frontoparallel square and one eye's image is magnified slightly in the horizontal direction, this simulates the retinal disparities associated with a slanted object, but does not change perspective cues. Prior researchers have shown that observers perceive the object to be slanted, but at the same time

the perceived shape becomes distorted into a trapezoid. (D) A trapezoid that is slanted to face the right eye can create a roughly square image on one retina and an elongated rectangular image on the other.

3.4.3 A slant distortion was also reported, but the effect was weaker and less consistent

While almost all participants robustly reported a distortion in perceived shape when holding objects in their hand, pilot testing suggested that people were less confident and consistent in their experience of object slant. Thus, we created a simplified slant judgement task that enabled participants to focus on reporting just the perceived slant direction. In this task, the two objects (the mobile phone and textured square) were placed one at a time at eye height against a wall, at a similar viewing distance to the shape judgement task. Participants were first asked to report if they perceived a slant at all (that is, was the object slanted away from frontoparallel). If they said yes, we then asked them to report the slant direction (left side closer or right side closer).

While virtually all participants reported a shape illusion, only about half of the participants reported that the objects looked slanted through the experimental spectacles (50% for the phone and 35% for the square). This was still qualitatively more than the number who reported slant through the control lenses (10% for the phone and 5% for the square) (Figure 3.3A). A Cochran Q test (similar to a repeated measures ANOVA, but for binary data) showed that there was a significant difference in the number of participants who perceived a slant between the conditions ($X^2(3) = 17.05$, $p < 0.001$). Pairwise follow up tests showed that a significantly greater number of participants perceived a slant when viewing their phone in the experimental versus the control spectacles ($X^2(1) = 6.13$, $p = 0.040$, odds ratio = 0.20), but this difference was not significant between the control and experimental spectacles when viewing the square ($X^2(1) = 3.12$, $p = 0.154$, odds ratio = 0.20). There was also no significant difference between the two objects in the control conditions ($X^2(1) = 0.00$, $p = 1.000$, odds ratio = 0.50) and the experimental conditions ($X^2(1) = 0.80$, $p = 0.445$, odds ratio = 0.70).

The slant-shape relationship hypothesis predicts not just that the object should appear slanted, but that it should appear slanted in a specific direction consistent with the shape distortion (in this case, with the left side closer). Figure 3.3B shows the breakdown of reported slant directions for the experimental spectacles (control spectacles not shown). When people did perceive the objects to be slanted, there was no significant difference between the direction of slant perceived ($X^2(3) = 1.46$, $p = 0.691$). That is, people were similarly likely to report a slant that was consistent with the shape illusion and one that was not. This observation is in line with prior work demonstrating a tendency in some situations for people to perceived slant reversals depending on the visual cues available [86,93].

Taken together, these findings bring into question the notion that the shape illusion observed for real objects derives from slant-shape consistency. That is, people could experience a robust distortion in perceived shape without also perceiving a slant distortion that created a consistent geometric interpretation of the retinal images. However, some link between binocular disparity and shape cues still seems the most likely explanation for the shape illusion, and it has also been hypothesized that slant information can influence perception outside of awareness [97,98]. Thus, we next adopted controlled stimuli to ask whether the shape illusion bears a consistent and lawful relationship to the slant specified by binocular disparities. Specifically, we leveraged the fact that horizontal and vertical monocular magnification produce opposing slant cues in controlled settings to ask whether these manipulations also produce opposing shape illusions.

