Monovision: Consequences for depth perception from large disparities

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Abstract

Recent studies have confirmed that monovision treatment degrades stereopsis but it is not clear if these effects are limited to fine disparity processing, or how they are affected by viewing distance or age. Given the link between stereopsis and postural stability, it is important that we have full understanding of the impact of monovision on binocular function. In this study we assessed the short-term effects of optically induced monovision on a depth-discrimination task for young and older (presbyopic) adults. In separate sessions, the upper limits of stereopsis were assessed with participants' best optical correction and with monovision (-1D and +1D lenses in front of the dominant and non-dominant eyes respectively), at both near (62 cm) and far (300 cm) viewing distances. Monovision viewing resulted in significant reductions in the upper limit of stereopsis or more generally in discrimination performance at large disparities, in both age groups at a viewing distance of 300 cm. Dynamic photorefraction performed on a sample of four young observers revealed that they tended to accommodate to minimize blur in one eye at the expense of blur in the other. Older participants would have experienced roughly equivalent blur in the two

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eyes. Despite this difference, both groups displayed similar detrimental effects of monovision. In addition, we find that discrimination accuracy was worse with monovision at the 3m viewing distance which involves fixation distances that are typical during walking. These data suggest that stability during locomotion may be compromised, a factor that is of concern for our older participants.

Highlights

- Assessed effects of monovision on stereopsis over the range of useable disparities.
- Monovision degrades stereoacuity but had less effect at large disparities.
- Stereopsis from large disparities may be more resistant to interocular blur.
- Disruption of stereopsis was more severe at fixation distances typical of walking.

Keywords

Monovision, stereoacuity, upper disparity limit, depth perception, presbyopia, stereopsis,

In monovision, one eye is corrected for distance, and the other is corrected for near vision. Although this results in clear vision at both near and far distances, the image on one eye is always blurred (except at intermediate distances where both eyes experience similar blur), which has a deleterious effect on binocular vision particularly in terms of visual acuity, contrast sensitivity (Freeman and Charman, 2007; Rajagopalan et al., 2007) and binocular depth perception at near (Back et al., 1992; Collins et al., 1994; du Toit et al., 1998; Freeman and Charman, 2007; Harris et al., 1992; Ito et al., 2014) and far distance (Back et al., 1992; Durrie, 2006; Freeman and Charman, 2007; Papas et al., 1990; Situ et al., 2003). Stereoacuity, the ability to discriminate small depth intervals using stereopsis, has generally been shown to be highly sensitive to monocularly induced blur. Consistent with this sensitivity, many studies have documented reduced stereoacuity with monovision correction in presbyopes (Back et al., 1992; Collins et al., 1994; du Toit et al., 1998; Freeman and Charman, 2007; Harris et al., 1992; Ito et al., 2014; Kirwan and O'Keefe, 2006). This reduction is of concern particularly given reports that the likelihood that patients would continue to use monovision contact lenses after an initial trial period decreased with increasing degradation in stereoacuity under monovision compared to balanced binocular viewing (du Toit et al., 1998).

Good stereoacuity is important for everyday tasks that involve precise manipulation of objects within near space (McKee, 1983). However, it has been well documented that stereopsis provides reliable depth percepts well beyond the fusible range of disparities; contour targets at the upper range of stereopsis are typically diplopic (for review see Wilcox and Allison, 2009). In addition to the utility of stereopsis in the large disparity range, there is strong evidence that stereopsis is available to support depth judgements at distances up to 200 m (Allison et al., 2009), and can be important for navigating through the environment, obstacle avoidance, and stair walking.

Despite the utility and potential significance of suprathreshold stereoscopic depth perception, relatively little is known about the effect of monovision on depth percepts for large disparities or on the upper limit for stereopsis. Qian et al. (2012) recently approached this issue by assessing the upper disparity limit using random-line stereograms. Interocular blur was introduced to the stimulus to simulate monovision, and its impact on upper thresholds recorded relative to performance with no blur. They report that the upper threshold is reduced substantially by the addition of unequal blur in the two eyes. Castro et al (2017) reported similar reductions in the upper disparity limit with interocular differences in image quality due to higher-order optical aberrations.

