Perceptual Adaptation to Continuous Versus Intermittent Exposure to Spatial Distortions

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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.

Keywords: adaptation, spectacles, distortions, binocular disparity

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.[1–11] 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.[12–15]

Previous research has examined how the visual system adapts to continuous exposure to spatial distortions.[1,2,16–19] However, there has been much less investigation of adaptation when spectacles are taken off and on throughout the day.[20] 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.[20,21] For example, intermittent exposure to altered colors has been associated with strong color adaptation across days,[21] and intermittent visuomotor disruptions are well known to drive motor adaptation (i.e., savings or context-specific adaptation).[22–25] 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.[26–33] 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 (Fig. 1A).[1,5,6,11,34] It also produces a change in perceived shape, but this is not as well understood (Fig. 1B).[4–6,34] Figure 1C provides a free-fusible stereo pair to demonstrate these perceptual effects.

Methods

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

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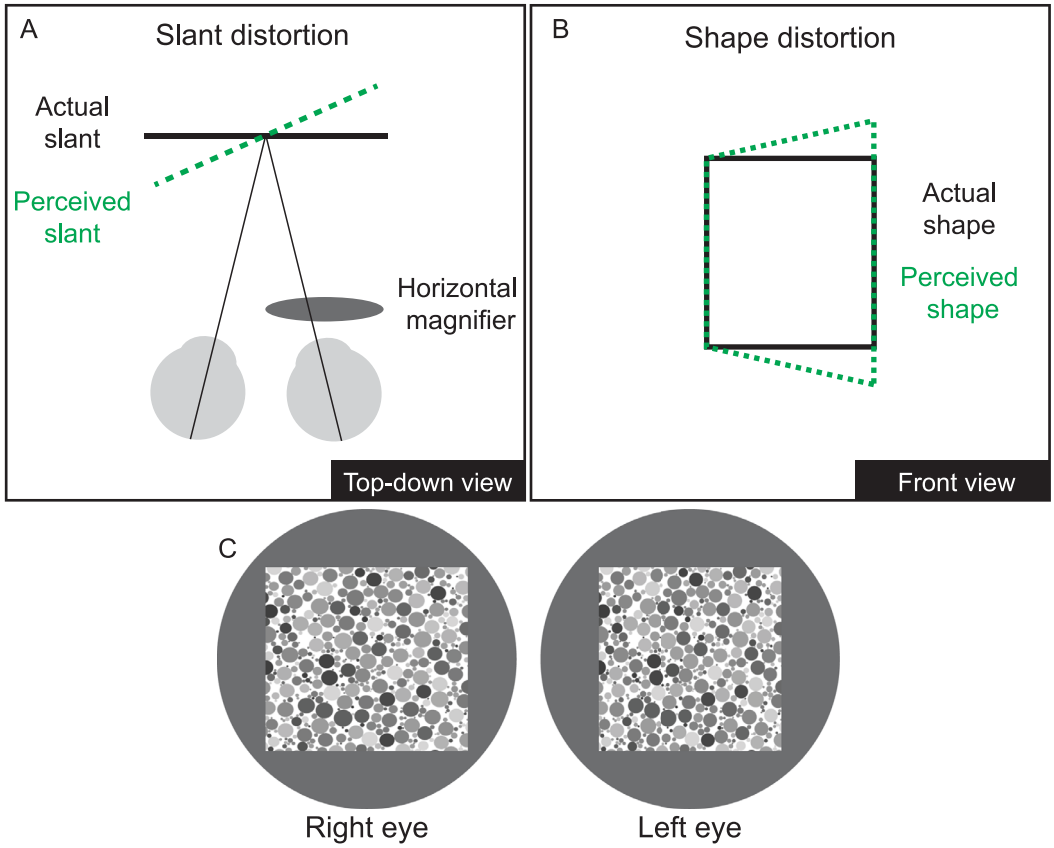

Figure 1. Spectacles that produce monocular horizontal magnification cause two perceptual distortions. (**A**) Surfaces appear to be slanted away from the magnified eye. (**B**) Surfaces appear taller on the side closer to the magnified eye. (**C**) Free-fusible stereo pair with one image horizontally 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.

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.

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 (Fig. 2).[1] 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.[35]

Figure 2. Experimental spectacles with a horizontal magnifier over the right eye.

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 (Fig. 1A).[1,5,6,11] We can describe how the magnification corresponds to slant as follows:[1,4,6]

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

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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 (Fig. 1B).[4–6,34] 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 (Fig. 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.

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/m^2 (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 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]

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.

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.

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° (Fig. 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.[26] 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.

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; Fig. 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.

Dual-Cue Stimulus. The same dot grid described above was presented binocularly so that perspective and binocular disparity cues for slant were present (Fig. 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.