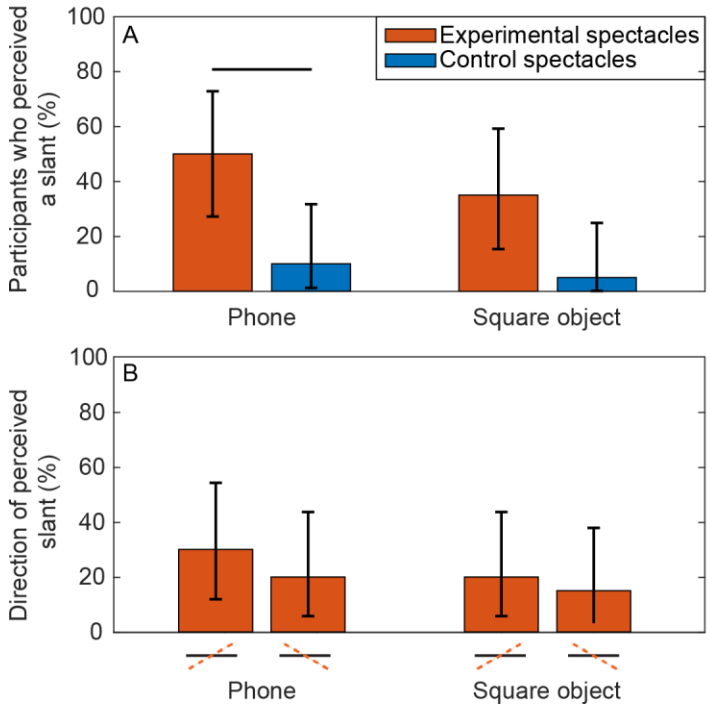

Figure 3.3. When viewing a phone and an unfamiliar square object in the experimental and control spectacles some participants perceived a slant while others did not. (A) The percent of participants who perceived the objects to be slanted when placed flat against a wall with the experimental spectacles (orange) and the control spectacles (blue). The error bars are the binomial confidence intervals. Horizontal lines represent significant differences. (B) The percent of participants in the experimental spectacles who perceived the phone or the square to be slanted with the right side back or left side back. Error bars represent the binomial confidence intervals.

3.4.4 Monocular horizontal and vertical magnification systematically change perceived surface slant in opposing directions

In this experiment, we used controlled stimuli presented on a stereoscopic display so that we could independently change the size of each eye's image. On a given trial, participants either adjusted the slant of a cloud of random dots until it appeared frontoparallel (i.e., not slanted in depth, Figure 3.4A) or they adjusted the edges of an untextured quadrilateral until it appeared square (i.e., not trapezoidal, Figure 3.4B). The random dot cloud stimulus enabled us to measure changes in perceived slant from binocular disparity with shape cues minimized. The quadrilateral stimulus enabled us to precisely measure changes in perceived shape by focusing on the object outline. The recorded responses reflect the amount of surface slant or shape change that participants required to undo the illusion induced by monocular retinal image magnification.

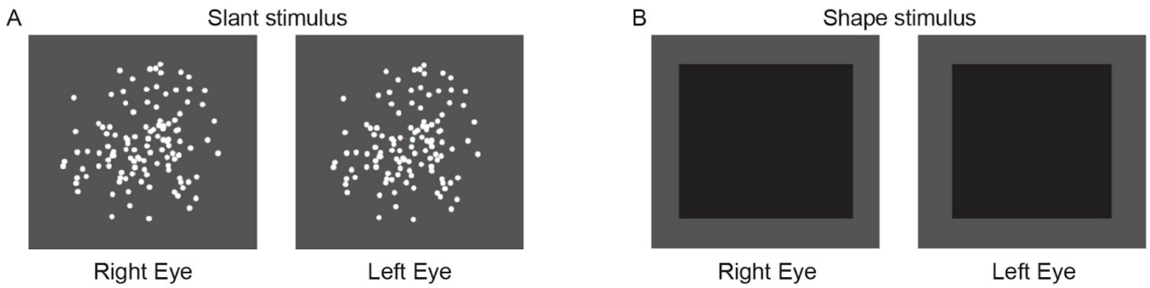

Figure 3.4. Cross fusible stereoscopic stimuli for the slant and shape adjustment tasks. (A) Random dot cloud presented during the slant tasks. (B) The stimulus presented during the shape task. In each panel, the right eye's image is horizontally magnified 6%. The dot density, dot size, and luminance in all panels have been adjusted for visual clarity. Further, during stimulus presentation there was a larger space (about 34 deg) between the edge of the stimulus and the edge of the screen.

First, we confirmed that our stimuli replicated the expected opposing slant percepts associated with vertical and horizontal monocular image magnification. As expected from previous work, we found that horizontal retinal image magnification caused participants to adjust the random dot cloud so that it was slanted to face away from the magnified eye (Figure 3.5A, blue circles). This is consistent with the notion that horizontal magnification produced a perceived slant facing towards the magnified eye. Consistent with previous literature, vertical magnification produced the opposite effect (Figure 3.5A, yellow circles) [3,40]. For both manipulations, the perceived slant increased lawfully with greater magnification: across participants, we observed significant Pearson correlations between magnification and perceived slant, going in opposite directions for the horizontal and vertical manipulations (horizontal: mean $r = -0.996 \pm 0.002$, $t(19) = -750.03$, $p < 0.001$, $d = 243.34$; vertical: mean $r = 0.97 \pm 0.02$, $t(19) = 120.13$, $p < 0.001$, $d = -38.97$). As described by previous literature, these slant percepts can be explained by the change in horizontal and vertical binocular disparity cues, and have been called the geometric and induced effects, respectively [3,40]. Consistent with previous findings, when magnification was in the vertical direction the perceived slant plateaued at higher magnitudes as compared to horizontal magnification [40].