While these studies suggest that interocular differences in image quality effectively reduce the useful range of stereoscopic disparities, both sets of experiments used global random-element stimuli. However, at large disparities false matches in such stimuli introduce depth noise, resulting in deceptively low upper disparity limits. In contrast, in experiments using isolated contours or patches, the upper limit of stereopsis is typically on the order of many degrees (Westheimer and Tanzman, 1956), and is robust to many of the stimulus manipulations known to have a deleterious effect on stereoacuity thresholds, such as varying stimulus contrast (Wilcox and Hess, 1996) and spatial frequency content (Wilcox and Hess, 1995). Contrary to Qian et al (2012), Li et al. (2016) reported resilience to interocular blur at large disparities in isolated Gabor patches. Indeed, both Hess and Wilcox (1994) and Li et al (2016) argue that at coarse scales observers rely on the overall envelope of the stimulus to make depth judgements, information that is unavailable in Qian et al's (2012) random-line pattern. Given the disparate conclusions of these studies, and the potential limitations of the stimuli used, the impact of monovision on the upper disparity range remains unclear.

Thus, one aim of the work presented here is to assess the impact of monovision viewing over a large range of binocular disparities. In an effort to document how this unequal refractive correction affects older viewers, we tested both young and senior participants. Another goal of the study was to determine whether the effects of monovision on stereopsis depend on viewing distance since viewing distance has typically been fixed (Qian et al (2012) used 97cm). Given that poor stereopsis has been shown to be a risk factor for impaired stability in aging populations (Buckley et al., 2005; Cummings et al., 1995; Lord and Dayhew, 2001; Nevitt et al., 1989) it is important to understand the effect of monovision on binocular visual function, particularly at intermediate distances important for locomotion (Allison et al., 2009). The few studies in which multiple viewing distances were tested with monovision correction (Back et al., 1992; Freeman and Charman, 2007; Situ et al., 2003) reported reduced effects of monovision on stereoacuity for larger viewing distances (6 m, 3 m and 2 m respectively) than small viewing distances (40 cm). In contrast, Odell, Hatt, Leske, Adams, & Holmes (2009) reported a larger negative effect of differential blur on stereoacuity in young adults at their far compared to near distance (3 m vs 40 cm). No previous studies have looked at the effect of viewing distance on stereopsis from large disparities for viewers with monovision. Given that the effect of differential blur on stereoacuity is distance dependent in young observers, we predict similar distance dependent effects on the upper limit of stereopsis. The present experiment is intended to confirm this in young observers and determine if this effect generalizes to presbyopes, who are the most likely candidates for monovision correction.

We measured depth discrimination in 16 young participants (6 Males, age from 18 – 24 years) and 12 older adults (6 Males, age from 60 – 70 years) from the York University community. The number of participants was chosen based on a series of experiments in progress at the time which used a similar task. As the sample sizes were not balanced, analysis was conducted separately for the two age groups in the interest of clarity of interpretation. An additional four participants in each group did not, or could not, complete testing and are excluded from analysis[2]. Individuals were compensated with course credit or were paid for participation. Older participants were also offered compensation for the cost of an optometric exam if they had not had one in the previous 12 months. The experiment was approved by the York University research ethics board, and followed the tenets of the Declaration of Helsinki.

A time-sequential polarized stereoscopic display was produced by a high-speed liquid crystal modulator panel (NuVision® SX21 Stereoscopic Display) mounted directly in front of a 21” CRT monitor (38.5 cm x 28.5 cm, 1024 x 768 pixels at 120 Hz). This allows different images to be presented to each eye when circular polarized filters are worn (60 Hz each eye). The subject’s

[2] One participant in each group withdrew after completing baseline testing, one of these stating that the task was too long and dull. The other excluded participants were not able to meet the criteria performance level of 70% correct during the training sessions. There was little else remarkable about these participants. All had comparable corrective prescriptions, scores on Snellen visual acuity, contrast sensitivity and Randot® stereoacuity as the participants who were able to achieve adequate performance on the task.

eyes were aligned with the centre of the monitor and at the correct viewing distance (62 or 300 cm) with head on a chin rest.