Shape Task

This task was used to quantify the initial shape distortion, adaptation, and aftereffects (Fig. 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; Fig. 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.

Procedure

As depicted in Figure 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

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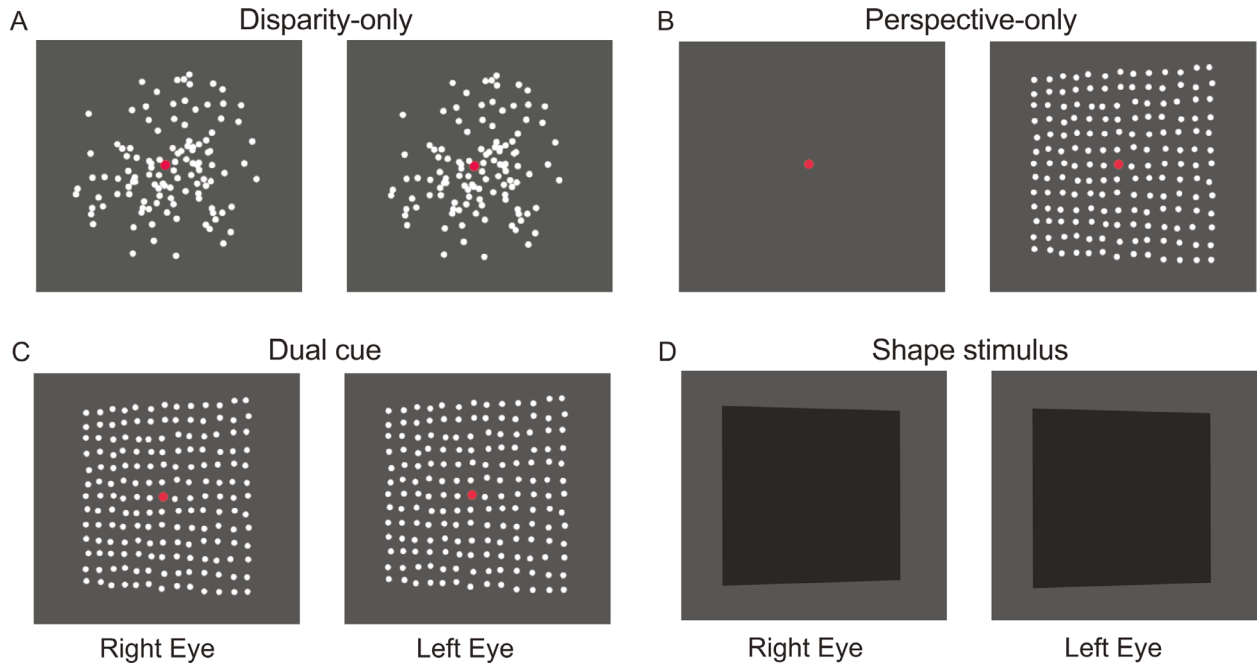

Figure 3. Schematics of stimuli presented during the slant task (**A–C**) and the shape task (**D**). Dot size, dot density, and luminance values are adjusted for visibility.

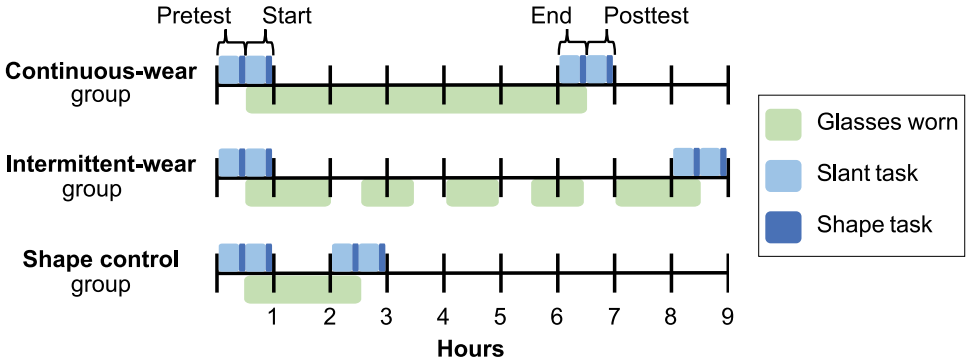

Figure 4. Procedure for the continuous, intermittent, and shape control groups. Four measurements (pretest, start and end of adaptation, and posttest) were taken for all groups. Participants went about their daily activities while wearing the spectacles.

at the end of the study to verify that participants performed the experimental tasks and procedure correctly.

Groups

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.

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.

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.