3.4.5 The shape illusion correlates with the perceived slant associated with horizontal and vertical magnification under controlled conditions

If the shape illusion is driven by binocular disparity cues to slant, we expected participants to perceive a specific trapezoid shape such that the difference in height on the left and right sides would counteract the amount of perspective convergence associated with the perceived slant. To test this hypothesis, we first computed the expected shape distortion from the previously measured slant distortion for each participant. We expected participants' responses to null the predicted shape distortion because the task was to adjust the stimulus until it was square. For these predictions, we again quantified the shape distortion as the ratio of the right side and left side of the trapezoid on the screen. These predictions based on the slant measurements are plotted as solid lines in Figure 3.4B.

We then compared these predictions to the responses on the shape adjustment task. For this task, we used a smaller range of magnifications because higher levels often lead to double vision, which made the task challenging to complete. In general, we found that when the right eye experienced monocular horizontal magnification, the right side of the shape appeared taller compared to the left side, and when the left eye experienced magnification the left side of the shape appeared taller (Figure 3.5B, blue circles). Like the slant percepts, the perceived shape distortion reversed for vertical monocular magnification (Figure 3.5B, yellow circles). Across participants, we again observed significant correlations between magnification and shape ratio, going in opposite directions for the two magnification types (horizontal: mean $r = -0.93 \pm 0.05$, $t(19) = -38.11$, $p < 0.001$, $d = 12.36$; vertical: mean $r = 0.66 \pm 0.12$, $t(19) = 10.41$, $p < 0.001$, $d = -3.38$).

To quantitatively compare the perceived shape to our geometric predictions (i.e., the predictions based on the data from the slant task), we calculated the coefficient of determination (r^2) and the root mean squared error (RMSE) for each participant. The geometric predictions accounted for a significant portion of the variance in shape percepts for both the horizontal magnification ($r^2 = 0.86 \pm 0.07$, $t(19) = 22.77$, $p = < 0.001$, $d = -7.39$) and vertical magnification ($r^2 = 0.51 \pm 0.14$, $t(19) = 7.40$, $p < 0.001$, $d = -2.40$). Across participants, the RMSE tended to be small for both manipulations, although in both cases the RMSE was significantly different from zero (horizontal: RMSE = 0.02 ± 0.00, $t(19) = 10.59$, $p < 0.001$, $d = -3.44$; vertical: RMSE = 0.02 ± 0.00, $t(19) = 19.90$, $p < 0.001$, $d = -6.46$). Overall, the amount of shape distortion was less than predicted by the change in perceived slant, particularly for the vertical magnification. This distortion is also notably less than the shape distortion recorded for the real objects, however, the drawing task used in that experiment provides less measurement accuracy making comparisons across tasks challenging.

These results support the theory that the shape illusion is a result of inferences made about the combined object slant and shape that are consistent with both the binocular disparity and linear perspective retinal image properties. Under controlled conditions, these shape and slant percepts can be isolated and studied, but under naturalistic conditions people seem largely unaware of the change in slant despite the salience of the shape illusion.