In all conditions, subjects viewed the displays through the filters and their habitual correction. To induce monovision blur, emmetropic young participants wore an additional +1D lens over the dominant eye and a -1D lens over the non-dominant eye. Non-emmetropic young participants were asked to bring their glasses to both sessions of the experiment and the required monocular blur was achieved by placing +1D and -1D lenses in front of their existing spectacles. Older participants with monofocal spectacles wore their distance correction for the experiment. For the baseline condition, additional +1.5D trial lenses were positioned in front of their corrective lenses for the near viewing (62 cm), and +0.37D lenses were added for far viewing (300 cm). To induce differential monocular blur in the near viewing condition, one +2.5D lens and one +0.5D lens was worn (1.5D +/- 1.0D). For the distance viewing condition, a +1.5D and a -0.5D (0.37 ≅ 0.5D +/- 1.0D) trial lens were worn in front of their regular distance correction. Bifocal wearers were corrected in the same way as monofocal spectacle wearers, but were asked not to use the lower section of their glasses. Participants wearing progressive lenses were asked to look through the portion of their lenses that they would typically use for a given viewing distance (i.e., top for distance, middle-bottom for near viewing). To induce blur a +1D lens and a -1D lens were positioned in front of their spectacle lenses.

Prior to the experiment, visual acuity, contrast sensitivity, distance Worth 4-dot test and distance +1D tests were conducted. All young participants had binocular visual acuity of 20/20 or better with their habitual optical correction. One participant had 20/25 acuity in the right eye and 20/20 in the left, the remaining 15 participants had visual acuity of 20/20 or better in both eyes. All young participants had binocular and monocular contrast sensitivity of 2.4% or better. All older participants had binocular visual acuity of 20/20 or better. One older participant had monocular acuity of 20/25 in both left and right eyes, the remaining 11 participants had visual acuity of 20/20 or better in both eyes. All older participants had binocular contrast sensitivity of 2.4% or better and monocular contrast sensitivity of 5% or better. The power of the participants' existing prescription lenses was measured using an auto-lensmeter (Nidek LM-1000P, Nidek Co.LTD, Japan). Stereoacuity was assessed using the Randot® Preschool Test. All young participants scored at least 40 arc seconds or better. Two older participants scored 200 arc seconds, three scored 100 arc seconds, one scored 60 arc seconds and the remaining six scored 40 arc seconds. The hole-in-card test for eye dominance was conducted using a card with a 6 mm aperture and a small target at 2 m.

During testing, participants fixated a black cross (see Figure 1B), which remained visible throughout the block, as did a zero-disparity frame that served as a strong fusion lock. On each trial, participants viewed a white line with binocular disparity relative to the fixation cross for 300 ms (see Figure 1A). The line was offset laterally in opposite directions in the left and right eye image to create horizontal disparity (0.67, 1, 2, 2.5, 3 and 3.5 degrees). Screen disparities were calculated assuming the average adult interpupillary distance of 63.3 mm (Dodgson, 2004). It should be noted that at a viewing distance of 300 cm, uncrossed disparities above 1.1 degrees are not ecologically possible. The participant indicated via button press whether they perceived the test line to come out of (crossed disparity), or into (uncrossed disparity) the screen relative to the reference frame. The next trial began 1 second after the participant entered their response.

Each experimental block consisted of 150 trials (5 disparity levels x 2 (crossed/uncrossed) x 15 repeats). The factorial experiment consisted of eight counterbalanced blocks of pseudo-randomized trials conducted over two sessions. Viewing condition and distance were varied across the blocks (Viewing Condition: Baseline/ Monovision; Viewing Distance: Near=62 cm/Far=300 cm). The proportion of correct depth-discriminations was computed at each disparity level and psychometric functions were fit to individual participants' data for each condition. The upper disparity limit was defined as the level at which the fitted proportion of correct trials decreased to a cut-off value of 75%. If the participant's performance was above the 75% threshold for all disparity levels, an upper limit disparity of 3.5 degrees was assigned. In conditions in which a participant's performance was never above the 75% threshold, a limit of 0.5 degrees was assigned.