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

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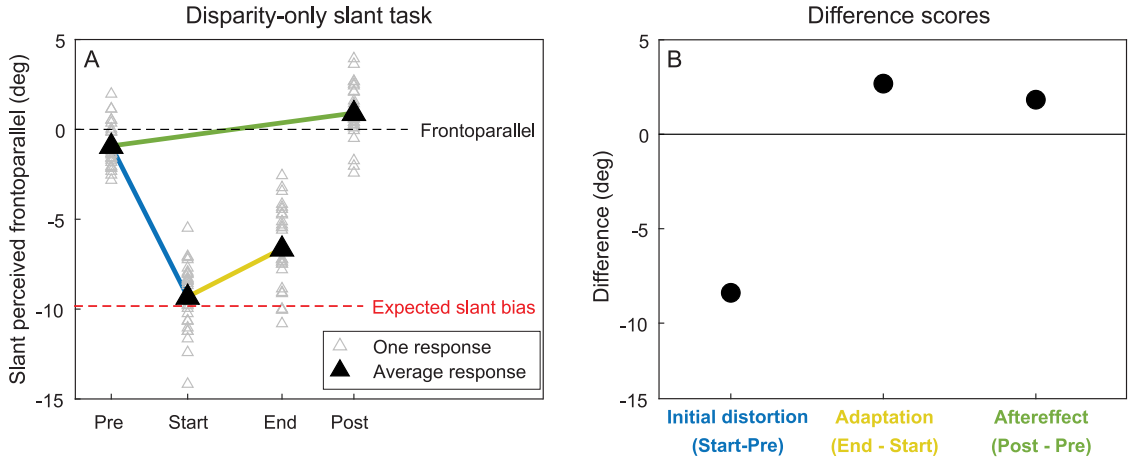

Figure 5. Example of how slant judgments are converted into difference scores for one participant. (**A**) Each slant judgment trial (*gray triangle*) and the average (*filled black triangle*) for the four measurements are shown for this participant. *Lines* connect pairs of averages that are subtracted to create each difference score. (**B**) The three resulting difference scores: initial distortion (*blue*), adaptation (*yellow*), and aftereffect (*green*).

freedom, and *P*-values, we report the mean (M), standard deviation, and effect sizes (quantified using Cohen's *d*) for each comparison.

Difference Scores. Changes in slant and shape perception were quantified for each participant using difference scores (Fig. 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 aftereffect 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.

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.[26]

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.[1,26,38] 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).

Results

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 (Fig. 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 (Fig. 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 (Fig. 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: $t(28) = 1.10$, $P = 0.279$, $d = 0.40$).

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 (Figs. 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: $M_{cont} = -0.76° \pm 1.65°$, $t(14) = -1.78$, $P = 0.096$, $d = -0.46$; $M_{inter} = -0.62° \pm 1.87°$, $t(14) =$

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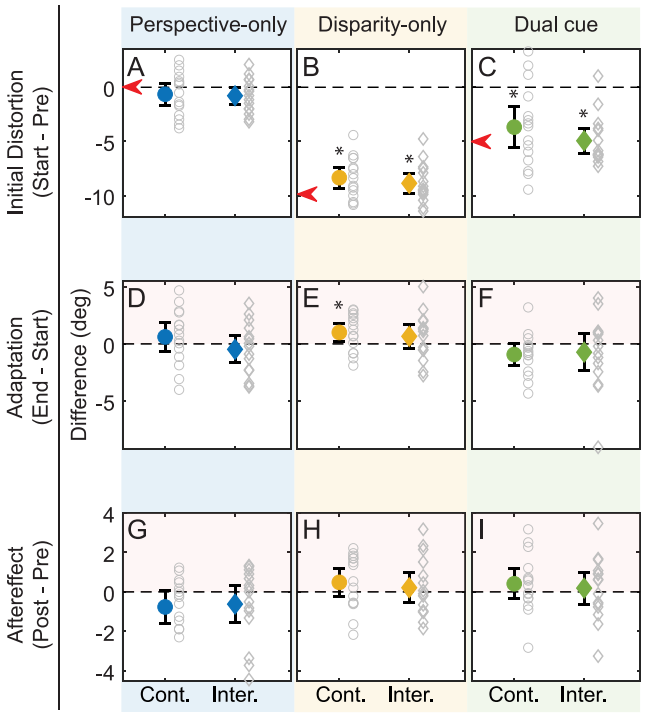

Figure 6. Results for the slant task. Initial slant distortion (**A–C**), adaptation (**D–F**), and aftereffects (**G–I**) for the continuous (Cont.) and intermittent (Inter.) groups are plotted as *circles* and *diamonds*, respectively. Each stimulus is plotted in a separate column. For the initial 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.

-1.28, $P = 0.221$, $d = 0.14$; between groups: $t(28) = -0.22$, $P = 0.825$, $d = -0.083$).