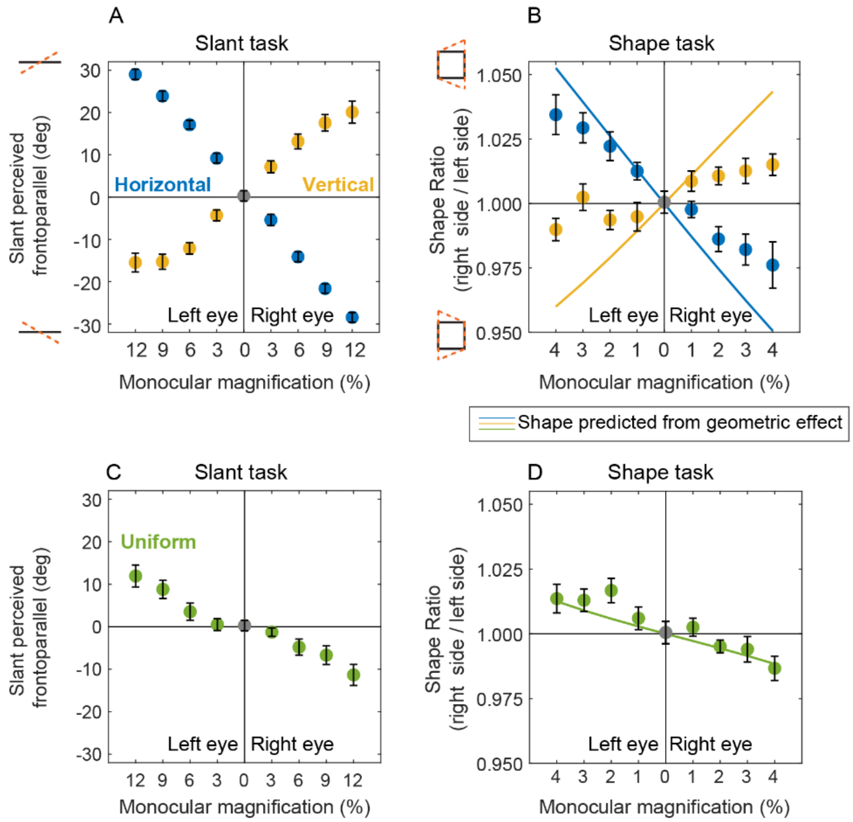

Figure 3.5. Results from the slant and shape adjustment tasks with uniform, horizontal, and vertical magnification. In each plot, circular markers indicate averages and error bars are 95% confidence intervals across participants. (A) The slant that was perceived frontoparallel while experiencing monocular horizontal (blue) and vertical (yellow) magnification in the left eye or the right eye. The symbols beside the y axis indicate the direction of a positive and negative slant from a top-down view. (B) Results of the shape adjustment task. Specifically, the ratio between the height of the right and left side of the stimulus that made the stimulus appear square while experiencing monocular horizontal (blue) and vertical (yellow) magnification simulated for the left or the right eyes. The icons next to the y axis represent shapes that would produce a shape ratio above and below 1. The lines indicate the fit of a third order polynomial to the predicted shape estimates based on the average responses from the slant judgment. (C) The slant percepts produced by monocular uniform magnification. (D) The shape percepts produced by a monocular uniform magnifier plotted in the same way as in B. The solid line again indicates the fit of a third order polynomial to the predicted shape estimates based on the average responses from the slant judgment.

3.4.6 Perceived slant and shape also covary when horizontal and vertical magnification are combined

Since monocular horizontal and vertical magnification produce slant percepts in opposite directions, one could predict that their effects would cancel out if the retinal image is magnified equally in all directions. Indeed, from a prior geometric analysis it is clear that equal amounts of horizontal and vertical magnification (uniform magnification) produce disparity cues consistent with a frontoparallel surface [104]. Prior perceptual work, however, suggests that monocularly uniform magnification can still slightly distort perceived stimuli [4,94]. We thus asked if uniform magnification would null both the slant and shape illusions in our stimuli. We found that uniform retinal image magnification in one eye still produced a systematic change in perceived slant (Figure 3.5C). Subsequently, we can again ask whether the perceived shape agrees with the slant that results from the combined effects of the horizontal and vertical magnification. The data were consistent with this expectation (Figure 3.5D): geometric predictions for the shape percept derived from the slant responses explained a substantial and significant portion of the response variance and tended to have a small RMSE ($r^2 = 0.65 \pm 0.08$, $t(19) = 15.58$, $p < 0.001$, $d = -5.06$; RMSE $= 0.04 \pm 0.01$, $t(19) = 11.92$, $p < 0.001$, $d = -3.87$). Thus, under three different conditions of retinal image magnification (horizontal, vertical, and uniform), the direction and amount of shape distortion was well-explained by the slant percepts produced by binocular disparity cues.

3.5 Discussion

Visual illusions can surprise us, stoke our curiosity, and even cause us to question the reliability of our own eyes. However, these illusions are often achieved by creating controlled stimuli and situations that deprive our visual system of the full array of cues available during daily life. Here, we demonstrated that a small manipulation of one eye's retinal image can robustly alter the perceived shape of a highly familiar object, viewed naturally and held in a person's own hand. Through a combination of natural and controlled perceptual investigations, our studies demonstrate that this shape illusion is linked to distorted binocular disparity cues to object slant, even if the distorted slant does not reach awareness during natural viewing.

3.5.1 Evidence of a real-world failure to discard a single distorted visual cue

If our interpretation is correct, then this illusion represents a notable failure of cue combination in the real world. In the research literature on cue combination, it has long been appreciated that ideal combination models should aim to incorporate as many cues as possible, while also being robust to corrupted or distorted cues [83,91,92]. These models do a good job of accounting for the results of various controlled cue conflict experiments [105–107]. However, our results reveal a scenario in which there is an inability to discard a distorted cue (binocular disparity) even in a fully natural environment where there are many correct cues available to the viewer. When participants viewed their own mobile phone in their hand, they had several correct multimodal shape cues, such as linear perspective, texture gradients, motion parallax, and tactile information. They also had substantial prior knowledge about the true object shape derived from daily experience using the device, which should support accurate percepts [108]. However, to reconcile the distorted binocular disparity cues (indicating a pose that is slanted), observers inferred that the object they were holding was a trapezoid, violating the other shape cues and their prior knowledge. The fact that the shape illusion was similarly strong for an unfamiliar and a highly familiar object is also surprising because it suggests that prior knowledge of the specific object did not have a notable influence on the percept, which would be expected by cue combination models that incorporate prior knowledge (i.e., Bayesian inference models).