Histograms showing upper disparity limit counts for young and old participants are shown in Figure 2A. For young participants, a Wilcoxon Signed Rank test (all tests were two-sided) indicated that the upper disparity threshold for the near viewing condition was not significantly higher ($p = 0.386$) in the baseline condition (Median = 3.5 degrees, Range = 1 – 3.5 degrees) than in the monovision condition (Median = 3.13 degrees, Range = 0.5 – 3.5 degrees). However, the median upper threshold was significantly higher for the baseline condition relative to monovision at a viewing distance of 300 cm ($p = 0.047$) (Baseline: Median = 3.0 degrees, Range = 1.5 – 3.5 degrees; Monovision: Median = 2.45 degrees, 0.5 – 3.5 degrees).

For the older participants, the median upper disparity threshold in the near viewing condition was at the maximum test value of 3.5 degrees at baseline (Range = 2.3 – 3.5 degrees) and with induced monovision (Range = 1.1 – 3.5 degrees), which were not significantly different (Wilcoxon signed rank test, $p = 0.674$). However, in the far viewing condition, the median upper disparity thresholds were 3.0 degrees at baseline (Range = 0.6 – 3.5 degrees) and 1.8 degrees with induced monovision (Range = 0.5 – 3.5 degrees). At this distance, median thresholds were higher for baseline relative to monovision conditions but the difference was not significant (Wilcoxon signed rank test $p = 0.062$).

We also analyzed the percentage correct responses, averaged across the participants as function of disparity, group, distance and view condition. A repeated-measures ANOVA indicated significant main effects (all p's <0.001) of disparity level, viewing distance, and viewing condition, as well as significant interactions between disparity level and viewing distance, and between viewing distance and viewing condition. Post-hoc pairwise Wilcoxon signed-rank tests (Holm–Bonferroni correction for $\alpha < 0.05$) showed that both younger and older adults seem to be relatively unaffected by induced monovision in the near viewing condition over our range of large disparities. However, at a viewing distance of 300 cm, older adults demonstrated significantly marked decreases in performance relative to baseline with induced monovision across the range of large disparities tested (except at 3.5 degrees where uncorrected $p = 0.069$). Younger adults showed marginal reductions due to monovision at 300 cm (not significant after correction, uncorrected $p < 0.05$ for four disparities). However, as with the older subjects, performance with induced monovision generally tended to be worse than baseline.

Maximum accommodation decreases from 10 +/- 2.0 diopters at age 26 to 1.5 +/- 1.0 diopters at age 60 (Durrie, 2006). Thus, the typical younger participants recruited as part of this study have a considerably larger accommodative range than the older adults. It is therefore possible that younger adults with induced monovision might exhibit a variety of accommodative responses. We expected that the insertion of a +1D lens in front one eye and a -1D lens in front of the other would cause a young observer to accommodate and eliminate the blur in one eye. At a distance 300 cm or 0.33D, accommodation could not be reduced beyond 0D to null the +1D lens, but it could be increased to compensate for the -1D lens. Thus, we assumed that accommodation would be close to 1.33D, resulting in +2D of defocus in the eye viewing through the +1D lens and clear vision in the dominant eye. At 62 cm, the normal accommodation range in young participants should have been sufficient to allow nulling of the blur in either eye (+0.61 and +2.61 D, respectively) so we predicted clear vision in one eye and 2D blur in the other eye, with the sign determined by which eye accommodated.