Slant Adaptation From Binocular Disparity

We expected that the continuous-wear group would undergo some disparity adaptation. While the continuous group did adapt significantly (Fig. 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 (Fig. 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 (Figs. 6F, 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: $t(28) = 0.39$, $P = 0.700$, $d = 0.14$).

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.[27,29,33,39] As depicted in Figure 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.

Evidence for Shape Distortion in Spectacles

As expected, both groups experienced a significant shape distortion upon putting on the spectacles (Fig. 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,

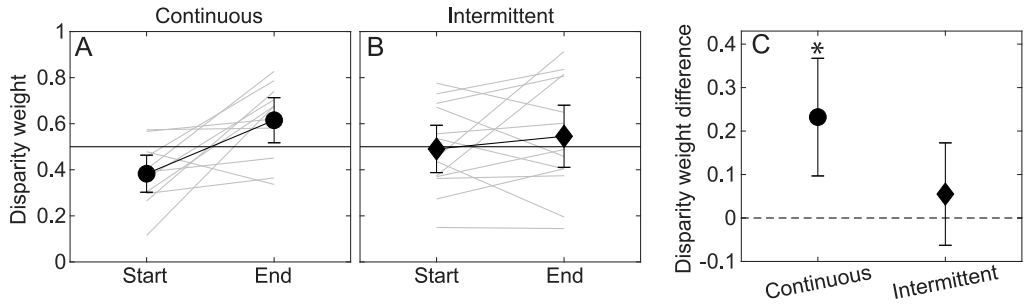

Figure 7. The average weight for binocular disparity in the start and end of adaptation measurements for the (**A**) continuous group (*circles*) and (**B**) intermittent group (*diamonds*). (**C**) For the continuous group, there was a significant change in disparity weight (end adapt – start adapt). *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.

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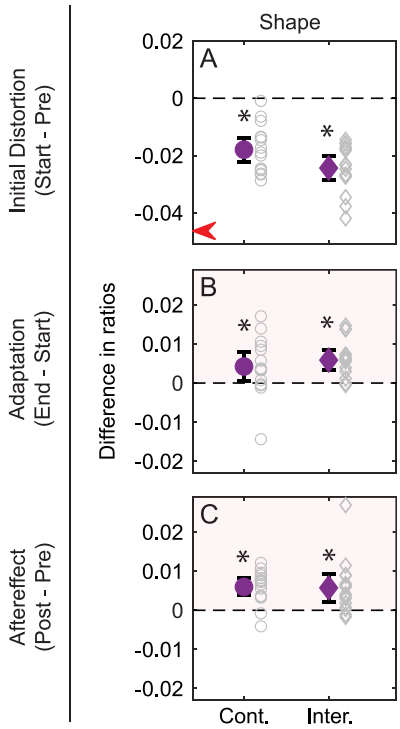

Figure 8. The average difference scores for the shape task. Initial distortion (**A**), adaptation (**B**), and aftereffects (**C**) for the continuous (Cont.) and intermittent (Inter.) groups are plotted in the same manner as Figure 6. The *red arrow* in A indicates the expected initial shape distortion, 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.

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.

Shape Adaptation

Both groups experienced significant shape adaptation (Fig. 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 (Fig. 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 ($t(28) = 0.11$, $P = 0.912$, $d = 0.041$).

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.

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.

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.[34] 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.,[1] 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.[2,40]

The notion that the frequency of distortion exposure may alter the type of adaptation could inform recommendations for new spectacle wearers (particularly those who

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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.

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 (Fig. 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 aftereffects (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.

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.[22,23,25] 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.[21] 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.

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.

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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:

$$\hat{S}_{combo} = w_d\hat{S}_d + w_p\hat{S}_p, \tag{A1}$$

$$w_d + w_p = 1. \tag{A2}$$

We also assume slant estimates from each cue are determined by the physical slant of the stimulus and

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an additive bias (B):

$$\hat{S} = S + B. \tag{A3}$$

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

$$\hat{S}_{combo} = w_d\,(S + B_d) + (1 - w_d)\left(S + B_p\right). \tag{A4}$$

To measure B_d and B_p 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 A3, we can then solve for the bias associated with each cue at each measurement time as follows:

$$B_d = -F_{disparity\text{-}only,} \tag{A5}$$

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

Note that when the glasses are on, B_d 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 A4 as follows, in terms of our measured quantities and a single unknown weight (w_d):

$$\begin{aligned} 0 &= w_d(F_{combo} - F_{disparity\text{-}only}) \\ &\quad + (1 - w_d)(F_{combo} - F_{perspective\text{-}only}). \end{aligned} \tag{A7}$$

This equation simplifies to

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

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.[26] However, the fact that the solution to Equation 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 A1.

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