Furthermore, the inconsistency between perceived shape and slant of the real objects suggests that our perceptual awareness of object shape can be influenced by imperceptible cues. This concept has previously been described as "registered slant," whereby object slant information influences percepts even when people cannot perceive it [97,98]. Similarly, several previous studies have noted the tendency for monocular image magnification to create variable slant percepts that do not clearly link to people's awareness of object shape [70,86]. While these discrepancies went away when we used controlled visual stimuli, the slant geometry still did not perfectly predict the shape illusion. Indeed, there is a long history of research examining the shape-slant invariance hypothesis, in which researchers have investigated whether observers make mutually consistent judgements of the shape and slant under different viewing conditions [99,109,110]. Importantly, while this previous work has established a lawful relationship between slant and shape percepts under a wide range of conditions, there is little evidence for perfect constancy in any specific viewing scenario.[111] Thus, while the differences in stimulus appearance in our study (random dots versus a solid shape) may contribute to the deviation between the slant and shape percepts, some amount of deviation likely persists in many situations.

Perceptual constancies are imperfect, but our data support the notion that there is a strong and lawful tendency for binocular disparity to distort shape percepts. Importantly, the visual stimuli available can change the magnitude of the perceptual distortions that people experience when binocular disparity cues are manipulated [3,40,92,93]. Taken together, our findings challenge the notion that our perception of object properties is robust to corrupted sensory information under rich, multi-cue viewing conditions and encourages us to consider potential alternative explanations.

3.5.2 Binocular disparity may play a unique role in shape perception

Based on our results, we speculate that the visual system may uniquely prioritize interpretations of object shape that are consistent with binocular disparity cues. For example, previous work has proposed a "primacy of stereopsis," whereby information from binocular disparity is given privileged status during both cue combination and learning [83]. The rationale is that once binocular disparities are successfully detected by the visual system, this cue provides a strong constraint on the possible object geometry. Cues that are derived from perspective, on the other hand, always rely on prior assumptions about shape and texture that may be violated. Related work on multisensory integration also supports the notion that more accurate sensory cues may have a special status in which they are used to calibrate the interpretation of less accurate cues that may drift over time [112]. Thus, a selective and small distortion of binocular disparity may present a unique situation in which cue combination is simply not robust to perceptual distortions.

It is possible that, with more time, people would learn to downweigh or re-interpret binocular disparity and eliminate the shape illusion. Indeed, previous work has established that the visual system's combination, weighting, and prioritization of visual cues can adapt over time [17,82,83]. Research on monocular image magnification has found that the associated changes to shape and slant percepts, measured with controlled stimuli, can adapt over hours and days [12,18]. Based on our results, we propose that this adaptation likely requires ongoing feedback indicating that disparity information is distorted.

3.5.3 Rectilinear objects may make illusions more salient, even if all objects are affected

Monocular image magnification affects binocular disparity cues for everything that someone looks at, but we chose to focus our study on rectilinear objects because these shapes were anecdotally observed to produce the strongest illusion. For example, although someone's own hand is presumably also a familiar shape, people did not seem to experience a large distortion of their hand while they were holding their phone. Why would that be the case? There is a long history of rectilinearity playing a privileged role in visual illusions. Famous optical illusions, such as the Ames room, leverage the fact that people infer that trapezoidal surfaces in a distorted room are actually rectilinear. Consistent with this notion, psychophysical studies suggest that, amongst the many assumptions people may make about object properties in order to interpret linear perspective, assumptions of rectilinearity prove particularly powerful for evoking three-dimensional percepts [95,96,99,113]. However, optical illusions often hinge on limiting the information available to the viewer from other cues. The illusion of an Ames room, for example, is easily broken if the observer is allowed to move around or view the room with both eyes. Thus, it is even more surprising that the shape illusion investigated here is robust to natural viewing conditions. This feature of the illusion makes it a unique candidate for investigating object perception and cue combination during natural viewing.