To assess this assumption, objective accommodation measures were obtained in 4 participants ranging from 23 to 30 years of age. All participants had monocular and binocular visual acuity of 20/20 or better. Due to the nature of the measurement process, all participants in this experiment were either emmotropic or corrected with contact lenses. The photorefractor consisted of an infrared sensitive CCD camera (PixeLink, Canada) connected to a computer through an IEEE 1394 port and high-speed video capture software (StreamPix Version 3.13, Norpix Inc., Montreal, Canada). A cluster of infrared LEDs served as the light source and were set on a plastic housing defining the camera aperture. The two-step calibration procedure employed to calibrate the photorefractor measurements for each participant is described in detail in Suryakumar et al. (2007).

The calibrated time record of the plane of focus for one participant is presented in Figure 2B for target at 62 cm and 300 cm. For these targets, the ideal plane of focus is at 1.61D and 0.33D, respectively. Artefacts due to blinks were identified and removed from the figures. It is apparent that, contrary to anecdotal reports of a sense of instability in focus while wearing induced monovision, the plane of focus of both eyes remained fairly stable under both baseline and monovision viewing conditions; this is evident in the dynamic photorefractor measurements of all four participants.

When viewing the near target, the mean plane of focus of the optical system (baseline = eye; monovision = eye + lenses) should be 62 cm or 1.61 D to be in clear focus. To achieve this under induced monovision, with different lenses in front of the two eyes, requires different accommodation in each eye. Three participants appeared to be focusing the near target for clear vision in their dominant eye which was viewing through the -1D lens rather than their non-dominant which was viewing through the +1D lens. This is indicated by the smaller lag of accommodation of the dominant eye compared to the lead in the non-dominant eye. The dominant eye lagged stimulus demand by approximately 1/3 to 1/2 diopters, likely within the depth of focus and therefore relatively clear. The other participant was likely focusing with her non-dominant eye which was corrected with the +1D lens, with her non-dominant eye leading by approximately 1/3D, and her dominant eye lagging by 1.89D with monovision. This participant made use of the +1 lens in order to relax accommodation relative to baseline.

The ideal focal distance for the far viewing condition was 0.33D. Three of four (same three as in the paragraph above) participants had positive values of accommodative response. This indicates that these participants either may have some slight latent hyperopia, or reflects a small error in absolute calibrations that were conducted only at the near distance. These values were all under 0.33D. As in the near viewing condition, baseline lead/lag in accommodation were less than 0.67 D, and therefore likely clearly perceived by the participants. Under induced monovision three of the participants again focussed the target with their dominant eyes, which were viewing through the -1D lens. This is indicated by the smaller lag of accommodation of the dominant eye compared to the lag the non-dominant eye. The fourth participant appears to have been accommodating only slightly more with monovision relative to baseline. It appears that she adjusted her accommodation so the eyes were almost bracketing the target plane of focus, and thus she lagged by 1D in her dominant eye, and led by 1.37D in her non-dominant eye. It is likely she was experiencing appreciable blur in both eyes.

The results of our experiment provide insight into the impact of optically induced monovision on the useful range of stereopsis in young and old adults. Consistent with Qian et al (2012), we found that for both groups of participants there were more significant decreases in depth discrimination accuracy in the small disparity range than in the large disparity range with monovision. As anticipated, we found that upper disparity thresholds in our study are much larger than that reported previously, even with unequal image quality. At a viewing distance of 62 cm, median upper limits of stereopsis were at or greater than 3.5 deg (the maximum disparity tested) and did not differ significantly between baseline and monovision for either age group. While there may be differences in the true upper limit, which would require further testing to even higher disparities, this does suggest that stereopsis from large disparities is more resistant to interocular differences in image quality than stereoacuity, as shown by Wilcox and Hess (1995).

In spite of stimulus-related differences, both this study and Qian et al (2012) consistently show that the useful range of stereopsis is reduced with monovision corrections. Our viewing distance manipulation showed that the impact of monovision is modulated by distance in that the median threshold (upper disparity limit) is lower for the monovision than the baseline condition at 300cm. The substantial monovision-related decrease in stereo-discrimination performance at 300 cm compared to 62 cm viewing distances is in line with the results of Odell et al (2009) and Lovasik & Szymkiw (1985) in which the magnitude of change in stereoacuity thresholds was larger at greater viewing distances when anisometropia was induced in young subjects. However, it is at odds with several studies testing monovision patients at multiple distances (Back et al., 1992; Freeman and Charman, 2007; Situ et al., 2003) in which the opposite pattern was found. It should be noted that the studies with contrary results employed different clinical tests at different distances; tests which have been found to give inconsistent results even at the same viewing distance (Odell et al., 2009). Thus, these contrary findings more likely reflect a lack of inter-test reliability of the standard tests routinely employed in clinical testing than a valid effect of viewing distance.

Interestingly, the visuomotor system of our young participants 'chose' a monovision solution. That is they tended to accommodate to minimize blur in one eye at the expense of blur in the other. If this were true of all the young observers then they would have experienced considerable interocular blur in our monovision conditions. In contrast, older participants could not accommodate and would have experienced roughly equivalent blur in the two eyes with a difference in direction but with roughly equivalent magnitude (such a situation would occur routinely for a monovision patient fixating an intermediate target distance). However, both groups displayed similar detrimental effects of monovision, and a more marked disruption at the larger viewing distance.

The primary objective of this study was to assess the short-term effect of optically induced monovision on stereopsis in young and older adults. We found that induced monovision reduced the range of stereopsis in observers from both age groups. Monovision also had a larger impact on upper limits of disparity at a viewing distance of 300 cm than at 62 cm. Poor depth perception has been identified as a risk factor for falls and hip fractures in aged populations (Cummings et al., 1995; Menant et al., 2008; Taylor et al., 2004). The results of this study indicate that monovision may be particularly disruptive to stereopsis at fixation distances typically used when navigating the environment.

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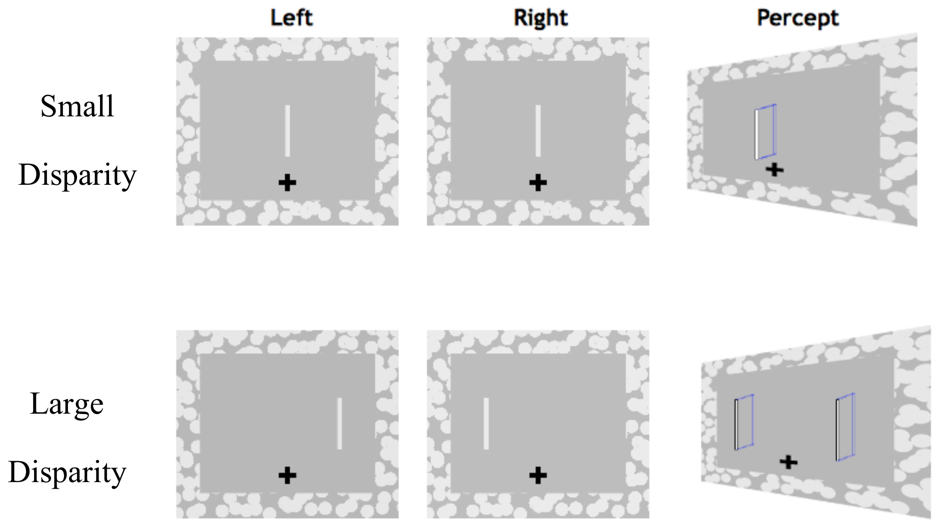
(A)



(B)