3.5.4 Conclusion

From a practical perspective, the constraints and dynamics of cue combination are important to understand because some prescription spectacles wearers experience modified binocular disparities on a regular basis. The inability to get used to a new pair of prescription spectacles may result from the failure to adapt to perceptual distortions [5,7,114]. Future research on adaptation and cue combination in natural settings may be able to develop guidelines for mitigating non-adaptation, for example, with different lens designs or prescribing strategies (e.g., increasing a prescription slowly over time or instructing people to take their spectacles on and off regularly).

3.6 Methods

3.6.1 Participants

Twenty adults participated in each experiment (real objects: 3 male, 17 female, mean age = 25.3 ± 3.7 years, simulated objects: 7 male, 13 female, mean age = 26.5 ± 4.0 years). In both experiments, inclusion criteria included normal visual acuity measured at 10 feet (20/20 binocular and 20/30 monocular equivalent or better), and normal stereoacuity (50 arcsec or better on a Randot test). The experiments were approved by the University of California, Berkeley Institutional Review Board and all participants provided informed consent and were compensated for their time.

3.6.2 Experiment using real-world objects

3.6.2.1 Tasks

Participants performed the same set of tasks while wearing control spectacles (a pair of plano lenses) and experimental spectacles (a plano lens in front of the left eye and a 3.8% monocular horizontal magnifier over the right eye) [12,18]. The order in which the spectacles were worn was counter balanced. Participants began by wearing each pair of spectacles for several minutes while exploring an indoor lab environment and looking at objects of various sizes. Then, participants performed structured observation of objects. Two objects were used: the participant's mobile phone with text on the screen and a black 3D printed rectangular prism (H = 7.5 cm, W = 7.5 cm, L = 1 cm) with 8 randomly placed dots to provide some texture. The mobile phones of all participants were rectangular, with varying aspect ratios.

The structured observation period began with the shape observation, participants wore each pair of spectacles while holding the objects at a comfortable viewing distance in their hand. Then participants removed the spectacles and drew the outline of each object using a ruler. For the slant observation, participants judged the slant of each object while it was at eye height against a featureless white wall to ensure that the object was fronto-parallel to the observer. Once placed against the wall, participants reported whether the object appeared slanted, and if so, in which direction. The slant and shape observations were both performed in near peri-personal space but the distances were not precisely controlled.

3.6.2.2 Analysis

The left and right side of each drawing was measured, and the shape ratio was calculated by taking the length of the right side and dividing it by the length of the left side. To evaluate the effect of the lenses and the objects, a 2x2 ANOVA was run. The ANOVA for the shape ratio did not pass assumptions for homogeneity, so we ran a permutation-based ANOVA (aovp function in the lmPerm package from R). There was no change in results so we report the results from the original ANOVA in this paper. Cohen's *d* was used determine the magnitude of the effect size of spectacle type for the two different objects. For the slant data, we used a Cochran Q for the omnibus test with McNemar follow-up pairwise comparisons and an odds ratio to determine the magnitude of the effect. The Cochran Q and the McNemar tests are analogous to an ANOVA for binary data and the associated follow-up tests. The odds ratio denotes the effect size with the control group divided by the experimental group. However, when the experimental and control groups are directly compared, then the square condition is divided by the phone condition. For pairwise comparisons, *p* values were corrected using a false discovery rate of 5%.

3.6.3 Experiment using simulated objects

3.6.3.1 Apparatus

Stimuli were presented on a VIEWPixx 3D display (LCD panel with LED backlight) with a resolution of 1920 x 1080 pixels, a pixel pitch of 0.27mm (subtending ~0.05°), and a global refresh rate of 120 Hz (VPixx Technologies, Montreal, Canada). Participants wore a 3DPixx shutter glass system to view the stimuli, allowing us to independently manipulate the images shown to the left and right eyes through temporal interlacing (Nvidia, Santa Clara, CA, USA). The maximum luminance through the right and left lenses of the shutter glasses was approximately 27 cd/m^2. All stimuli were presented with Psychtoolbox version 3.0.18 in MATLAB (MATLAB R2022a; The MathWorks, Natick, MA, USA). Participants sat 29.3 cm from the screen with their head on a chin rest and eyes aligned to the center of the screen. To prevent the straight edges lining the screen from being used as a reference, irregularly shaped paper was attached to the edge of the monitor.

3.6.3.2 Tasks

Participants performed two interleaved tasks that measured the magnitude of the shape and slant distortions associated with monocular magnification. The stimuli were manipulated to create horizontal, vertical, or uniform magnification in just the right eye or just the left eye. Magnification was applied to one eye by changing the distance between points on the screen in one eye but not the other. There were different levels of monocular magnification in the slant task (0%, 3%, 6%, 9%, 12%) and the shape task (0%, 1%, 2%, 3%, 4%). These magnitudes of magnification were chosen to minimize the likelihood of diplopia (double vision) in the shape task and to be similar to the ranges in previous literature. Each condition (magnification level and eye) was repeated 4 times and participants freely viewed the stimuli.