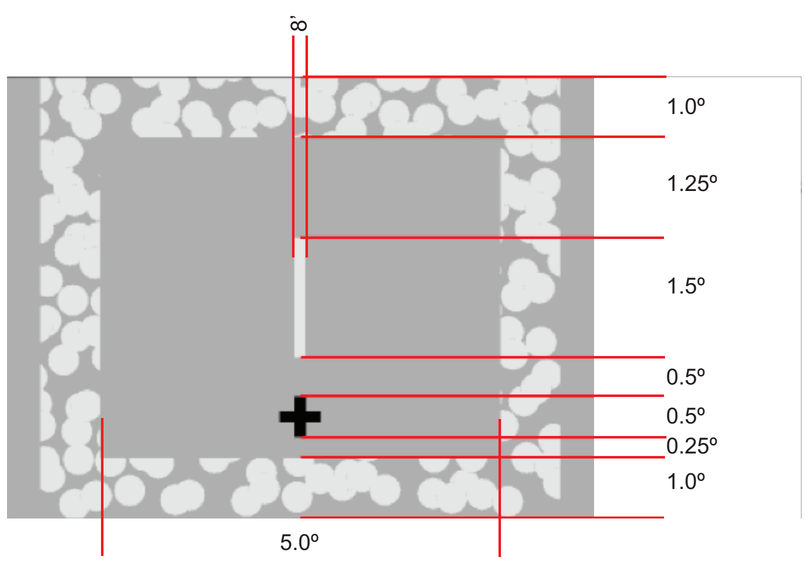
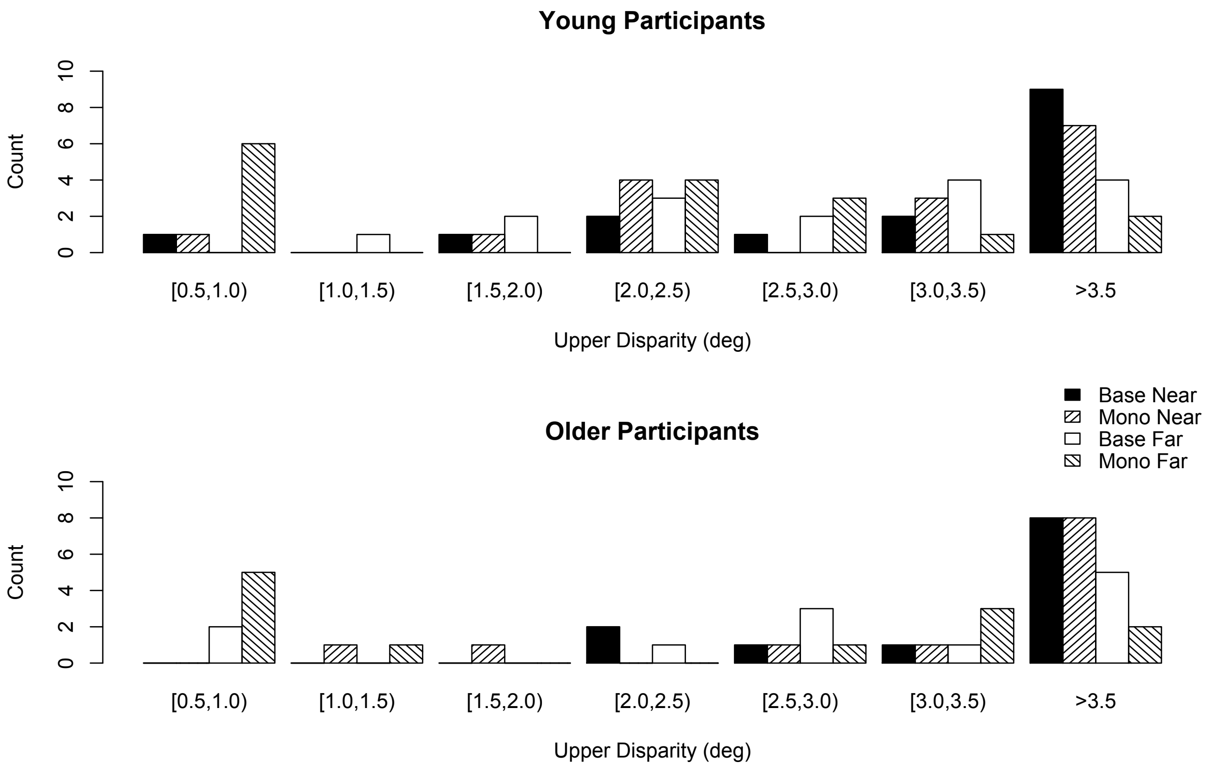


Figure 1:(A) Example of the experimental stimuli. (Top) Stimuli presented to left and right eye with small horizontal retinal disparity. These lines fuse to create a percept of a single line in front of the zero disparity plane created by the cross and border (behind with crossed free fusion). (Bottom) Stimuli presented with large disparity will be perceived as diplopic although relative depth may still be apparent. (B) Stimulus configuration in terms of visual angle. Elements of the stimulus were scaled relative to the viewing distance to maintain a constant visual angle.

(A)


Young Participants
Count
0
2
4
6
8
10
[0.5,1.0)
[1.0,1.5)
[1.5,2.0)
[2.0,2.5)
[2.5,3.0)
[3.0,3.5)
>3.5
Upper Disparity (deg)
Base Near
Mono Near
Base Far
Mono Far
Older Participants
Count
0
2
4
6
8
10
[0.5,1.0)
[1.0,1.5)
[1.5,2.0)
[2.0,2.5)
[2.5,3.0)
[3.0,3.5)
>3.5
Upper Disparity (deg)

(B)

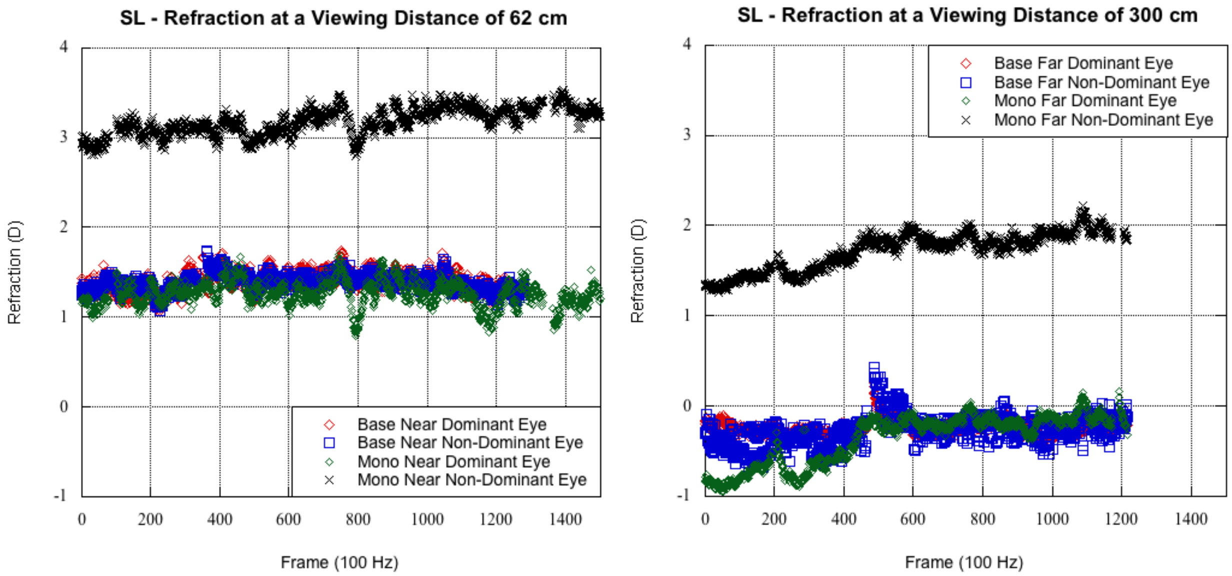


Figure 2: (A) Histogram of upper limit of stereopsis disparity levels for young (top) and older (bottom) participants. Each panel shows the frequency for fitted upper disparity limits at near (62 cm) and far (300 cm) viewing distance under both baseline and monovision conditions. Bins are specified as [*lower*, *upper*) and indicate the range *lower* ≤ value < *upper*. (B) Participant SL refraction (D) at a viewing distance of 0.62m (≈1.61D) and 300 cm (≈0.33D). Baseline dominant (red), baseline non-dominant (blue), monovision dominant (-1 lens, green), monovision non-dominant (+1 lens, black).