Slant task: This task aimed to quantify the perceived slant produced by changes to horizontal or vertical binocular disparity. To measure the full magnitude of this effect without other depth cues dampening the illusion, we created a stimulus that aimed to isolate cues from binocular disparity (Figure 3.4A). We presented a random dot stereoscopic stimulus whose slant could be adjusted without a change in shape or dot density. This way, participants could only use binocular disparity, but not shape or dot density, to make their slant judgements. This method of binocular disparity isolation is described in Hillis et al. (2004). The stimulus was a roughly 16° diameter region composed of white dots (0.05° in diameter and 100% maximum luminance) over a gray background (2% luminance). Dot density on the screen decreased from the center outward with a central 8° region having a dot density of 0.31 dots/deg^2 and the outer area a density of 0.062 dots/deg^2. This tapering of density allowed us to improve cues from binocular disparity without adding strong information about the size and shape which could have been used by participants to judge slant. When magnification was applied to one of the eye's images, this changed the distance between the dots on the screen in one of the eyes, but it did not change the dot size or shape. On each trial, participants used left and right arrow keys to adjust the slant of the circular dot cloud around a vertical axis until it appeared frontoparallel. The initial slant was randomized, and the maximum and minimum slants were also jittered.

Shape task: The aim of this task was to quantify the magnitude of the shape distortion while encouraging participants to focus on the overall object shape. Participants used the arrow keys to adjust the y positions of the top right and bottom corners of a black quadrilateral (0.9% luminance) on a gray background (2% maximum luminance) until it appeared square (Figure 3.3B). When the shape was a perfect square, it subtended 16° by 16°. On each trial, a random initial position and maximum and minimum adjustment was generated for the right top and bottom corners. The shape distortion was quantified as the ratio of the height of the right side to the left side.

3.6.3.3 Analysis

We expected that the perceived shape distortion could be predicted from the magnitude of the perceived slant. Specifically, we expected that the magnitude of the shape distortion for each participant would be equal but opposite to the perspective convergence of a 16° by 16° square viewed at 29.3 cm and slanted at the magnitude of the reported slant in the slant task. We ran an analysis to compare the actual shape responses to our estimates for each participant for uniform, horizontal, and vertical magnification. We calculated an estimate for each slant data point and then fit a third order polynomial to the estimates for uniform, horizontal, and vertical magnification for each participant. Then we calculated the r^2 values and RMSE for each subject. In addition, t-tests and Cohen's *d* were calculated to compare the r^2 and RMSE values for all participants against a null hypothesis of no relationship ($r^2 = 0$).

4 DISCUSSION

These three Chapters provide insight into the many varied effects of distortions in wearable optics and how they change over time. I specifically focused on comfort, perception, and adaptation, because understanding these three elements of experience can create a more holistic and realistic account how these distortions affect people. I hope that this foundational research will help provide evidence-based advice for clinicians and AR/VR engineers. Not only can this research be applied to improve observers' comfort, but Chapter 3 showed that it can also be leveraged to gain a better understanding of the visual system and how it processes ambiguous information. While these three chapters improve our understanding of the impact of optical distortions, much more research is needed to obtain a complete account of the perceptual and physical impact of optical distortions and how they change overtime. I summarize several key areas for future research below.

Additional research is needed to understand how the symptoms associated with wearable optics evolve over time. For example, to continue our investigation of adaptation to optical distortions, I am collaborating with a colleague to examine how physical and perceptual symptoms change over 1 hour of lens wear. This work follows directly from the study reported in Chapter 1, in which we investigated the physical and perceptual symptoms produced after a few minutes of wearing binocular and monocular minifiers. Since the monocular 4% minifiers were reported as being most uncomfortable in this original study, we plan to investigate if viewers symptoms improve after wearing these lenses for an additional hour. We hope that this study will provide a better understanding of how physical and perceptual symptoms develop over time, which may help clinicians give improved guidance to individuals who are getting used to new prescription spectacles.

My dissertation only focuses on two common types of optical distortions—magnification and minification—however, there are many other types of optical distortions that can be present in wearable optics. For example, radial distortions are sometimes present in optical lenses and are defined as an increase in minification or magnification from the optical center outward.[2] Radial distortions create what is known as a pincushion or barrel distortion. Previous research has established that these optical distortions are perceptible and can affect the perceived movement of the world during head or eye rotation.[10,24] For example, as the head or eyes move, the magnitude of distortion across different regions of the visual field changes resulting in what is sometimes reported as a rippling or instability of the world. As radial distortions are present in many wearable optics, future research should investigate how the unique features of these distortions may create additional perceptual and physical effects.

Up to this point, the distortions discussed here are those that affect the entire visual field in a systematic way. However, there are also distortions referred to as "local distortions" which only change the retinal image size in a specific location in the visual field.[115] Local distortions may be caused by manufacturing errors or by complex distortions such as those present in progressive spectacle lenses.[116] Results from Bex (2010) indicate that detection of local distortions may increase for higher spatial frequencies peaking around 4 cycles/deg. However, they found that detection varied depending on the background scene and the eccentricity of the distortion.[115] The lack of continued research on local distortions may be attributed to the fact that these optical distortions vary greatly in size and shape and, therefore, are challenging to study.

Outside of the lab, these types of optical distortions (e.g., global minification, pincushion, local) do not occur alone, they actually appear together in one optic.[22,28,116] While there are ways to quantify the severity of these distortions in isolation, there is no standard way to quantify the magnitude of optical distortions when they are combined in one optic. Further, even if there were such a measurement, it would likely not correspond to the perceptual and physical severity of the symptoms produced by the lens. Therefore, I believe it is immensely important for future investigations to consider performing experiments that are generalizable to many types and combinations of optical distortions.

For example, one idea proposed in previous literature is to decompose an optical distortion into its spatial frequencies.[115,117] It is well known that the visual system is differentially sensitive to high and low spatial frequencies and, therefore, this could be a perceptually relevant way to categorize optical distortions.[118] Ideally, the physical and perceptual effects of optical distortions could be explained by the composition of spatial frequencies present in the optical distortion. This type of approach could help to create a generalizable metric for the severity of optical distortions. Unfortunately, this approach cannot explain some binocular effects produced by optical distortions including the slant illusion created by monocular magnifiers. Nonetheless, this line of research may still be useful for created a unified framework for the severity of local distortions.

Investigations of visuomotor interactions may also deepen our understanding of the effects of optical distortions. Gaze stabilizing reflexes, for example, are important to study because their disruption can lead to both perceptual and physical consequences as a result of visual vestibular conflicts.[22] In Chapter 1, we discussed the fact that minification can disrupt a gaze stabilizing response known as the vestibulo-ocular reflex,[11] but there are other types of gaze stabilizing responses including the ocular following response that may also be affected by optical distortions. The ocular following response is a short latency reflex that responds to the onset of motion in the visual field.[46,119–123] During locomotion, objects on the retina move at different speeds depending on the observer's motion, the object's motion, and the observer's distance from the object.[124] This poses a challenge for the visual system because only one speed at a time can be stabilized by a given eye movement. If we can identify the regions of the visual field that the visual system preferentially stabilizes, this could provide insight about which regions of the visual field may be most disrupted by optical distortions. We can conclude that greater magnitudes of distortion in these regions may be the most visually and possibly physically disruptive during locomotion.

In this dissertation I have discussed the effects of distortions produced by optics, however, there are other elements in a wearable headset that can produce a change in retinal image size or shape. For example, magnification and minification can be created by display calibration errors and would likely create similar effects.[36,125] Depending on the rendering pipeline, images could also be compressed and stretched along a single dimension, mimicking the effects of a horizontal or vertical magnifier. Further, additional distortions may be created by see-through components such as the wrap around visor present in some AR devices. All of the elements that change the retinal image size and shape should be taking into account when considering the effects of a device on perception and comfort.

Finally, optical distortions are not just present in our wearable optics, they are also present in our eyes. The lens and cornea are optical elements that help bring images into focus and, therefore, they also inherently have optical distortions.[126] Differences in the retinal image size between the eyes can sometimes cause a difference in the perceived size of objects between the eyes called aniseikonia.[3] While it is likely that individuals with habitual aniseikonia adapt in some ways to the differences between their eyes, under controlled environments it is still possible to measure a difference in the perceived size and depth of stimuli.[127] While optical distortions present in the eye will likely be very small compared to those created by wearable optics, it is still important to keep this in mind when considering how optical distortions affect viewers.

5 CONCLUSION

In this dissertation I have presented three chapters that describe research on the topic of optical distortions and visual perception in wearable optics. I have shown that mild to moderate levels of optical distortions can produce significant perceptual and physical effects that alter the viewer's experience of the world. Even though many people experience optical distortions regularly, the effects of optical distortions on their comfort and perception remains understudied. It is my hope that this research will help inform clinicians and engineers of the varied effects of optical distortions and to inspire efforts to improve the viewer's experience in wearable optics.

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